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KENYA Aquatica

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A Scientific Journal of Kenya Marine and Fisheries Research Institute

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Editorial

The current edition of the Kenya Aquatica Journal presents a range of interesting findings on research conducted on Kenya's aquatic resources and ecosystems. The studies inform the management of these vital ecosystems to enhance the sustainable utilization of the Blue resources for socio-economic development.

One paper assesses cage fish farming practices in Lake Victoria and their implications on sustainable resource use and community well-being, identifying challenges and opportunities for improving ecological and socio-economic outcomes. Another paper quantifies fish bycatch in Lake Turkana, exploring the potential for discard utilization to contribute to local economies, and highlighting the need for a multi-species approach to sustainable fisheries management.

A study on replacing fishmeal with black soldier fly larvae meal in diets for African catfish demonstrates the potential of this alternative protein source to improve the economic and environmental sustainability of aquaculture. Another one investigates the impacts of mangrove die-back due to sedimentation on associated fauna, revealing significant changes in the composition and diversity of crabs and molluscs, and underscoring the vulnerability of mangroves to climate change and land use practices.

An assessment of the stock status of a commercially important reef fish species using length-based approaches indicates the stock is currently overexploited and recommends measures to protect juveniles and spawning biomass. Finally, a study on remote sensing and GIS demonstrates how to integrate mapping and distribution of springs in forested watersheds of Taita Tavela, informing conservation and water resource management planning.

The Kenya Aquatica journal continues to play a crucial role in improving accessibility of scientific knowledge to policy makers, resource managers and stakeholders thus supporting evidence-based decision making on the sustainable use of Kenya's aquatic resources. This aligns with the Bottom-Up Economic Transformation Agenda (BETA) of the Kenya Government, which seeks to optimize the Blue Economy as a key pillar for socio-economic development, as outlined in Kenya's Medium Term Plans III and IV. The research findings published in the Kenya Aquatica journal can contribute in unlocking the potential of the Blue economy to drive employment creation, food security, and economic growth, while ensuring ecosystem conservation. By linking KMFRI with partners across academia, government and communities, Kenya Aquatica provides a platform for collaboration and application of research findings. KMFRI remains committed to generating and sharing scientific knowledge to support the Blue Economy agenda and address challenges facing aquatic ecosystems. It is partly in pursuit of this innovative linkage on reporting research output among partners that the Western Indian Ocean Marine Science Association (WIOMSA) has consistently funded production of Aquatica Journal. The Editorial Board and KMFRI management owe WIOMSA much gratitude in this regard.

About Kenya Aquatica

Kenya Aquatica is the Scientific Journal of the Kenya Marine and Fisheries Research Institute (KMFRI). The aim of the Journal is to provide an avenue for KMFRI researchers and partners to disseminate knowledge generated from research conducted in the aquatic environment of Kenya and resources therein and adjacent to it. This is in line with KMFRI's mandate to undertake research in "marine and freshwater fisheries, aquaculture, environmental and ecological studies, and marine research including chemical and physical oceanography", in order to provide scientific data and information for sustainable development of the Blue Economy.

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Submitting Articles

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Featured front cover picture: Community members participating in mangrove planting at Gazi, Kwale County (Photo Credits: Dr. Amina Hamza, KMFRI).

Featured back cover picture: Logo of the SolCoolDry Project denoting drying and cooling of fish and other perisheable products using solar energy

Contents

Catch characteristics, gears, and fishing effort in reef fisheries: rabbit and emperor fish at Nyali landing site, Mombasa, Kenya

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Abstract

Coral reefs are some of the most productive marine ecosystems, comprising a wide range of fish biodiversity and other marine organisms. Reef fisheries influence the ecosystem health, productivity and sustainability. The present study contributes to knowledge on the reef fish species, their sizes and the gears used with emphasis on *Siganus* spp. and *Lethrinus* spp. due to their importance as indicator fish families in the coral reef ecosystem. To achieve the goal, the study determined catch per unit effort (CPUE) of reef fishes by using in-depth key informant interviews targeting fishers and fish traders. Descriptive statistics was used to summarize the data, while single factor Analysis of Variance (ANOVA) was used to evaluate differences in weight for different fishing gears. Findings revealed that 20 fish families with 32 fish species were recorded dominated by Siganidae contributing 19% and Lethrinidae contributing 18%. Lethrinidae and Siganidae were dominant in hand lines, basket traps and long lines. Average sizes were 22.81 cm for Siganidae and 20.4 cm for Lethrinidae. Overall, a fisher landed an average 5.4 kg day^{-1}. There was a significant difference in the weight of fish harvested using different fishing gears, with basket traps, handlines, long lines and handlines landing the highest catches with 13, 11 and 10 fish families respectively. The results of this study are essential in catch assessment of reef fisheries and contribute to the formulatin of measures on conservation and management of coral reef ecosystems and the sustainable utilization of the Blue Economy.

Key words: species composition, fishing gears, fish sizes, catch per unit effort, coral reef ecosystem

Introduction

Coral reefs are among the most productive marine ecosystems comprising a range of fish diversity and other marine organisms (Parravicini *et al.,* 2021). Concerns have emerged globally, on the future of coral reef ecosystems as they are threatened by climate change and local anthropogenic impact such as use of destructive fishing gears and overexploitation (Parravicini *et al.,* 2021).

Demersal reef fisheries are important, contributing approximately 45 % of the total marine fish caught in Kenya (Okemwa *et al.,* 2018). Additionally, the unclassified demersal finfish group in the reef ecosystem contribute an extra 5%, while the rest includes other groups such as pelagic species (35%), molluscs (9%), and crustaceans (3%).

At the South Coast of Kenya, standard fishing gears commonly used by artisanal fishers in the coral reef ecosystem catch a wide variety of fish species (Samoilys *et al.,* 2011). Different fishing gears target specific fish families and size classes.. Basket traps primarily target Siganidae, Lethrinidae, and Leptoscaridae, while gillnets are more selective towards Siganidae, Lethrinidae, Batoidea, Nephropidae, and Scombridae, with 49% of the catch consisting of juveniles in the targeted families. Handlines catch fish from the families Lethrinidae, Epinephelidae, Carangidae, and Scombridae, whereas spear guns target Octopodidae, Batoidea, and Muraenidae. Beach seines are effective in capturing Siganidae, Lethrinidae, Clupeidae, and Scaridae. The dominant fishing gears reported in published literature include basket traps, gillnets, handlines, spear guns, and beach seines (Samoilys *et al.,* 2011).

A frame survey conducted by the State Department for Fisheries, Aquaculture and the Blue Economy revealed that the dominant fishing gears used in the reef ecosystem include basket traps (3169), gillnets (3956), hand lines (4132), and spear guns (1007), while beach seines recorded the lowest number (139) (Samoilys *et al.,* 2017).

Siganidae and Scaridae families dominated most of the catch by all gears except for handlines (Samoilys *et al.,* 2011). Approximated catches of *Siganus* spp. were 44.8% of total catch and 47.3% were *Leptoscarus* spp. Hand lines catches were dominated by *Lethrinus* spp., estimated to be about 49.9%. Handlines and basket traps contributed most of catches in the reef ecosystem, while spear guns contributed the least (Samoilys *et al.,* 2011).

Sustainable management of reef fisheries has been challenging to implement due to limited stock assessment, insufficient information on the catch composition and limited data to support science-based management (Okemwa *et al.,* 2018). Other challenges facing reef resources include; unregulated fishing activities, use of destructive fishing gears (Tuda *et al.,* 2016) and climate variability (Jury *et al.,* 2010). These challenges have led to declining stocks, yield, sizes, species richness, and species composition in coral reef ecosystems (Tuda *et al.,* 2016).

The present study aimed at providing data and information on types of coral reef fish species, their sizes, fishing gears and Catch Per Unit Effort (CPUE) which are essential in catch assessment and contribute to formulation of management and conservation measures for the coral reef ecosystems.

The objectives the study were: i) to identify the fish species caught, with a focus on Siganidae (rabbit fish) and Lethrinidae (emperor fish); ii) to investigate the fishing gears employed to catch reef fish, particularly those targeting Siganidae and Lethrinidae; iii) to determine the size distribution of reef fish, specifically Siganidae and Lethrinidae; and iv) to calculate the Catch Per Unit Effort (CPUE) of fish landed at Nyali landing site.

Materials and methods

Study area

The study was conducted for 15 days, between June and July 2021, at Nyali landing site located on the mainland North of Mombasa County, Kenya (Fig. 1). Nyali landing site is located between latitude 4°30′ - 4°35′S and longitude 39°22′ - 39°27′E North of Mombasa County, Kenya.

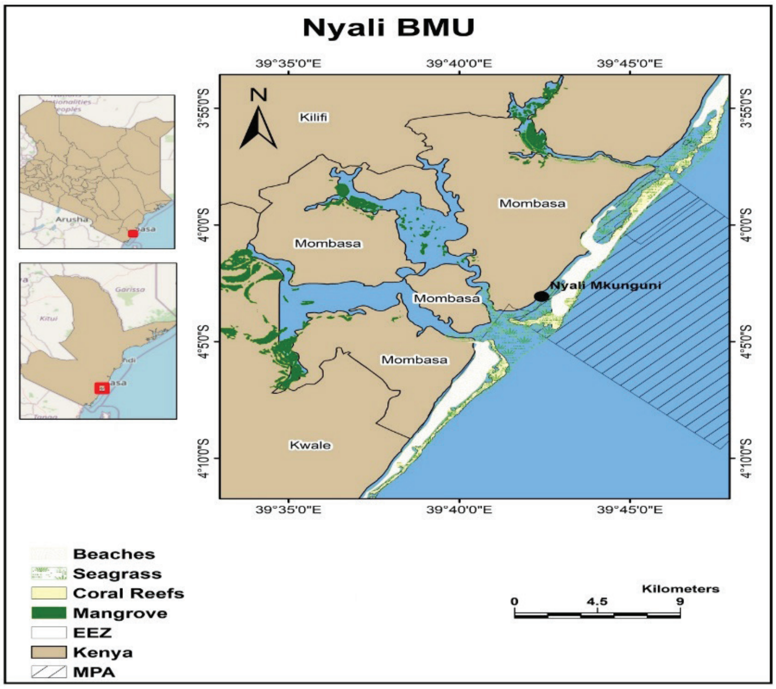

Figure 1. Map of Kenya coastline showing Nyali landing site, coastal Kenya (Source: Authors).

Respondent sampling

Respondents were selected through purposive sampling. A pre-designed questionnaire (Annex 1) was administered to the fishers and owners of fishing vessels at the landing site. Out of the total 85 questionnaires administered, 78 (91.8%) were deemed suitable for analysis, as they contained all the basic data required. The remaining questionnaires with missing data were excluded from the analysis due to incomplete information.

Catch sampling

Catch data was collected at the landing site during the survey. The data included types of fishing gears used by different fishermen, number of fishermen and the fishing ground, weight of fish landed in kilogram (kg), number of trips made by different fishers per day, types and sizes of fish species caught using different gears.

Fishing vessels were randomly selected to represent the entire fish caught by different fishers. One of the fishers, either the captain or a fisherman in the same vessel was interviewed as guided by the questionnaire after weighing the total catch. Approximately a quarter of the total fish catch was randomly sampled, and the fish species therein identified using Anam and Mosdarta's (2012) fish identification guide. For each species in the sample, the total lengths of 2 to 5 individuals were measured to the nearest centimeter using a tape measure and recorded.

Data analysis

Data was entered into Microsoft Excel for analysis. Pivot tables were utilized to interpret the data, and the results were visualized using tables and bar graphs. Descriptive statistical analysis was performed to summarize the data. Single-factor analysis of variance (ANOVA) test was conducted to determine significant differences in catch weight among different fishing gears, . The total catch weight of fish landed by each gear recorded daily over the 15-day sampling period was entered into separate columns in an Excel spreadsheet, each column representing a different gear type. The one-way ANOVA was then performed to test for significant differences in catch weight across the fishing gears. Subsequently, a post-hoc analysis was carried out to identify which specific gear types exhibited statistically significant differences in catch weight.

Results

Fishing gears

Seven gear types were noted to be commonly used by fishers at Nyali landing site (Fig. 2). Basket traps and hand lines were the gears of choice for majority of the fishers. "Basket traps were ranked as the most dominant gear utilized to exploit coral reef fisheries, representing 57% of the gear utilized, followed by handlines (18%), long lines (17%), stationary gill nets (4%)

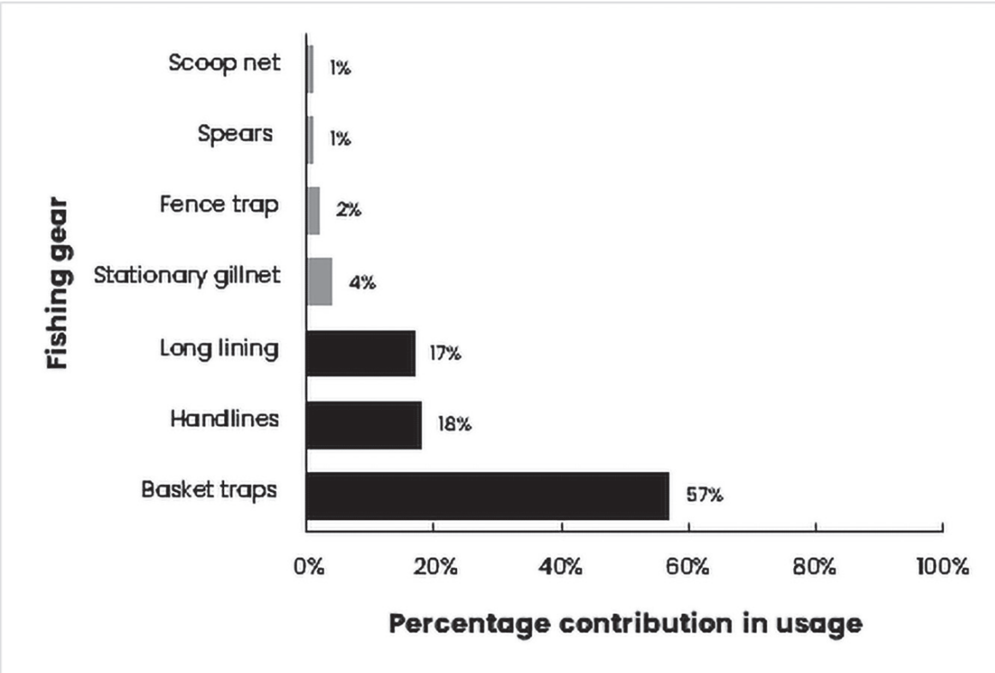

Figure 2. Percentage contribution of various fishing gears used by fishers at Nyali landing site, coastal Kenya.

and fence traps (2%), while spears and scoop nets each accounted for the lowest proportion at 1% of the fishing gears used at the study site. On contribution to total landings, basket traps landed the highest proportion of the catch i.e., 323 kg followed by long lines (133 kg), stationary gill nets (88 kg), hand lines (76 kg), fence traps (36 kg), spears (7 kg) and finally scoop nets (4 kg)

Different fishing gears targetted different fish families (Table 1). A total of 20 fin fish families were landed; basket traps landed 13 families, long lines landed 11 families, handlines landed 10 families, stationary gill nets landed 1 family, while spears landed 3 families. Fence traps and scoop net did not catch any finfish families, but each landed 2 non-fin fish families (Fig. 3).

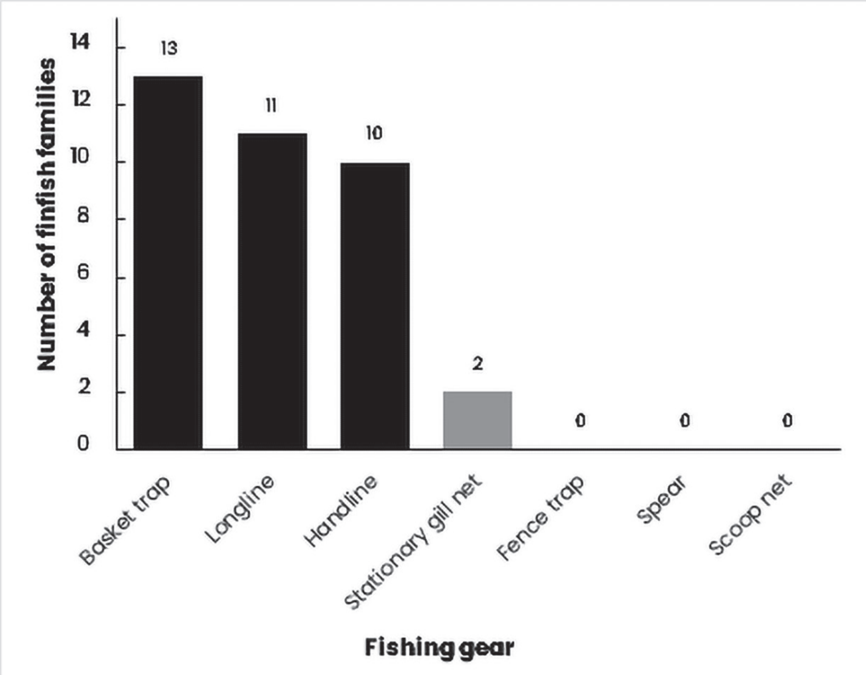

Figure 3. Number of finfish families landed by different fishing gears at Nyali landing site, coastal Kenya.

Catch composition

Based on the pooled data, 20 finfish families were recorded from a sample of 32 fish species. The top ten families constituted 88% of the total fish landed and were dominated by Siganidae (19%) and Lethrinidae (18%) (Fig. 4). Other finfish families included Mullidae (goatfish), Lutjanidae (jobfish), Mugilidae (mullet), Teraponti-dae (grunter), Clupeidae (sardines), Muraenidae (moray eels), and Carangidae (shrimp scads). Non-finfish families, including Octopodidae (octopus), Penaeidae (prawns), and Palinuridae (lobsters), contributed 12% of the total catch.

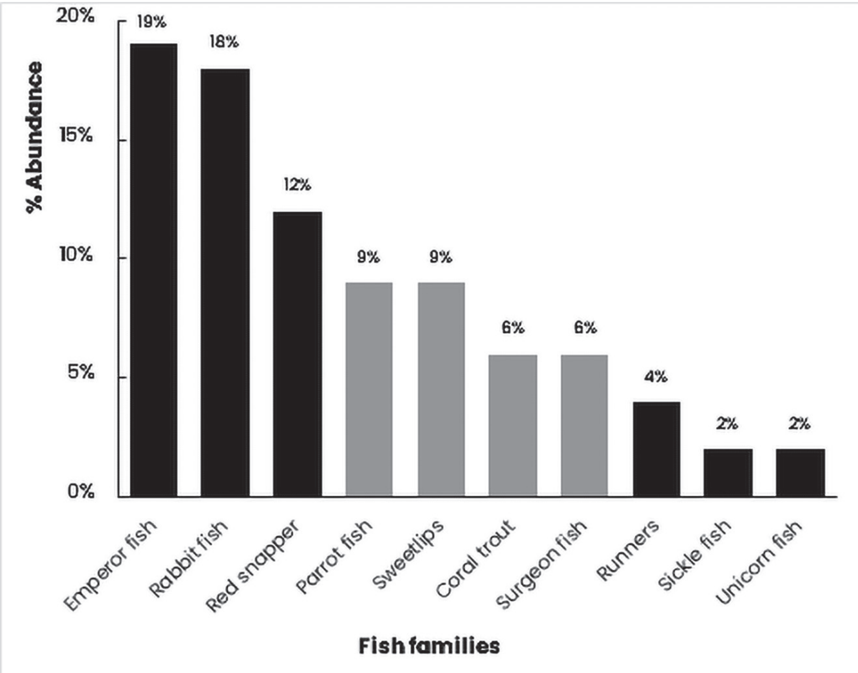

Figure 4. Abundance of the 10 most abundant finfish families.

There were differences in catch composition from different fishing gears (Table 1). Up to 82.5% of Siganidae family, mainly *Siganus sutor* was caught using basket traps, 10% by hand line and 7.5% by long line. Up to 41.46% of Lethrinidae, mainly *Lethrinus lentjan (L. lentjan)* was landed by hand line, 46.34% by basket traps and 12.2% by long line.

Table 1. Catch composition of different gears at Nyali landing site.

GEAR TYPE	TYPE OF FISH FAMILY CAUGHT
Hand lines	Key indicators fish families; emperor fish and rabbit fish and other fish families such as red snapper, coral trout, sickle fishes, parrot fish, job fish, goat fish and sweetlips
Basket traps	Key indicators fish families; rabbit fish and emperor fish and other fish families such as parrot fish, goatfish, red snapper, unicornfishes, coral trout, sickle fishes, spade fishes, runners, lobsters, rubber lips, grunt, moray, prawn, surgeon fish and job fish
Fence traps	Sardines, prawns
Stationary gillnet	Parrot fish, mullets, sardines
Long line	Key indicators fish families; Emperor fish and rabbit fish and other fish families such as runners, red snappers, moray, unicorn fish and parrot fish
Spears	Lobsters, moray, octopus
Scoop nets	Octopus, prawns

Fish sizes

The sizes of key fish families and other finfish families varied from one gear to another (Fig. 6). The mean total length of fin-fish caught during the study was 26.68 cm. The average total length of Siganidae (rabbitfish) varied by fishing gear, with fish caught by basket traps, hand-lines, and longlines measuring 22.44 cm, 18.31 cm, and 23.72 cm, respectively.

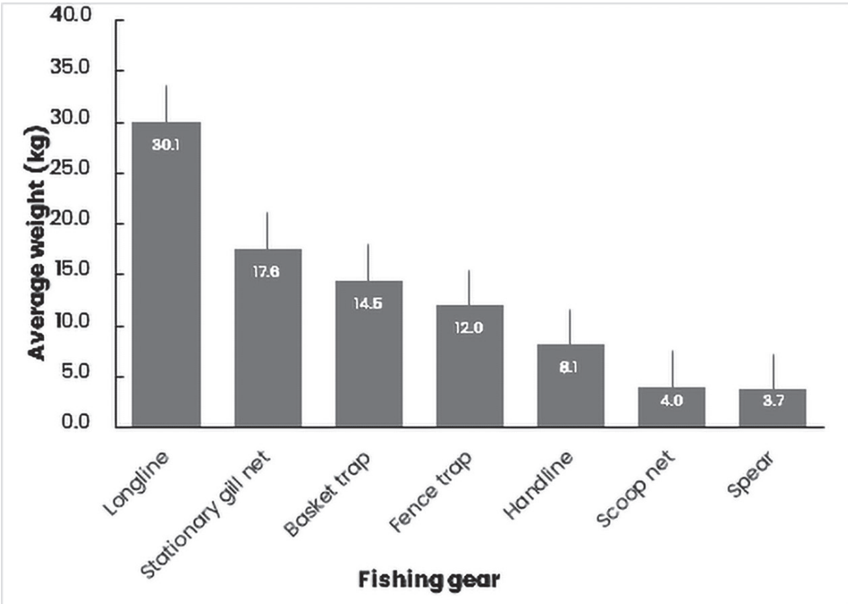

Figure 5. Average catch per gear at Nyali landing site, coastal Kenya.

Table 2: Variation of catch volumes and catch per unit effort among different fishing gears.

Type of gear	Average catch weight (kg)	Average number of fishers	Catch per unit effort (kg fisher^{-1} trip^{-1})	Total catch (kg)
Long line	30.1 ± 2.98	4 ± 0.50	7.5 ± 2.83	323
Stationary gillnet	17.6 ± 3.64	3 ± 1.11	5.9 ± 2.64	88
Basket trap	14.5 ± 1.35	3 ± 1.35	4.8 ± 0.75	133
Fence trap	12.0 ± 5.29	2 ± 1.41	6.0 ± 3.46	36
Hand line	8.1 ± 0.99	2 ± 0.58	4.05 ± 0.96	76
Scoop net	4.0	2	2.0 ± 2	4
Spear	3.7 ± 0.33	1 ± 0.47	3.7 ± 2.14	7

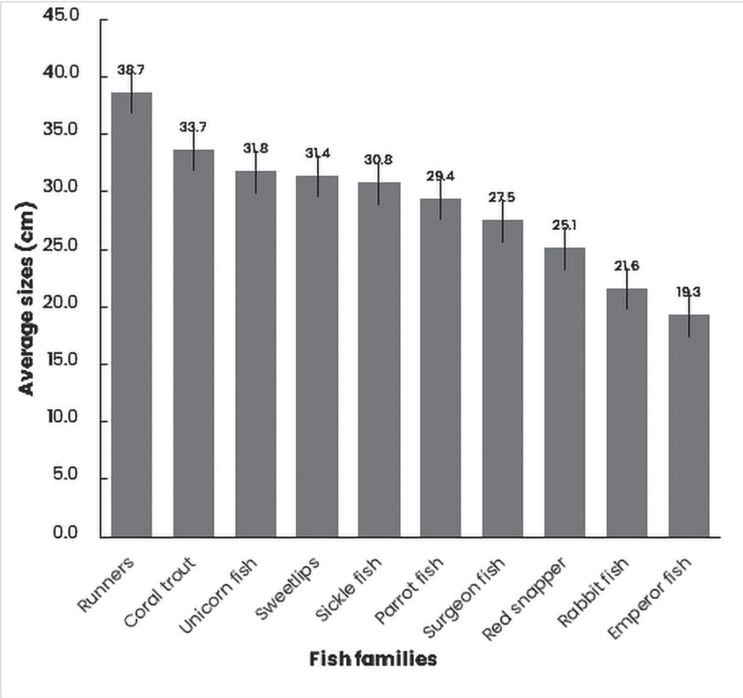

Figure 6. Average sizes of 10 most abundant finfish families.

Table 3. Singe-factor ANOVA comparing catch rates among different fishing gear types. The results revealed a highly significant effect of gear type on catch ($p < 0.005$).

ANOVA: Single Factor						
Groups	**Count**	**Sum**	**Average**	**Variance**		
Basket trap	15	595	39.67	563.02		
Hand line	15	145	9.67	47.38		
Long line	15	211	14.07	375.78		
Stationary gillnet	15	88	5.87	117.84		
Fence net	15	36	2.40	42.40		
Spear gun	15	11	0.73	2.35		
Scoop net	15	4	0.27	1.07		
ANOVA						
Source of Variation	*SS*	*Df*	*MS*	*F*	*p value*	*F crit*
Between Groups	17267.96	6	2877.99	17.52	<0.005	2.19
Within Groups	16098.8	98	164.27			
Total	**33366.76**	**104**				

Table 4. *p*-values for post-hoc pairwise comparisons for different fishing gear types.

	Basket trap	**Long line**	**Handline**	**Stationary gill net**	**Fence trap**	**Spear**	**Scoop net**
Basket trap		0.003199	0.00024	6.62 E-05	2.39 E-05	1.82 E-05	1.59 E-05
Long line				0.166928	0.041141	0.018822	0.015546
Stationary gill net					0.299858	0.089815	0.06661
Handline		0.418918		0.263506	0.004816	0.00019	0.000102
Fence trap						0.348949	0.22931
Spears							0.337705

The average sizes of emperor fish caught by hand lines was 18.70 cm, basket traps 21.65 cm and long line 21. 35 cm. The largest rabbit fish was 30 cm caught by long line while the smallest size was 17 cm caught by basket traps. The largest fish caught during the study was a *Carangoides armatus*, measuring 46 cm in total length, while the smallest fish was a Lethrinus lentjan, with a total length of 16 cm.

In this study 25 cm total length was considered as the size of first maturity. Approximately 75.76% of Siganidae and 82% of Lethrinidae landed by basket trap were below 25 cm total length. All species from Siganidae and 98.08% Lethrinidae fish families landed by hand line were below 25 cm total length. Fifty percent of Siganidae and 87.5% of Lethrinidae landed by long line were below 25 cm total length. The lengths of 26 % of the key fish families (Lethrinidae and Siganidae) was less than 19 cm and were considered as juvenile species in this present study. In this study 25 cm total length was considered as the size of first maturity.

CPUE

Long lines recorded the highest average catch (30.1 kg), followed by stationary gill nets (17.6 kg) and basket traps (14.5 kg). The lowest average catch recorded (3.7 kg) was harvested using spears (Fig. 5). Overall, fishers landed an average of 5.4±2.04 kg fisher^{-1} day^{-1}. All the fishers made a single trip per day, with the average number of fishers per vessel being greater in long line and least in spears (Table 2). The CPUE varied in different fishing gears with long lines recording the highest CPUE and scoop nets having the lowest CPUE.

Discussion

The aim of this study was to determine the variation of the catches of common reef fish families including Siganids and Lethrinids at the Kenya coast. The study noted seven gear types in use at Nyali fish landing site. Basket traps and handlines were the most dominant gears used in the coral reef while scoop nets and spears were the least used gears. Samoilys *et al.* (2017) identified five gear types commonly employed by small-scale fishers along the Kenyan Coast: gillnets, basket traps, handlines, spear guns, and beach seines. However, at Nyali landing site, beach seine which is considered illegal gear was not recorded.

In the present study, basket traps, handlines, and long lines yielded the highest catch, primarily targeting species from the families Lethrinidae and Siganidae. At the species level, *Siganus sutor* was the main species caught by basket traps, while *Lethrinus lentjan* was the dominant species caught by hand lines. These findings are consistent with a similar study conducted in Kenya by Tuda *et al.* (2016), which reported that basket traps mainly caught *Siganus sutor* and *Scarus sordidus*, while beach seines primarily captured *Lethrinus nebulosus*, *Lutjanus fulviflamma*, and *Leptoscarus vaigiensis*. Further, Tuda *et al.* (2016) reported that hook and line predominantly caught *Lethrinus mahsena* and *Lethrinus lentjan*, and that species from the families Siganidae and Leptoscaridae constituted a significant proportion of the catch from basket traps and beach seines."

Gillnets, beach seines, handlines, spear guns and basket traps were the most dominant fishing gears used in similar coral reef ecosystems at Lombok Island in Indonesia (Campbell *et al.,* 2018; Humphries *et al.*, 2019). In the same study, Siganids dominated spear gun catches while Lethrinids dominated by hand lines catches, an indication that different fishing gears target different species.

It was evident that Nyali landing site was moderately diverse in reef fish species but with a small number dominating the catch. Similarly, a study by Gell and Whittington (2002) shows that most tropical reef fisheries are characterized by a high diversity of species, but with a relatively small number dominating the catch. A related study by Musembi *et al.* (2019) show that species from Siganidae, Scaridae and Lethrinidae dominate catches in Kenyan small-scale fisheries from a sample of 41 fish families from 85 fish species. This is important since these fish families represent the most abundant and commercially important species of the Kenyan small-scale fisheries.

There was variation in the average sizes of finfish species. *C armatus* had the largest size of 46 cm while *L. lentjan* had the least size of 16 cm total length. This was different compared to a study by Musembi *et al.,* (2019), where *Scarus ghobban* had the largest size of 32.60 cm total length and *L. lentjan* had the least size of 8.8 cm total length. The result of the present study shows that the catch sizes of reef fish have increased, which can be attributed to the presence of an adjacent marine park where fishing activities are prohibited. The marine park serves as a protected area, allowing fish to grow to larger sizes without being subjected to fishing pressure. As these fish mature and their populations increase within the protected area, they may eventually migrate to the adjacent fishing grounds, contributing to the observed increase in catch sizes (McClanahan *et al.,* 2001).

This phenomenon, known as the "spillover effect," has been documented in various marine protected areas worldwide (Gell and Roberts, 2003; Halpern, 2003). The spillover of adult fish from no-take zones to surrounding fishing areas can help replenish fish stocks and support local fisheries. The findings of this study provide further evidence for the effectiveness of marine protected areas in promoting the recovery and sustainability of reef fish populations."

In the present study, the average total length of finfish caught was estimated to be 26.68 cm. The length of 60% of the catch was less than 30 cm, indicating that the small-scale fishery is based on small to medium-sized species. In a different study, Tuda *et al.,* (2016) recorded an average size of 21 cm total length of catch at South Coast of Kenya. The length of 91% of those catches was less than 30 cm total length indicating that small-scale fishery was based on small-medium sized species.

Catch per unit effort at Nyali landing site showed that fishers landed an average of 5.4 ± 2.04 kg fisher^{-1} day^{-1}. This CPUE is notably higher than the 2.8 ± 0.2 kg fisher^{-1} day^{-1} reported by Tuda *et al.* (2016) for the South Coast of Kenya. The higher CPUE in the current study suggests that the presence of a marine park in the adjacent areas of the fishing ground might have contributed to an increase in fish populations, resulting in improved catches (McClanahan *et al.*, 2001; Kaunda *et al.*, 2004).

Gear comparisons in the present study, revealed varying catch per unit effort (CPUE) across different fishing methods. Stationary gillnets had the highest CPUE at 5.9 ± 2.64 kg fisher^{-1} day^{-1}, followed by basket traps at 4.8 ± 0.75 kg fisher^{-1} day^{-1}, hand lines at 4.05 ± 0.96 kg fisher^{-1} day^{-1}, and spears at 3.7 ± 2.14 kg fisher^{-1} day^{-1}. These findings are comparable to those reported by Tuda *et al.* (2016) in a similar study, where the CPUE for each gear was as follows: basket traps 2.0 ± 0.1 kg fisher^{-1} trip^{-1} hook and line 4.2 ± 0.7 kg fisher^{-1} trip^{-}, gillnets 3.0 ± 0.5 kg fisher^{-1} trip^{-1}, spear guns fisher^{-1} trip^{-1}, and monofilament 4.1 ± 1.2 kg fisher^{-1} trip^{-1}. Comparing the two studies, it is evident that the CPUE has increased for all gear types, with the exception of handlines.

The overall increase in CPUE across most gear types suggests an improvement in the availability of fish resources in the study area. This increase could be attributed to various factors, such as the implementation of effective fisheries management measures, the presence of marine protected area adjacent to the study area, or favorable environmental conditions (Russ & Alcala, 2004; Worm *et al.*, 2009). However, the decline in CPUE for handlines warrants further investigation to identify the underlying causes and potential implications for the sustainability of this particular fishing method.

Conclusion and recommendations

The sizes of fish harvested from the studied coral reef ecosystem have been contributed by lack of capacity among fishers on the use of sustainable fishing gears such as basket traps, handlines, and stationqry gill nets with the recommended mesh size. Awareness creation on the importance of using sustainable fishing gears, provision of sustainable fishing gears and training fishers on how to use fishing gears will promote sustainable fishing.

CPUE have increased from 2.8 ± 0.2 kg fisher^{-1} day^{-1} (Tuda *et al.,* 2016) to 5.4 kg fisher^{-1} day^{-1}, indicating high dependence of fishery resources by the local communities for food and income. Overdependence on fishery resources can be reduced by providing alternative sources of food and income to the local communities such as seaweed farming, carbon trading, and bee keeping.

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Annex 1 . Questionnaire

Local knowledge and socio-economic questionnaire

Name of respondent...Tel:...

Site:...Date..

Gender: ☐ Male ☐ Female

Age: ....

Level of education:...

1. What activity are you involved with in the sea?..

2. How frequently do you go out at sea to fish?...

3. How many years have you been involved in fishing?...

4. What type of fishing gear do you use? ....

5. Do other fishers use the same fishing gear as you? If not name at least five fishing gears they use for fishing (in order of the most used)?

6. Name at least five types of fish families (species) you catch (in order of the most caught)?

7. Do other fishers catch the same species as you? If not name at least five fish families (species), they catch(in order of the most caught)?

Assessing cage fish farming practices in Lake Victoria, Kenya, for sustainable lake utilization and community well-being

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Abstract

The proliferation of cages in the Great Lakes of Africa is accompanied by the potential socio-economic outcomes which underscores a significant trend in the aquaculture industry that is supplementing the traditional fisheries production. In light of these considerations, the study herein was undertaken to comprehensively evaluate the potential impacts of high intensity of cages at a site in Lake Victoria, Kenya with the leading numerical focus. Anyanga Beach has consistently registered the highest number of cages, making it a focal point for assessing the broader implications of cage aquaculture in the region. The survey exclusively targeted cage aquaculture farmers with the use of structured three-part questionnaires involving the particulars of cages, socio-demographic features and farm operations and investments. Majority of the cages surveyed were found to be locally fabricated, accounting for 93.3% (n = 28), with the main materials used for constructing cage frames being metallic. The use of locally sourced and fabricated materials may indicate a practical approach motivated by considerations such as ease of accessibility, cost-effectiveness and locally-sourced knowledge. Most of the cage aquaculture farmers reported managing between 1 to 6 cages (n = 20; 66.7%), with the most common dimensions being small-sized measuring 2.5 m × 2.5 m × 2 m, suggesting the need to create cohorts of firms that could lead to the development of cooperatives and ease the implementation of regulatory frameworks. Fish escapees from the cages were also reported, with approximately 60% of respondents indicating that they had experienced such incidents. Such occurrences pose a significant risk, which may result in genetic disruption and adversely impacting the overall fisheries. The study recommends for the need to enhance awareness and engagement with key institutions to foster a more informed and compliant approach, while ensuring that practice of cage culture intensification is aligned with legal and environmental guidelines.

Keywords: cage culture, intensification, biosecurity, Great Lakes, Kenya

Introduction

Aquaculture is the world's fastest-growing food industry, with over 600 aquatic species farmed globally (FAO, 2018). Over the past two decades, this sector has undergone a remarkable transformation, shifting from a relatively minor role to playing a mainstream part in the global agri-food system (Simmance *et al.,* 2022). Forecasts indicate that future expansion of fish food production will mainly come from aquaculture (Anderson *et al.,* 2017; Aura *et al.,* 2018). For instance, aquaculture production is projected to increase from 60 million in 2010 to 100 mt in 2030, and up to 140 mt by 2050 (FAO, 2020). In Africa, the fisheries and aquaculture sectors support the livelihoods of approximately 6 million people, a number that has been steadily increasing over the last decade. In many Sub-Saharan African (SSA) countries, including Kenya, aquaculture is dominated by both extensive and semi-intensive practices (Béné *et al.,* 2016), resulting in low unit production and often falls short of meeting the projected demand for the growing human population. Since 1970, aquaculture production has been exceeding the growth rate of any other food production system, including poultry, beef, pork, dairy or cereal crops, growing at an average annual rate of 8.4% worldwide (FAO, 2016). This growth has been attributed to the increase in cage aquaculture (Hall, 2011).

Cage culture, a component of aquaculture, is the practice of growing fish in existing water resources while enclosed in a net cage that permits free passage of water (Aura *et al.,* 2021). It is an established and profitable system in many countries and is considered a major remedy to increase fish supply in the face of declining wild fish stocks to meet rising demand for fish. Cage culture globally is hugely varied, ranging from subsistence-level, holding of a few kilos of fish in small nets, to salmon farms producing more than 5,000 mt per year. Cage culture was introduced in several African countries in the 1970s, though only few of these early attempts proved to be sustainable (FA0, 2016). Since 1995, the production of farmed fish in SSA has expanded more than sixteen fold (FAO, 2018), mostly due to the expansion of tilapia cage aquaculture (Satia, 2011). Lake Victoria in Kenya (Aura *et al.,* 2018), Lake Victoria in Uganda (Blow and Leonard, 2007), Lake Volta in Ghana (Asmah *et al.,* 2016), Lake Kariba in Zimbabwe (Berg *et al.,* 1996), and Lake Malawi in Malawi are all notable examples of the rapid spread of cage fish farming in SSA (Blow and Leonard, 2007).

Despite the existence of aquaculture through pond and cage fish farming for supplementing the supply of white proteins, Kenya still fails to meet the demand, necessitating the importation of fish from other countries (Munguti *et al.,* 2014; Opiyo *et al.,* 2018). This imbalance has economic ramifications, since a decline in fish supply leads to increased demand, hence driving prices up (Brander, 2007). The dwindling diversity of fish in Lake Victoria has aggravated the problem, with some species, such as *Oreochromis niloticus*, becoming increasingly scarce (Njiru *et al.,* 2018). This shift in species availability has had a considerable impact on household feeding choices in Kenya's riparian counties along Lake Victoria. For instance, species such as Omena (*Rasterineobola argentea*), which were earlier regarded inferior, are now considered a superior food option. Reduced fish harvests have an impact not only on local diets, but also on the fisheries food system's ability to provide sustainable nutrition, because fish is an important source of nutrients recognized in most national dietary requirements (Burlingame and Dernini, 2012).

The proliferation of cages in Lake Victoria, accompanied by the documented potential benefits, underscores a significant trend in the aquaculture industry (Aura *et al.,* 2018; Orina *et al.,* 2018). Unfortunately, a concerning aspect is the inconsistent adherence to the cage aquaculture guidelines by some investors during cage installation in the lake. To ensure maximum economic benefits and long-term sustainability of the cages, it is important to understand the biosecurity measures employed and the sources of inputs for cage aquaculture business. In light of these considerations, this study was undertaken to comprehensively evaluate the potential impacts of cages in Lake Victoria, with a specific focus on Anyanga Beach. Notably, Anyanga Beach consistently registers the highest number of cages, making it a focal point for assessing the broader implications of cage aquaculture in the region.

Materials and methods

Study area

Figure 1 shows where the study was carried out in the Kenyan potion of Lake Victoria. Lake Victoria provides important ecosystem services to over 40 million inhabitants in the three riparian countries, *viz.* Kenya, Tanzania and Uganda. These include fisheries, transport and water for domestic, agricultural and industrial uses (LVFO, 2015). The lake is the largest tropical and the second largest freshwater lake in the world with a surface area of 680,000 km^2. The surface is partitioned between Tanzania (51%), Uganda (43%) and Kenya (6%) (Aura *et al.,* 2013). In Kenya, it is the second largest inland water body after Lake Turkana, covering 4,100 km^2 with an average depth of 6-8 m (within the Winam Gulf) and a maximum depth of 70 m (in the open waters) (Odada *et al.,* 2004). The lake is monomictic, experiencing complete annual mixing between the months of June to August (MacIntyre, 2012). In addition to the annual mixing, wind induces strong shear in the lake bottom and vigorous vertical mixing within the gulf especially around the mid-Gulf area (Okely *et al.,* 2010; Guya, 2013).

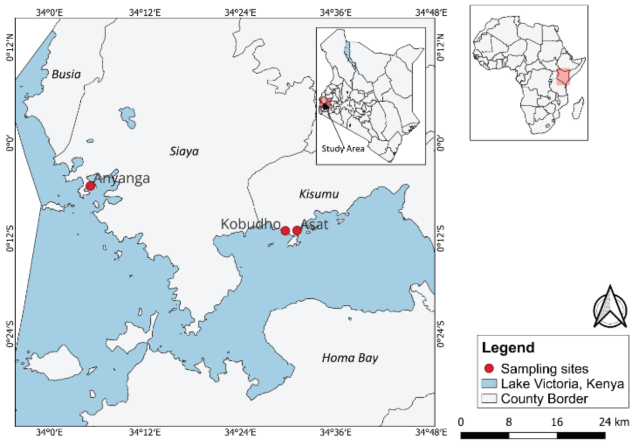

Figure 1. Map showing the focal point of cage aquaculture activity at Anyanga, Asat and Kobudho in Lake Victoria, Kenya (Source: Authors).

Data collection and analysis

The survey was conducted in the Kenyan waters of Lake Victoria in November–December 2023. The specific sites were Anyanga beach in Siaya County and Asat and Kobudho beaches in Kisumu County. The selection of these sites was deliberate, taking into account their significance as representative sites for cage aquaculture operations within the region. The survey

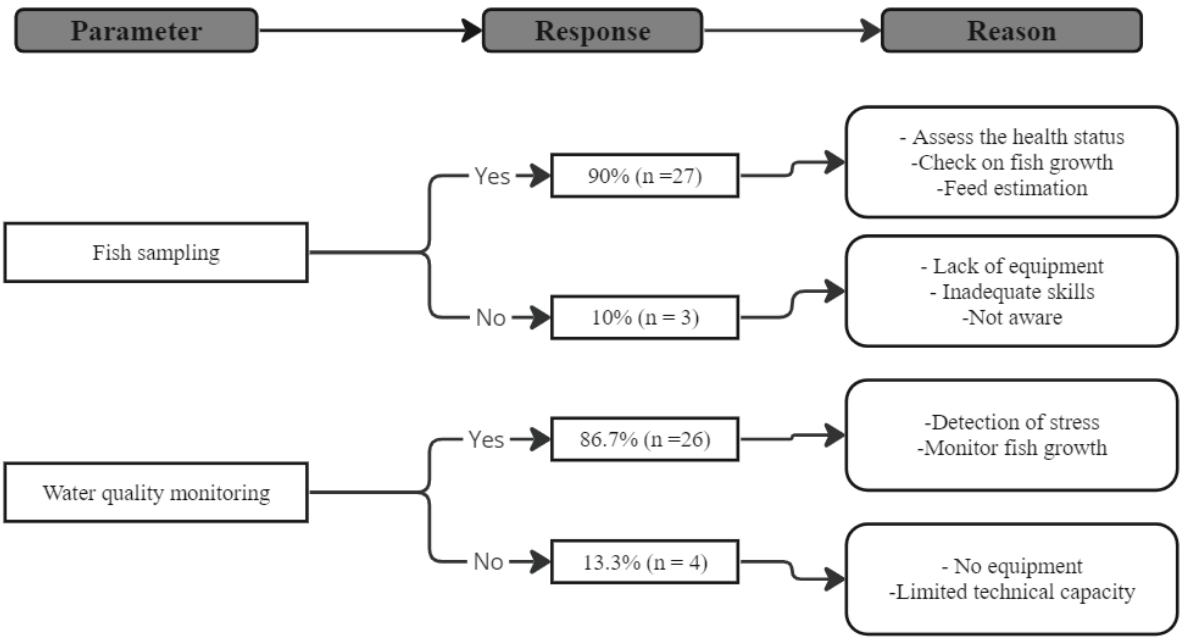

Figure 2. Respondents' feedback on the operational practices adopted within their enterprises.

exclusively targeted cage aquaculture farmers and it involved the use of structured three-part questionnaires (particulars of cages, socio-demographic features and farm operations and investments), and interviews as well as mapping the presence of cages in the lake. Global Positioning System (GPS) coordinates indicating the cage culture sites and the number of cages at all the stations were recorded. All the socioeconomics data were entreted into Microsoft Excel spreadsheets and eventually analyzed using Microsoft Excel and R statistical software version 3.6.0.

Results and Discussion

Socio-demographic characteristics of individuals in cage aquaculture operations

Table 1 shows the characteristics of cage farmers. Majority of the cages were individually owned (n = 28; 93.3%), and among the respondents, 53.3% were cage owners (n = 16), 26.7% were managers (n = 8) and 20% were feeders (n = 6). About 97% (n = 29) were males suggesting that the cage industry is male-dominated (Aura *et al.,* 2018). The majority of the respondents were between the age of 18 to 35 (n = 20; 66.6%), signifying a substantial representation of the youth. Some youth were reported as cage owners suggesting a trend where the industry is attracting young generation as an alternative source of employment (Aura *et al.,* 2018; Obiero *et al.,* 2022). Most of the respondents are married (n = 22; 73.3%), a trend suggesting that married individuals may be drawn to the cage aquaculture business due to the stable employment opportunity provided by the sector, enabling them acquire income to support their families (Orina *et al.,* 2018).

Education levels varied among respondents with 60% (n = 18) having attained primary education, potentially influencing various aspects with cage aquaculture establishments, including the nature of responsibilities performed and decision-making processes. The high number of respondents with primary-level education may imply that these people are largely involved in practical and hands-on tasks within the venture, contributing to the overall operational dynamics of cage aquaculture activities. Furthermore, their level of education may affect their access to and use of information, thereby influencing managerial practices and decision-making in the business (Odende *et al.,* 2022). In addition to their involvement in cage aquaculture operations, a considerable proportion of respondents (73.3%, n = 22) were fishermen. This dual position shows that the respondents have a diverse skill set, with experience in traditional fishing practices supplemented by participation in cage aquaculture business (Aura *et al.,* 2018; Anjejo, 2019). This may indicate an expansion of livelihood activities, implying a potential shift toward more sustainable and economically viable practices in the broader fisheries sector.

Table 1. Socio-demographic characteristics of cage aquaculture farmers in L. Victoria, Kenya.

Variable	Category	n	Proportion
Gender	Male	29	96.70%
	Female	1	3.30%
Age	18 - 25	10	33.3%
	26 - 35	10	33.3%
	36 - 45	8	26.7%
	46 - 55	1	3.3%
	>56	1	3.3%
Marital status	Married	22	73.3%
	Single	7	23.3%
	Widow/er	1	3.3%
Education	Certificate	1	3.3%
	Diploma	1	3.3%
	Primary	18	60.0%
	Secondary	9	30.0%
	Undergraduate	1	3.3%
Main occupation	Businessperson	3	10.0%
	Fish trader	3	10.0%
	Fisherman	22	73.3%
	Community Health Services	1	3.3%
	Welder	1	3.3%

Dynamics of cage aquaculture operations

Majority of the cages surveyed were found to be locally fabricated accounting for 93.3% (n = 28), with the main material used for constructing cage frames being metal. The use of locally sourced and fabricated materials may indicate a practical approach motivated by considerations such as ease of accessibility and cost-effectiveness of these materials (Obwanga *et al.,* 2020). Metal frames are used because they are affordable and durable (Aura *et al.,* 2018; Mwamburi *et al.,* 2021). Furthermore, it was observed that cage net materials were mostly sourced locally, with the primary supplier being Monasa Limited Company in Kisumu. This selection of local suppliers emphasizes the use of locally available resources, contributing to the sustainability of the industry (Orina *et al.,* 2018).

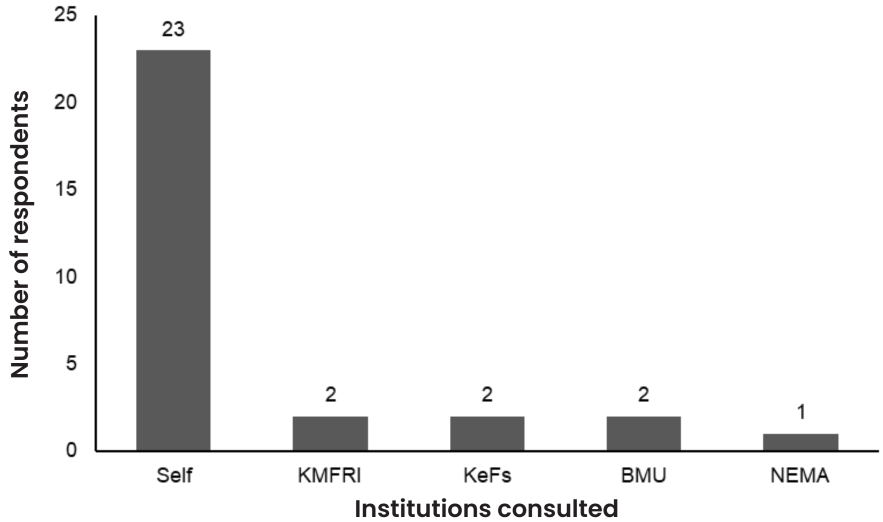

Figure 3. Institutions consulted before installing the cages in the Lake. (KMFRI = Kenya Marine and Fisheries Research Institute; KeFs = Kenya Fisheries Service; BMU = Beach Management Unit and NEMA = National Environment and Management Authority).

Most of the cage aquaculture farmers reported that they are managing between 1 to 6 cages (n = 20; 66.7%) with the most common dimensions being 2.5 m × 2.5 m × 2 m. Majority of the cages were active with only a few reported as dormant, primarily attributed to the recent fish harvesting activities. This observation is a common operational cycle within the cage aquaculture system, in which periodic dormancy aids in the management of fish populations as it leads to flushing of accumulated nutrients within the cages, thus improving the overall effectiveness of the aquaculture practices (Mwamburi *et al.,* 2021).

Key Practices in Cage Aquaculture

The farmed fish is Nile tilapia and the fingerlings are mainly sourced locally from hatcheries in close proximity. The fingerlings stocked are mainly mono-sex (n = 28; 93.3%). Farmers stocked between 600 to 70,000 fingerlings depending on the size of the cage. This adaptability could be influenced by factors such as available resources, market demand or specific production goals (Opiyo *et al.,* 2018; Orina *et al.,* 2021). About 96.7% (n = 29) of the farmers reported having only one production cycle per year, a finding that corroborates similar studies conducted on cage aquaculture in Kenya (Aura *et al.,* 2018; Orina *et al.,* 2018; Obiero *et al.,* 2022). In terms of fish health, 90% (n = 27) monitor fish growth mostly after every 3 months while 86.7% (n = 26) test the water quality after every 2 months but they do this individually through observation. This reliance on observational water quality assessment raises concerns about the accuracy of the monitoring process. In addition, no proper water quality equipment is used for monitoring, which suggests a potential gap in awareness regarding the importance of accurate water quality monitoring for improved fish production. Given its critical role in fish growth (Opiyo *et al.,* 2018; Okechi *et al.,* 2022; Musa *et al.,* 2023), accurate monitoring of water quality is essential.

Figure 2 shows a schematic representation of respondents' feedback onto the operational practices adopted within their practices. The diagram is divided into three main parts: the first part lists parameters such as whether respondents perform sampling and water quality monitoring. The second part displays the responses, which are categorized as either "yes" or "no". The third part details the reasons behind respondents' choices, including why they do or do not engage in fish sampling and water quality monitoring. In addition, reasons for not sampling or monitoring are provided if the response is negative.

Market dynamics of farmed fish in cages

The respondents indicated that the size of fish preferred by the market ranged between 0.25 kg to 0.5 kg, although the average weight of harvested fish is usually 0.5 kg (n = 20; 66.7%). This small disparity can be a sign that farmers are deliberately maximizing their output to satisfy the needs and expectations of the market (Aura *et al.,* 2018; Opiyo *et al.,* 2018; Obiero *et al.,* 2022). The annual harvest of fish varied among respondents, with majority harvesting between 100 to 500 kg (n = 12; 40%). This variation implies a diverse scale of operations among cage aquaculture farmers (Aura, 2020; Orina *et al.,* 2021), which could be attributed to factors such as the number of cages per farmer, stocking density and general management practices (Njiru *et al.,* 2019; Kyule-Muendo *et al.,* 2022; Okechi *et al.,* 2022). Understanding these differences is critical for tailoring support mechanisms and interventions to the individual needs of farmers operating at various scales of production.

Biosecurity management

About 60% (n = 18) of respondents reported having experienced fish diseases in their farms, with symptoms such as white spots and scratches on the skin. According to Mwainge *et al.* (2021), these infections may stem from bacterial, parasitic or fungal sources. Fungal infections have been reported to occur when fish are stressed or have wounds on their skin, which often lead to the development of white, cotton-like growths on the skin (Opiyo *et al.,* 2020; Mwainge *et al.,* 2021). The identified symptoms were managed at the farm using salt bath. The use of salt is a recommended measure to control the spread of infections in the production systems (Sadhu *et al.,* 2014; Opiyo *et al.,* 2020; Mugendi *et al.,* 2022).

Fish escapees from the cages were also reported, with approximately 60% of respondents indicating that they had experienced such incidents. Such occurrences pose a significant risk, which may result in genetic disruption - adversely impacting the overall fisheries (Arechavala-Lopez *et al.,* 2018). The escape of fish from cages not only has immediate consequences for the individual fish but also raises concerns about potential long-term effects on the genetic integrity of local fish populations and the ecological balance of the fishery (Blow and Leonard, 2007). In addition, 40% (n = 12) of surveyed farmers reported instances of fish mortalities. Fish mortalities can have implications for aquaculture operations and the broader fisheries environment. The causes of fish mortalities vary and may include factors such as disease outbreaks, poor water quality, nutritional issues and stress during handling or sampling (Kyule-Muendo *et al.,* 2022; Otachi *et al.,* 2022).

Cage aquaculture guidelines

The cages were installed at approximately 100 m to 600 m (n= 18; 60%) with an average depth of 6.2 m. Notably, the majority of farmers (76.7%, n = 23), used self-sourced information from fellow cage farmers and personal knowledge to locate suitable cage installation sites (Fig. 1), while some respondents sought advice from external entities such as the Kenya Marine and Fisheries Research Institute (KMFRI, n = 2; 6.6%), Kenya Fisheries Service (KeFS, n = 2; 6.6%), National Environment Management Authority (NEMA, n = 1; 3.3%) and Beach Management Units (BMU, n = 2; 6.6%). The relatively low consultation rates indicate that the legally mandated agencies in charge of cage aquaculture establishment were not adequately consulted. This suggests a potential communication breakdown between farmers and regulatory entities, which might hinder proper management of cage aquaculture (KMFRI-ABDP Unpublished Report, 2022).

Figure 3 shows the number of respondents that consulted relevant institutions before installing the cages in the Lake. Before installing cages, investors are required to consult with key institutions overseeing the management of the Lake's resources. This process entails obtaining the necessary approvals from responsible institutions such as KMFRI, KeFs, NEMA and County governments. Furthermore, establishing a Memorandum of Understanding with the BMUs is critical for compliance and coordination (LVFO, 2018).

Conclusions and Recommendations

This study provides an insight into the dynamics of cage aquaculture development in Lake Victoria, Kenya. The growth of the sector offers economic opportunities, particularly for the youth, who have a significant representation in the venture. However, concerns exist about adherence to cage aquaculture regulations during installation, which could jeopardize long-term sustainability of cage aquaculture development. Enhancing awareness and engagement with key institutions could foster a more informed and compliant approach to cage aquaculture establishment, ensuring that practices align with legal and environmental guidelines. This study highlights an opportunity for improved communication channels and knowledge dissemination within the cage aquaculture community.

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Quantifying fish bycatch in Lake Turkana: Potential for sustainable livelihood diversification

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Abstract

The sustainability of fisheries in Lake Turkana is threatened by the pervasive issue of fish bycatch, wherein non-target species are unintentionally caught in fishing gear. This paper addresses this concern, recognizing its ecological and economic ramifications. Utilizing a mixed-methods approach, data was gathered on fish species diversity, bycatch rates and discard practices from various fishing gear types. Results indicate a predominance of gillnets and longlines in the fishery, with tilapia, silverside, and Nile perch comprising the majority of commercial catches. The species caught in the various nets were *Alestes baremose* (2.5"), *Synodontis schall* (entangled) and *Distichodus niloticus* (4" and above). Mean catch per boat varied depending on the effort group but was highest for motorized sesse boats (SMS) at 21.5 ± 12.3 kg per boat. *Lates longispinis* and catfish contributed over 95% of the bycatch's commercial value. Despite concerns over the potential impact on endangered species, gillnets with single netting remained popular due to perceived selectivity. Importantly, the study identifies the potential for bycatch species to contribute significantly to fishery yields and local economies, emphasizing the need for multispecies management strategies. By quantifying the extent of bycatch and evaluating its economic value, this research informs efforts towards sustainable livelihood diversification and fishery management in Lake Turkana.

Keywords words: bycatch, commercial viability, gear selectivity, target catches

Introduction

The issue of fish bycatch in Lake Turkana fishery is a growing concern (Cohen *et al.,* 1996; Odada *et al.,* 2003 Gownaris *et al.,* 2015) that poses significant challenges to the sustainable management of the fishery. According to the studies, one of the main challenges in the fishing industry is overfishing, which is exacerbated by the issue of fish bycatch. Fish bycatch refers to the unintentional catch of non-target fish species and other marine creatures in fishing nets or gear. This problem is particularly prevalent in Lake Turkana, where there are indications of destructive fishing methods due to increased presence of illegal fishing gears (Mgana *et al.*, 2019). These destructive methods, such as the use of inappropriate fishing gear or techniques, contribute to the high levels of fish bycatch in the Lake. The high fishing pressure in Lake Turkana also contributes to the issue of fish bycatch (Kolding, 1995). As a result of fish bycatch, there is a decline in catch per unit effort in certain areas of the lake. This not only affects the population of target fish species, but also leads to the depletion of non-target species and disrupts the balance of the ecosystem.

The challenge of fish bycatch in the Lake Turkana fishery extends beyond ecological concerns by having economic implications. The high levels of bycatch translate to a significant loss of potential income for fishers, particularly those who depend heavily on the fishery. Fishing for a certain target species frequently leads to the capture and killing of non-target species. Discarded fish often include juveniles of commercially valuable species, further hindering the fishery's long-term health and overall productivity (Mwanjela, 2011). This economic strain can incentivize less selective fishing practices to maintain income, creating a vicious cycle of declining fish stocks and increased bycatch. Bycatch can have serious effects on populations, food webs, and ecosystems in numerous forms. The economic impact of bycatch can have a significant impact not only on fisheries' yields, but also on allocations among competing fisheries. It is estimated that worldwide, 27 million tons of bycatch is caught every year, accounting for 40 percent of the world's annual marine catch (Davies *et al.*, 2009). The lack of extensive monitoring systems in most places to assess bycatch and integrate it into population and multispecies models makes it difficult to fully comprehend the impacts of bycatch and the efficacy of mitigation efforts (Read *et al.*, 2006).

The scientific understanding of Lake Turkana has benefitted greatly from past research on limnology, fish biology, and aquatic ecology. However, crucial knowledge gaps remain. While development plans hinge on a comprehensive understanding of the Lake's current state, aspects like species and quantity dynamics, socioeconomics and water balance are not well documented (Kolding, 1993; Muška *et al.*, 2012). Fish bycatch is a particular area of concern, with limited data on rates across species, fisheries, and lake basins. The effectiveness of existing mitigation measures and the demographic responses to bycatch are also poorly understood. With being majority artisanal fishers, it is likely that bycatch forms part of their 'daily bread' for consumption rather than being discarded. However, quantitative data to document this is scarce (Seto, 2017). To address this knowledge gap, this study aims to assess the status of fish bycatch in Lake Turkana. By identifying key bycatch issues, collecting quantitative and qualitative data, and finally determining the commercial value of bycatch, this research seeks to explore its potential as an alternative source of income for fishers.

Materials and methods

Lake Turkana, situated within the northern Kenyan Rift Valley, is the largest of the Country's lakes measuring about 250km long, 30km wide

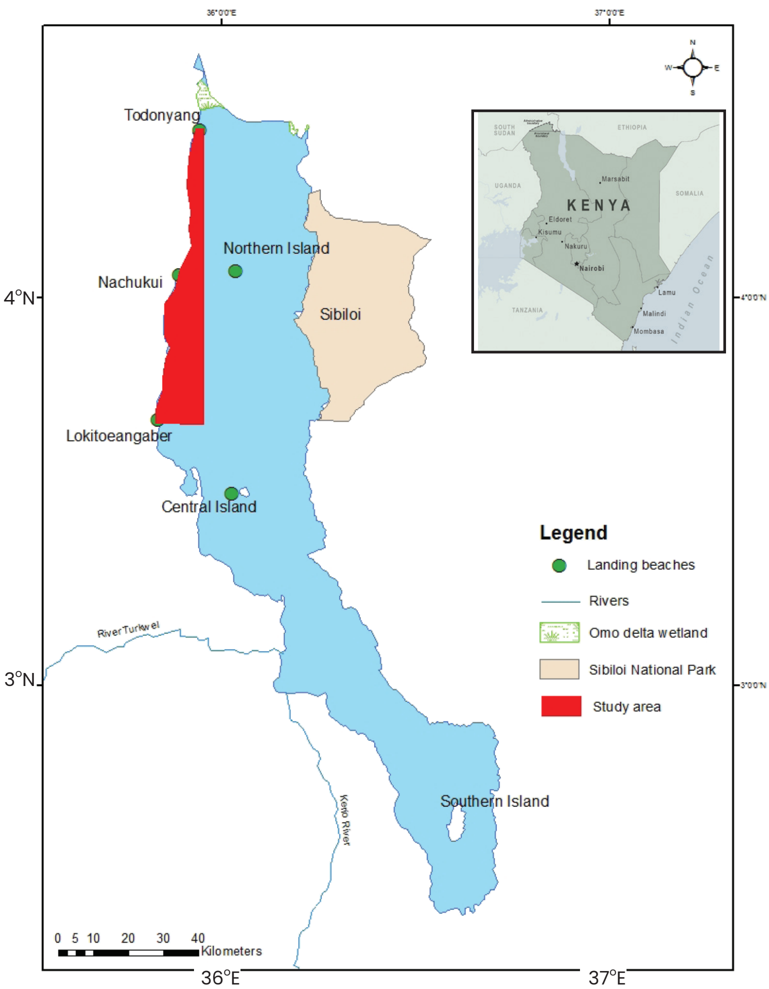

Figure 1. Map of Lake Turkana showing the study area (Source: Author).

and a surface area of 7,000 km². With a maximum depth of 125 meters and an average depth of 35 meters, it holds the distinction of being the world's largest permanent desert lake. The predominant inhabitants of the basin surrounding Lake Turkana are the Turkana people, who have historically practiced pastoralism, with a focus on livestock rearing and handicraft production. However, due to increasing incidences of erratic rainfall patterns and extended droughts, a growing segment of the Turkana population has turned to fishing as a primary source of livelihood. This shift in alternative resource utilization has raised concerns regarding the long-term sustainability of Lake Turkana's fish stocks, necessitating studies into the fishing practices on the Lake to determine whether they are sustainable for the continued well-being of both the Lake's ecosystem and the communities dependent on the lake.

Figure 1 shows the areas of Lake Turkana where this study was conducted. This was predominantly on the Western shores of the lake since this is where most fish is landed. This study aimed at collecting both qualitative and quantitative data. Data on fish species diversity, bycatch and discards was obtained from gillnet, purse seine and beach seine gears used by fishermen. The number of nets was estimated by counting the number of nets joined together while mesh size was measured using a tape measure to obtain the full mesh distance between the centres of the two opposite knots of a stretched mesh. Fish were sorted into target catch, bycatch and discards. Data was collected at designated fishing sites using a team of locally hired data recorders and KMFRI staff visited the landing sites to administer questionnaires by orally interviewing local fishermen and conducting key informant discussions. Vessels were categorized into five groups namely Sesse Motorised Canoes (SMS), Sesse Paddled Canoes (SP), Parachutes (PA), Rafts (RT) and Fibre Fishing (FF), while fishing gears were grouped into two, namely, gillnets and hook and line. Data collected included catch weight, composition by species and size, fishing gears and methods, craft type and length, value of catch and fishing frequency.

Results

Number, type, distribution and size of fishing vessels and gear

Thirty fishing vessels were enumerated at the 11 fish landing sites within the six beach management units (BMUs) located in Turkana North subcounty. Figure 2 shows the proportion of each vessel type used in the Lake Turkana fishery. Sesse Motorized Canoe (SMS) was the most dominant fishing vessel used at Keriakar in Loarengak BMU. Fishers from Lowarengak fish at the Omo River delta, which is an insecure, conflict prone zone, and fishers must use motorized boats due to limiting weather conditions. Raft fishers dominated landing sites such as Lomekwi and Loropio as most fishers lack fishing gear. Table 1 shows the mean length of the vessels deployed at the selected landing beaches. Fishing rafts had the shortest length (2.8 ± 0.1 cm). This is because they are mainly operated by a single fisher and constructed shorter for ease of handling.

Fishers in Lake Turkana deploy mainly gillnets and longlines. The size of the commonly used gillnets ranges is from 2.5″ (84 mm) stretched mesh to 7″ (180 mm). The 4″ (101 mm) mesh was the most deployed (35.7%) followed by 3.5″ (89 mm) and 2.5″ (84 mm) nets. The three gillnet sizes constitute 75.1% of all the nets deployed in the Northern part of Lake Turkana. The species targetted using the various nets are *Alestes baremose* (2.5″), *Synodontis schall* (entangled) and *Distichodus niloticus* (4″ and above). As shown in Fig. 3, mean catch per boat varied depending on the effort group but was highest for motorized sesse boats (SMS) at 21.5 ± 12.3 kg per boat. Sesse paddled canoes (SP) fished daily during the week, had the highest number of crew per boat and spent less time in the lake as compared to the other effort groups. Sesse motorized boat had the highest catch per unit effort (CPUE) at 48.2 kg boat^{-1} day^{-1} while raft fishers recorded the lowest CPUE.

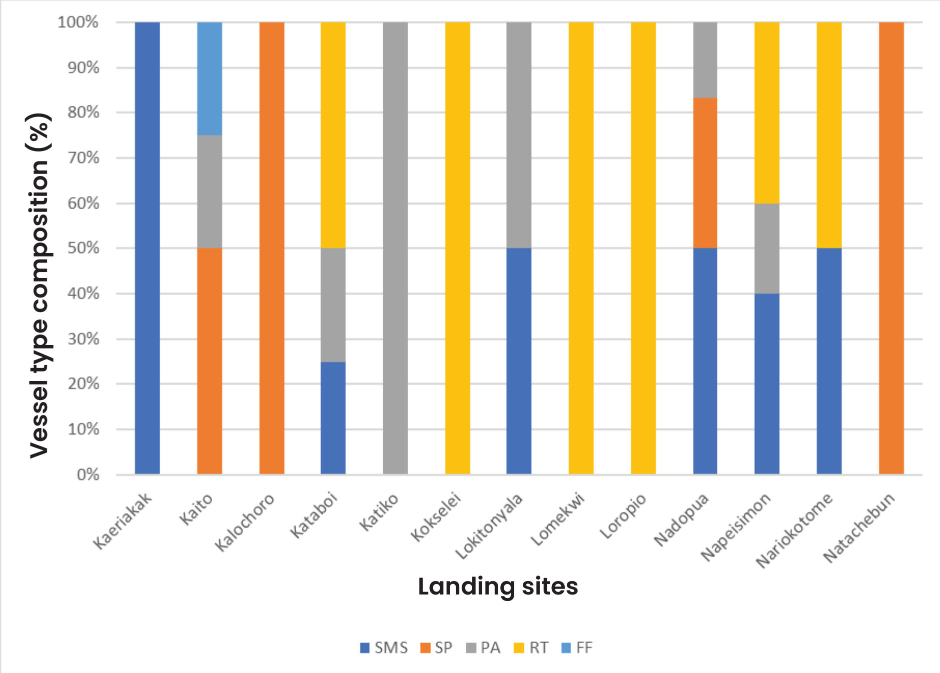

Figure 2. Percentage occurrence of various types of fishing vessels enumerated along north western Lake Turkana. The gear types were: Sesse Motorised Canoes (SMS), Sesse Paddled Canoes (SP), Parachutes (PA), Rafts (RT), and Fibre Fishing Boats (FF).

sought-after commodity, worth more than five times the price of bulk *L. niloticus* and *O. niloticus* at over KShs. 150 per kg. Tilapias are targeted in shallow areas using seine nets and are an especially important fishery resource during years of high production. Ferguson's Gulf, for example, with an area of only 10 km^2, produced about 16,000 tonnes of tilapia at its peak in 1976 (Kimani *et al.,* 2018).

Table 1. Mean length fishing vessel types encountered along the northwestern side of Lake Turkana. The vessel types were: - Sesse Motorised Canoes (SMS), Sesse Paddled Canoes (SP), Parachutes (PA), Rafts (RT), Fibre Fishing (FF).

Vessel type	SP	FF	SMS	PA	RT
Mean Length (m)	7.8	7.1	8.1	7.5	2.8
Standard Error	0.5	0.2	0.3	0.3	0.1
95% C.L.	+/-1.0	+/-0.3	+/-0.6	+/-0.5	+/-0.3

Fish Species composition and commercial importance

Even though there are about twelve commercially exploited fish species in Lake Turkana (Table 3), tilapias are particularly targeted because of their popularity both in the local communities and markets around the country. Top predators also target tilapia as a key component of their diet. *Lates niloticus* and *Oreochromis niloticus*, two of the most important species by volume in the Lake Turkana Fishery, are also the most commercially valuable. The swim bladder of *L. niloticus* is a highly

Bycatch fish prices and their commercial viability

The presente study revealed that tilapia, silverside, and Nile perch dominate commercial catches, making up over 80% of the total haul. Interestingly, the most common bycatch species were the dwarf Lake Turkana robber and the dwarf perch (Table 4). The study identified potential for the dwarf robber to be specifically targeted for industrial fish feed production, given its significant bycatch volumes. Another interesting finding was the lack of data on the dwarf perch, despite annual bycatch reaching nearly 1000 tons, contributing to the gap in its IUCN categorization. Gillnets with single netting were found to be the most commonly used fishing gear, likely due to the belief in their selectivity for specific fish sizes. However, the study raises concerns about the potential for these nets to also catch endangered species in certain areas. To address this, researchers recommend further studies to develop methods for reducing unintended catch of endangered fish, particularly in breeding and habitat areas of the lake. It's important to note that this study acknowledges limitations in its analysis, as it did not consider variations in gillnet construction that can also influence bycatch.

Table 2. Catch per unit effort of Lake Turkana and characteristics of vessels used on the fishery.

	Parachute Paddled / Motorised	Raft	Sesse Motorized	Sesse paddled
Catch (Kg boat^{-1})				
Mean	16.5	3.7	21.5	14.5
SE	5.5	1.2	12.3	8.4
CL	10.7	2.4	24.0	16.5
Days fished week^{-1}				
Mean	6.3	6	5.2	7
SE	0.8	1	1.4	0
CL	1.5	2.0	2.8	
Hours fished Day^{-1}				
Mean	12	12	6.5	9.5
SE	0	0	2.0	2.5
CL			3.9	4.9
Crew Boat^{-1}				
Modal	4	1	4.0	6.0
CPUE (Kg Boat^{-1} Day^{-1})				
CPUE	**37.0**	**8.3**	**48.2**	**32.5**

Table 3. Commercial fishes of the Lake Turkana Fishery. Source: Own data collection.

	Fish scientific name	Common name	Local name	Average Monthly Landings 2021 (Tonnes)	Percentage of Total Commercial Landings (2021)
1	*Oreochromis niloticus*	Tilapia	Kokine	595.10	45.2%
2	*Alestes baremose*	Silverside	Juse	321.17	24.4%
3	*Lates niloticus*	Nile Perch	Iji	134.52	10.2%
4	*Synodontis schaal*	Catfish	Tir	92.98	7.1%
5	*Bagrus bayad*	Black Nile catfish	Loruk	68.75	5.2%
6	*Labeo horie*	Turkana carp	Chubule	62.45	4.7%
7	*Hydrocynus forskalii*	Tigerfish	Lokel	41.50	3.2%
	TOTAL			1,223.50	100%

Untargeted fish from Lake Turkana form a crucial part of the fish catches that are landed from the fishery annually (Table 5). The Lake Turkana fishery bycatch is composed of species including *Brycinus minutus, Lates longispinis, Schilbe uranoscopus, Labeobarbus bynni, Clarias gariepinus* and *Distichodus niloticus* which are commercially viable. These species make up more than 3,000 metric tonnes or 16% of the Lake Turkana fish catch as per the modelled total catch of 19,000 metric tonnes from January 2021 to December 2021. With Davies *et al.* (2009) establishing that marine bycatch accounts up to 40% of total marine catch, the Lake Turkana bycatch of below 20% falls within the sustainable bycatch threshold according to Pillai *et al.* (2014). Most literature under-estimated the tonnage of bycatch from Lake Turkana, but the study established that more fish was being landed from the Lake Turkana fishery than was being officially documented.

Lates longispinis, a commercially valuable relative of Nile Perch, comprised a significant portion (20%) of the gillnet bycatch. This species fetches prices similar to fresh Nile Perch (KShs. 75 kg^{-1}), exceeding tilapia's value. Notably, unlike these, most bycatch species have limited market appeal beyond local consumption due to low demand and preference for fresh consumption. This minimizes spoilage concerns and renders post-harvest preservation techniques like drying or salting ineffective in increasing value. Despite fetching lower prices, bycatch provides crucial supplementary income for fishers and a valuable protein source for

Table 4. Fish landings from Lake Turkana Fishery that are categorized as bycatch and their IUCN Status.

	Fish scientific name	Common name	Local name	December 2021 – December 2022 Landings (Tonnes)	IUCN Status
1	*Brycinus minutus*	Dwarf Lake Turkana robber	Lochakolong	2,100	Least Concern
2	*Lates longispinis*	Dwarf perch	Iji	750	Data deficient
3	*Schilbe uranoscopus*	Butter catfish	Iyinte	200	Least concern
4	*Labeobarbus bynni*	Nileharb	Momwara	50	Least concern
5	*Clarias gariepinus*	African sharptooth catfish	Kopito	25	Least concern
6	*Distichodus niloticus*	Cowfish	Golo	5	Least concern

Table 5. Computation of commercial value derived from fish categorized as Lake Turkana bycatch from July 2020 to June 2021. 1USD = KES 125.

	Species	Price per Kilo (Fresh) KES	Total Annual Value (Fish sold at the Beaches) '000 (KES)
1	*Lates longispinis*	75	56,250
2	*Brycinus minutus*	15	31,500
3	*Schilbe uranoscopus*	12	2,400
4	*Labeobarbus bynni*	20	1000
5	*Clarias gariepinus*	25	625
6	*Distichodus niloticus*	10	50
	TOTAL		**91,825**

local communities. This finding highlights the importance of multispecies management plans, particularly for the vulnerable catfish resource. Future efforts should focus on developing such plans to ensure sustainable practices across gillnet and longline fisheries and prevent overexploitation of target and bycatch species.

Conclusion and recommendations

The presence of significant bycatch species, such as the dwarf Lake Turkana robber and dwarf perch, underscores the need to consider the entire catch composition in fisheries management planning. The commercial viability of these bycatch species suggests opportunities for maximizing economic returns and minimizing waste. The study suggests that bycatch levels are currently sustainable. However, the presence of valuable bycatch species and potential for endangered species bycatch necessitates the development and implementation of multispecies management plans. Overall, the findings of the study stress the importance of adopting sustainable management practices that address gear selectivity, bycatch reduction, and the conservation of vulnerable species. Such policies should be grounded in scientific evidence and aim to balance ecological conservation with socio-economic needs, ensuring the long-term sustainability of Lake Turkana's fishery for present and future generations.

These plans should ensure sustainable practices across all fisheries to prevent overexploitation of both target and bycatch species. Implementing these recommendations can promote a balanced approach to Lake Turkana's fishery, considering both commercial interests and the conservation of aquatic life and local livelihoods.

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Effect of replacing Black soldier fly (*Hermetia illucens*) larvae meal with fish meal in diets for African catfish (*Clarias gariepinus*) reared in earthen ponds

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Abstract

The effect of replacing fish meal for black soldier fly larvae meal (BSFLM) on growth and feed utilization of African catfish (*Clarias gariepinus*) was evaluated in earthen ponds at Sagana research Centre. 240 fish were distributed in a completely randomized design with four treatments in triplicates. Fish were fed increasing inclusion levels of BSFLM replacing fish meal (FM) at 0%, 33%, 66%, and 100 designated as D1, D2, D3 and D4 respectively. Fish were fed to satiation and sampling for growth assessment taken every 28 days while physico-chemical parameters were measured weekly. Growth performance results for *C. gariepinus* showed significant variation ($p < 0.05$) between treatments. The highest mean final weight (MFW) (91.30 ± 51.39 g) was exhibited by fish fed 33% BSFLM diet and the lowest (68.13 ± 40.45 g) for fish fed the 66% BSFLM inclusion. Recorded mean weight gain was highest on D1 (83.00 ± 34.50 g), but no significant difference was reported between the formulations. In summary, it was demonstrated that BSFLM can replace FM in the diets of African catfish by up to 33% and that a further increase in the amount of BSFLM in the diets translates to lower growth performances as reflected in the decrease in mean weight gain.

Keywords: body weight gain, growth performance, organic waste

Introduction

Food security continues to be of great concern globally due to rapid population growth which is projected to continue increasing from the current 7 billion to 9.7 billion individuals by the year 2050 (Nadathur *et al.*, 2017). Climate change, increasing water pollution, and competition for scarce natural resources are making it increasingly difficult to feed the population. An additional 70-100% of food needs to be produced to address the imbalance between supply and demand (Wang *et al.*, 2018) and the average global temperature is predicted to rise due to the increasing greenhouse gases (GHGs) emissions.

The ever-increasing demand for fish protein has led to overfishing of capture fisheries, which poses a serious threat to resource-dependent communities. With a ceiling of 110.2 million tons in 2016, aquaculture production has been one of the primary sources of high-quality fish and fish products for rural areas (FAO, 2020). Although, the industry's expansion has been characterized as modest, its expansion has been judged to be gradual which is attributed to high taxation of feed inputs, poor quality of the fish feed, limited supply, and overreliance on fish meal as a protein source (Opiyo *et al.,* 2018).

Any aquaculture business must start with high-quality fish feed (Munguti *et al.,* 2021). However, fish feeds have been noted to account for more than 60% of aquaculture production costs (Munguti *et al.,* 2012, Nairuti *et al.,* 2021). Protein is considered the most imperative and the most expensive nutrient in fish diets (Lee *et al.,* 2020). Over the years, fish meal has been preferred as a major protein source in fish feed formulation (Shukla *et al.,* 2019). This is primarily due to the high-quality protein it contains, lack of anti-nutritional factors, high digestibility and palatability and balanced amino acid and fatty acid profile, among other attributes which promote fish immunity, health, and feed efficiency (Golden *et al.,* 2016). Overreliance on fishmeal poses challenges to fish farmers in Kenya due to its escalating costs resulting from its scarcity as a result of the Lake Victoria fisheries' periodical closures, climate change and competition from other value chains, especially other animal feed suppliers (Munguti *et al.,* 2014, Adeoye *et al.,* 2020).

Sustainability in aquaculture may not be achievable with fish meal as the sole protein source, thus diversification of protein sources must remain a key priority as recommended by fish nutritionists. Studies have been conducted on fish diets with FM replaced with plant-based protein derivatives. Some of these plant-based protein sources include pea seed, sunflower seed, lupin seed, cotton seed, soybean meal, and rapeseed meal (Nasr *et al.,* 2021). However, these components do not contain major amino acids that are important for the development and growth of fish (Nagel *et al.,* 2012). For example, cotton seed cake contains high levels of gossypol, an antinutritional molecule that prevents feed from being effectively digested, and is deficient in cysteine, lysine, and methionine amino acids, which are key ingredients necessary for fish growth and development (Munguti *et al.,* 2014).

Experimentation on different protein sources in fish nutrition has been conducted, with the incorporation of insects in fish feed formulation being recently in focus (FAO, 2020). This is because insects are part of the fish food web in nature, at least for most farmed fish species. The application of black soldier fly (BSF) in substituting FM in diets of different fish species has demonstrated a high potential and this is because the BSFL have high-quality protein, an essential amino acid characterization almost similar to FM, the ability to utilize a variety of local organic waste materials, and they are inexpensive to produce (Wang and Shelomi 2017, Nairuti *et al.,* 2021). These larvae can also be produced in mass at a relatively reduced cost, thus confirming its sustainability as a protein source (Ssepuuya *et al.,* 2017). Black soldier fly larvae meal (BSFLM) has been successfully used in the diets of different fish species, such as redband trout (*Oncorhynchus mykiss*), channel catfish (*Ictalurus punctatus*) and blue St. Peter's fish (*Oreochromis aureus*) (Kroeckel *et al.,* 2012). Significant growth performance was achieved when BSFLM substituted up to 48% of FM in the diets of yellow catfish (*Pylodictis olivaris*) (Xiao *et al.,* 2018). However, there were no significant differences in fish growth in studies conducted by Hu *et al.* (2017), Zhou *et al.* (2018) and Magalhàel *et al.* (2017) between Jian carps and European seabass fed on FM and BSFLM-based diets.

This study was motivated by BSF's ability to convert organic waste into valuable proteins that can be used to provide quality feed for *Clarias gariepinus* and also improve waste management, especially in protocols involving integrated aquaculture systems. In the long-term, this will encourage commercially and environmentally sustainable aquaculture production (Ayoola, 2010). Upon this background, the effect of replacing fish meal for black soldier fly larvae meal (BSFLM) on growth and feed utilization of African catfish (*C. gariepinus*) was evaluated to assess how well *C. gariepinus* grew on diets that replaced FM with BSFLM in increasing proportions.

Materials and methods

Source of ingredients and proximate analysis

Black soldier fly (BSF) larvae were procured from the International Centre for Insect Physiology and Ecology (ICIPE), Nairobi while propagation and mass production were performed at Sagana Research Centre. Other feed components,

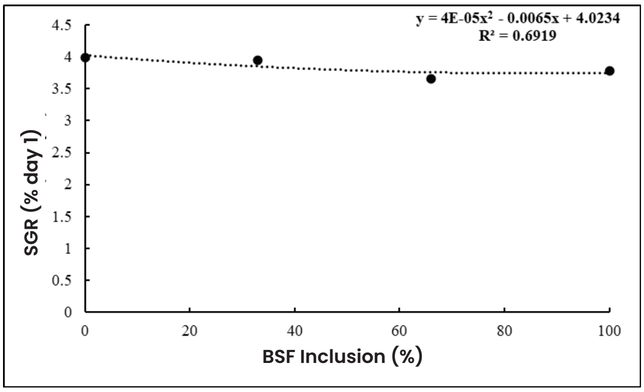

Figure 1. Variation in SGR in different the BSF inclusion levels.

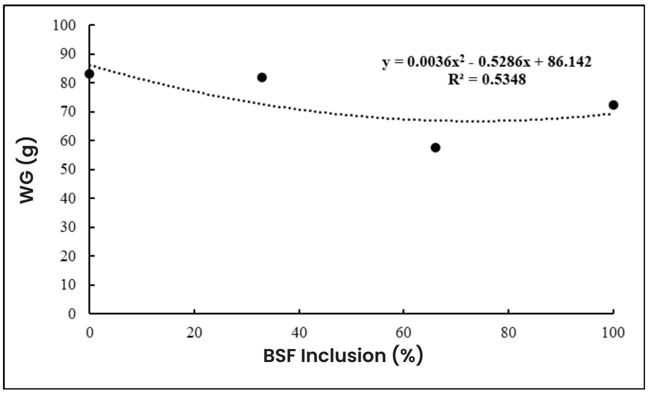

Figure 2. Variation in body weight gain (WG) in the different BSF inclusion levels.

such as fishmeal (Omena, *Rastrineobola argentea*), soybean meal (*Glycine max*), and maize bran (*Zea mays*), were procured from local feed suppliers based on cost and availability.

The formulated diets and individual ingredients underwent proximate analysis in triplicates using standard methods (AOAC, 1995). Analyses of dry matter (DM), crude protein (CP), crude fiber (CF), crude fat and ash content were performed in triplicate at Cropnuts Laboratory Services, Lim-

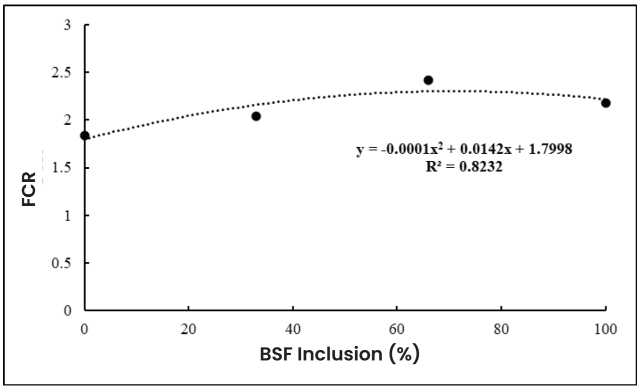

Figure 3. Variation in FCR in the different BSF inclusion levels.

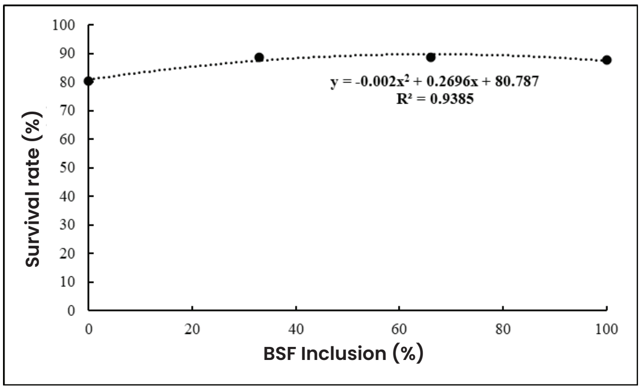

Figure 4. Variation in survival rate in the different BSF inclusion levels.

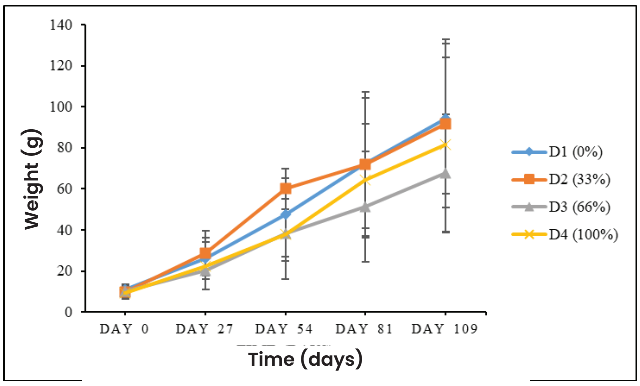

Figure 5. Trends in weight of C. *gariepinus* fed diets with varying levels of BSFLM.

** D1 (0% BSFLM inclusion); D2 (33% BSFLM inclusion); D3 (66% BSFLM inclusion); D4 (100% BSFLM inclusion)

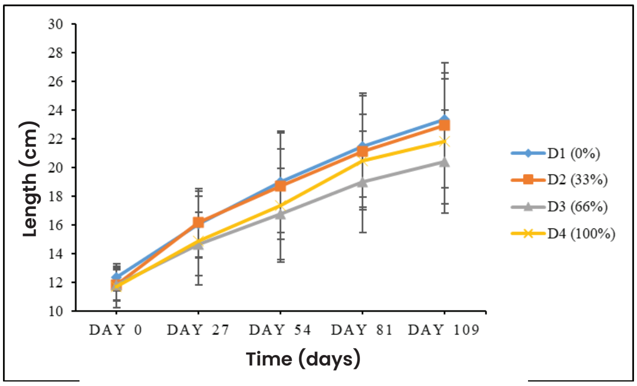

Figure 6. Trends in length of *C. gariepinus* fed diets with varying levels of BSFLM.

** D1 (0% BSFLM inclusion); D2 (33% BSFLM inclusion); D3 (66% BSFLM inclusion); D4 (100% BSFLM inclusion) uru, Kenya. DM was derived by drying the sample in an oven to constant weight for six hours at 105°C. Ash content was measured by heating the samples in a muffle furnace at a temperature of 600°C for three hours. The CP was measured using the conventional micro-Kjeldahl nitrogen analysis, and CF analysis comprised 4 hours of heating at 550°C in a muffle furnace after four consecutive alkaline-acid digestions.

Experimental test diets

Experimental diets were generated by substituting FM protein with BSFLM protein at substitution rates of 0, 7.5, 15, and 22.5% of BSFLM, or 0, 33, 66, and 100%, respectively. The ingredients were thoroughly mixed before diet formulation. A soft dough for pelletizing was prepared by addition of clean water to the feed mixture then pulverized several times and pelletized using a commercial 2-4 mm diet pelletizing machine to produce a homogeneous diet. The pellets were evenly spread and exposed to the sun to achieve proximate moisture content. Table 1, indicates the chemical composition and proximate composition of different test diets while Table 2 indicates the proximate composition of BSFLM.

Table 1. Ingredient formulation and proximate composition of test diets. D1- Diet 1- control (without black soldier fly larvae meal inclusion), D2-Diet 2 (33% substitution rate), D3-Diet 3 (66% substitution rate) and D4-Diet 4 (100% substitution rate, i.e., maximum BSFLM inclusion).

Ingredient inclusion (%)	D1 (0%)	D2 (33%)	D3 (66%)	D4 (100%)
Fish meal	20	13.3	6.6	0
Black soldier fly larvae meal	0	7.5	15	22.5
Soybean meal	60.9	59	63	64.1
Maize bran	4.7	10	7	6.7
Lipid	7.3	5.1	3	0.9
Monocalcium phosphate	0.5	0.5	0	0.5
Vitamin premix	0.5	0.5	0	0.5
Carbohydrate	6.1	1.7	1.4	0
Filler	0	2	4	4.8
Total	100	100	100	100
Proximate composition of test diets (%)				
Moisture	7.38	6.86	9.46	8.64
Ash (dry)	15.9	12.8	11.1	7.27
Crude protein	37.9	44.6	45.4	47.8
Crude fat	8.93	6.20	4.60	4.05
Crude fibre	4.86	3.93	5.48	5.22
Nitrogen free extract (NfE)	24.9	25.6	23.9	26.9
Dry matter	92.6	93.1	90.5	91.36

Table 2. Black soldier fly larvae meal (Whole crushed) proximate composition.

Parameter	Abbrev.	Unit	Result
Energy	E	MJ/kg	14.4
Protein	CP	%	51.1
Total Ash	Ash	%	15.6
Fat	Lipid	%	11.8
Fibre	Fibre	%	7.10
Nitrogen free extract	NfE	%	14.3
Dry Matter	DM	%	93.8

Even though the diets were intended to be isoproteinous and isolipidous, analysis of the diets' crude protein (CP) levels revealed that they varied among diets but were frequently greater than the estimated 36% CP. However, there were overarching patterns throughout the test diet regimens, showing that the measured crude protein rose proportionately with increasing inclusion on BSFLM. In contrast to diet 1 (D1) with 0% BSFLM, which recorded the least amount of proximate crude protein (37.96 ± 0.02), diet 4 (D4) with 100% BSFLM had the highest CP (47.83 ± 0.03). The proximate crude fat showed the similar trend, with diet D1 having the greatest level (8.93 ± 0.00) and diet D4 having the lowest level (4.05 ± 0.01). the ash content decreased with increasing BSFLM in the diets.

Experimental design and trial

This study was carried out at Sagana Research Centre (0°19´S and 37°12´E) for 109 days. 352 one-month old *C. gariepinus* of uniform sizes were obtained from Sagana research station hatchery. The fish were stocked in hapa nets (4 x 4 m) installed in earthen ponds for 1 week to acclimatize, while being fed with commercial floating feeds. Thereafter, two hundred and forty fish were selected from the acclimatized stock and distributed in a completely randomized design with four treatments in triplicates. Fish were fed to satiation, increasing inclusion levels of BSFLM, replacing Fishmeal (FM) at 0%, 33%, 66%, and 100% designated as D1, D2, D3 and D4 respectively. To control predators, the cages were covered with predator nets. Daily records of fish mortality were kept. To track the growth performance criteria that guided feed quantity adjustment, fish samples were taken after every 28 days.

Analysis of dietary performance

The following metrics were evaluated, and these formulas were applied, to assess the efficiency of growth and feeding:

Specific growth rate (SGR, %) = 100 × [(Ln BW final (g) – Ln BW initial (g) / days of experiment]

Body weight gain (BWG, g) = Final weight (g) - Initial weight (g)

Feed conversion ratio (FCR) = Feed provided/ Live weight gain (g)

Survival rate (%) = (Number of fish harvested)/ (Number of fish stocked) × 100

Statistical analysis

Statistical analysis was done using MS Excel and SPSS statistics (Version 21). For normality checks, Shapiro-Wilk test was applied to assess normality of the data obtained and then ANOVA was used to test for significant at α = 0.05. Tukey-HSD post hoc was used to determine the variance amongst the means.

Results

Water quality

The results of the water quality parameters analyzed are shown in Table 3. There were no significant variations in physico-chemical parameters during the study period ($p > 0.05$). All the values were within the acceptable levels for African catfish culture.

Table 3. Water quality parameters recorded during the study period. Mean, minimum and maximum values are presented.

Parameter	Mean	Minimum	Maximum
Temperature (°C)	24.5	22.0	29.4
Dissolved oxygen (DO) (mg/L)	4.75	2.54	7.07
Conductivity (µS/cm)	71.6	51.1	103
Total dissolved solids (TDS) (mg/L)	67.6	53.7	81.9
pH	7.92	7.82	9.97

Growth performance

The growth performance of *C. gariepinus* fed on diets with differing BSFLM proportions showed no major variances in specific growth rates (SGR) (Fig. 1), mean body weight gain (WG) (Fig. 2), feed conversion ratio (FCR) (Fig. 3), and survival rates (Fig. 4) during the study period ($p >$ 0.05). Diet D1 had the lowest FCR (1.84 ±1.01) while the fish fed on D3 (66% inclusion) had the highest FCR (2.42±1.08). In comparison to the control diet (D1), the survival rates of the African catfish fed with D2, D3, and D4 were significantly higher ($p <$ 0.05). Fish fed diet D2 had the highest survival rate (88.62 ± 9.23%).

Growth trend (weight and length) of *C. gariepinus* over the study period is shown in Fig. 5 and 6 respectively. The growth trend from day 0 to day 109 showed overlap and similarity between treatments. However, there appeared a clear segregation on the 81st day between the diets, up until the last day of the study. At the end of the culture period, diet D1 (0% BSFLM inclusion) and D2 (33% BSFLM inclusion) showed the best growth performance of *C. gariepinus* in terms of final mean weight and length.

Discussion

During the study period, there were no observed incidences of fish deformity or ill health. The survival rate of fish amongst the dietary treatment was generally high (above 75%) perhaps due to the stability of the trial conditions but higher survival rates (above 98%) were reported by Adeoye *et al.* (2020) when *C. gariepinus* fingerlings were fed diets with increasing inclusion levels of BSFLM. The difference in survival rates could be attributed to the adoption of the tank system hence ensuring more control as opposed to the cage system in the current study. Further, in comparison to previous studies, lower survival rates were realized in the present study than those of Rainbow trout (Caimi *et al.,* 2021), Nile tilapia (Tippayadara *et al.,* 2021; Limbu *et al.,* 2022), Jian carp (Zhou *et al.,* 2018), rainbow trout (Cardinaletti *et al.,* 2019), zebrafish (Zarantoniello *et al.,* 2019; Ordoñez *et al.,* 2022) and African catfish (Njoroge, 2020) when fed on diets containing varying proportions of the BSFLM.

Fish fed diet D2 with 33% BSFLM substitution of fishmeal exhibited improved final mean weight and length though not significantly different from control diet 1, (0% BSFLM). Studies by Kroeckel *et al.* (2012) and Wachira *et al.* (2021) reported a higher mean weight gain of 15% at an inclusion level of 33% in juvenile turbot (*Psetta maxima*) and Nile tilapia (*Oreochromis niloticus*), respectively. Increasing inclusion levels of BSFLM beyond 50% resulted in lower growth as observed in fish fed diet D3, which agrees with the study by Tippayadara *et al.* (2021) who reported significant decreases in BWG and SGR of *O. niloticus* with substitution levels of FM by BSFLM above 50%.

The final weight, BWG and SGR in this study showed that fish fed on a diet with 0% and 33% BSFLM inclusion performed significantly better than the fish fed on the 66% BSFLM inclusion which concurs with results presented by Nairuti *et al.* (2021) and Maranga *et al.* (2023). Previous studies have shown the protein quality in BSFLM to be high and also to possess almost similar amino acid profile as that of fish meal (Henry *et al.,* 2015). This may have been the reason for the excellent performance of fish fed on diets containing the insect meal. Lipid level in diet D1 and D2 are 8.93 % and 6.2 % respectively which are the levels optimum for the growth of *C. gariepinus*.

Replacing of FM by BSFLM at 66% and 100% showed reduced growth. The reason for the decrease in growth with increasing BSFLM inclusion could be due to increased fat content at inclusion levels of BSFL-66% and BSFL-100% in the diets, which might inhibit feed intake or diet digestibility (Watanabe, 1982, 2002; Ali and Jauncey 2004). For example, Fasakin *et al.* (2003) observed a decline in the growth of *C. gariepinus* fed full-fat maggot (*Musca domestica*) meal compared to the fish meal. The authors attributed this growth reduction to poor palatability and digestibility as well as poor amino acid content. In support of this, Talamuk (2016) found that the fat contents in the test diets increased with increasing BSFLM inclusion. In other studies, increasing dietary lipids in the diet of Nile perch juveniles produced poor growth, and poor FCR was achieved with fish fed on high lipid diet of 15%.

Furthermore, BSF has a naturally occurring polymer called chitin especially in its unprocessed form. Therefore, increased inclusion levels of BSFLM contributes to high chitin levels in the respective diets. Diets at substitution levels beyond 33% BSFLM could have contributed to reduced final weight, BWG and SGR. Chitin has been reported to inhibit lipid digestibility and lower nutrient absorption from the gastrointestinal tract, further lowering proper food absorption as confirmed in a study carried out by Kroeckel *et al.* (2012) who reported a reduction in growth rate in the juvenile turbot when fed on diets with substitution of FM by BSFLM above 33%, due to increased chitin which may have contributed to the slower growth of the fish. Gopalakannan *et al.* (2006) and Olsen *et al.* (2006) noted that any slight increase in the inclusion rate of chitin (>1%) in the diets of tilapia (*O. niloticus* × *O. aureus*) compromises the feed intake leading to poor growth.

Conclusion and recommendations

The findings from this study shows that black soldier fly larvae diet has the potential of replacing fishmeal and providing affordable quality protein in the diets of the African catfish. Feeding *C.*

gariepinus with a 33% BSFLM has the capacity to improve weight gain and other growth parameters the same way as the diet containing fish meal i.e. control diet containing no black soldier fly diet. With proper processing and value addition methods associated with the removal of chitin content, BSF can be used in formulations of the African catfish diet to improve growth performance. This can decrease the aquaculture production costs and improve sustainability and alleviate food shortage around the world.

Acknowledgement

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Mangrove dieback due to massive sedimentation and its impact on associated biodiversity

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Abstract

Emerging scientific evidence strongly suggests that the 1997/8 and 2000 rains in the Western Indian Ocean (WIO) region previously attributed to El-Niño were mainly caused by the Indian Ocean Dipole (IOD), a phenomenon whose frequency and intensity have increased over the years due to climate change. The abnormally high rainfall experienced during this time combined with poor land use managment, caused intense sedimentation due to erosion of terrigenous sediments, leading to extensive mangrove die-back in several areas in the WIO region. The extent and impact of this die-back on mangrove-associated biodiversity has not been assessed to date. The objective of this study was to assess the impact of the die-back on mangrove associated biodiversity at Mwache Creek, Mombasa, Kenya, where about 200 ha of mangroves were decimated. Biodiversity in impacted sites was compared to reference sites (natural forests) in order to assess the impact of IOD-related massive sedimentation to mangrove-associated biodiversity namely crabs and molluscs. Transects (sea-landward transect) were laid 10 m apart to ensure independence of sampling units in both impacted and natural sites. Along each transect, 5 m² quadrats were made at 100 m intervals. Within the 5 m² quadrats, one 2 m × 2 m sub-quadrat was randomly placed for actual sampling where relevant physico-chemical variables were measured and mangrove biodiversity determined as an indicator of ecosystem change. Environmental factors showed a strong variability among transects whereas faunal assemblages significantly differed among the treatments (impacted and non-impacted). Salinity, temperature and total dissolved oxygen (TDSO) were the environmental factors that contributed to the changes in biotic composition among the treatments, whereas *Uca inversa, Uca annulipes, Cerithidea decollata* and *Perisesarma guttatum* contributed more to the differences in faunal composition between treatments. The degradation seems to have significantly reduced crab and mollusc species richness and densities and led to loss of other mangrove-associated faunal species in the impacted site. These results emphasize the effects of climate change-related impacts on mangrove-associated biodiversity and by implication, the ecosystem functions they support.

Key words: mangrove, sedimentation, fauna, molluscs, crabs, biotic

Introduction

Mangroves are important ecosystems, providing economic, cultural and ecological benefits where they occur (Bosire *et al.,* 2016; Carugati *et al.,* 2018; Rodriguez *et al.,* 2019). These forests provide a habitat to a unique and diverse set of associated fauna (Farnsworth and Ellison, 1996; Bosire *et al.,* 2008; Kairo *et al.,* 2008; Jenoh *et al.,* 2019; Barbanera *et al.,* 2022), with crabs and molluscs being the most abundant macrobenthic groups (Vannini *et al.,* 2006; Cannicci *et al.,* 2008). Crabs and molluscs play various important ecological roles in the mangrove ecosystem by influencing vegetation structure through selective predation of seedlings (Bosire *et al.,* 2005; Dahdouh-Guebas *et al.,* 1998; 2011), nutrient cycling (Lee, 1998; Cannicci *et al.,* 2008; Nagelkerken *et al.,* 2008; 2009; Carugati *et al.,* 2018), aerating and altering the mangrove sediments by the numerous burrows they dig (Bartolini *et al.,* 2011; Dahdouh-Guebas *et al.,* 2011) and reducing the pore water salinity by allowing flushing of the sediments via their burrows (Ridd, 1996). Despite the importance of mangroves, they have one of the highest rates of degradation (Mukherjee *et al.,* 2014; Bosire *et al.,* 2016; Brown *et al.,* 2020) due to varied causes (Farnsworth and Ellison, 1997; Alongi, 2002; Mohamed *et al.,* 2008; Jenoh *et al.,* 2019). Global environmental changes ranging from sea level rise, flooding, aridity and elevated salinities have added to the list of threats to the integrity of mangrove ecosystems (Kitheka *et al.,* 2002; Hansen *et al.,* 2003; McLeod, 2006; Bosire *et al.,* 2006; Case, 2006; IPPC, 2007; Mclanahan *et al.,* 1988; 2008; Di Nitto *et al.,* 2008; Huxham *et al.,* 2010).

In 1997/8 and 2000 the abnormally high rainfall experienced in the Western Indian Ocean (WIO) region, previously attributed to El-Niño (Kitheka *et al.,* 2002; Bosire *et al.,* 2016) and more later linked to Indian Ocean Dipole (IOD) (Saji *et al.,* 1999; Overpeck and Cole, 2007; Nakamura *et al.,* 2009; Bosire *et al.,* 2016), a phenomenon whose frequency and intensity has increased over the years due to climate change. The IOD causes either prolonged droughts or intense rainfall (during the short rain season), with diverse attendant consequences e.g. flooding, sedimentation and crop failure among others (Bosire *et al.,* 2006; Overpeck and Cole, 2007; Hanley *et al.,* 2020; Krauss and Osland, 2020), with the potential to disrupt livelihoods of millions of dependent communities. In 1997/8 and 2000, the IOD-instigated heavy rains coupled with poor land use management systems upstream caused massive sedimentation due to erosion of terrigenous sediments, leading to extensive mangrove die-back in several areas in the WIO region. For instance, in Kenya, the peri-urban mangroves of Mwache Creek in Mombasa were severely affected, losing close to 200 ha of forest cover (Kitheka *et al.,* 2002; Bosire *et al.,* 2006). Other affected mangroves in Kenya were those in Tudor creek, Tana River and Lamu, but the extent of the die-back in these sites has not been determined.

While the response of coral reefs to these IOD events has been well documented in the region (Saji *et al.,* 1999; Wilkinson *et al.,* 1999: 2000; Obura, 2005; Overpeck and Cole, 2007), scanty information is available on the response of mangrove-associated biodiversity to the extensive sedimentation and the subsequent mangrove dieback. Mangrove-associated biodiversity has an intricate association with the mangroves and thus will indirectly suffer the impacts of mangrove ecosystem degradation, depending on their differential abilities to adapt to the resultant environmental changes (Hansen *et al.,* 2003; Brown *et al.,* 2020), which can greatly alter faunal composition, density and assemblages (Lovett *et al.,* 2005; Brown *et al.,* 2020). In some cases, this will cause reduction of biodiversity or even localized extinction (Erasmus *et al.,* 2002; Malcome *et al.,* 2002; Brown *et al.,* 2020; Barbanera *et al.,* 2022). Extensive mangrove dieback due to ecological degradation like extensive sedimentation is likely to affect species composition, constrict species range due to loss of habitats and eventually affect the population size of a species (Warren and Niering, 1993; Mumby *et al.,* 2004; Case, 2006; Brown *et al.,* 2020). The objective of this study was to assess the response of mangrove-associated biodiversity to the dieback following the 1997/8 and 2000 massive sedimentation.

Materials and methods

Description of study site

This study was conducted at Mwache Creek (Fig. 1), located in the upper Port Reitz area (Kitheka, 2003). Mwache Creek ($4^{0}3.01'$ S, $39.06^{0}38.06'$E) is located 20 km Northwest of Mombasa city in Mombasa County, Kenya. The total area of the wetland is approximately 17 km^2 with about 70% of the surface area covered by mangroves. The creek has both basin and riverine mangroves and a distinct mangrove-fringed channel in the lower sections. The mangrove species found in Mwache Creek are: *Avicennia marina* (Forsk.) Vierh, *Rhizophora mucronata* (Lamk), *Ceriops tagal* (Perr.) C.B. Robinson, and *Sonneratia alba* Sm. (Kitheka, 2002). The creek receives freshwater from Mwache River, which is seasonal and thus there is usually no flow during the dry season, mainly between December and March, and July and September. The rate of sediment production within Mwache River basin reaches a maximum of 3,000 tons yr^{-1} due to poor land-use activities e.g. overgrazing, shifting cultivation, cultivation on steep slopes without the application of soil conservation measures, high rainfall intensity during the rainy season and steep land gradient, among others (Kitheka, 2002).

These high erosion rates and sedimentation led to severe mangrove dieback due to smothering of mangrove roots as a result of excessive input of terrigenous sediments especially at the landward zone (Kitheka, 2002) during the IOD-related flooding of Mwache River. The most extensively affected species was *R. mucronata*, whereas *A. marina* was relatively less affected. The area affected is about 17% of the total mangrove forest acreage within the creek (Bosire, 2009).

Experimental design

The study was conducted during two spring tides of July and August 2008. To assess the impact of the mangrove dieback on associated biodiversity, two degraded sites (S1D and S2D) within Mwache Creek were used as the experimental units for this study. Each degraded area was sandwiched between natural forests (S1F1, S1F2 and S2F) which were either not impacted or relatively less impacted during the IOD event and were thus used as reference sites. The first degraded site had an additional reference forest (S1F2) at the landward side of the impacted site. Two transects perpendicular to the shoreline were made for both treatments (impacted and non-impacted) at the first site. Along each transect, 8 quadrats (5 m^2 each) per transect were made after every 100 m. whereas three transects were laid at the additional reference forest of the first site. However, due to small size of the additional reference forest of the first degraded site (S1F2), only two quadrats per transect were made at this additional reference forest. In the second impacted site, the reference plot was wider than longer,

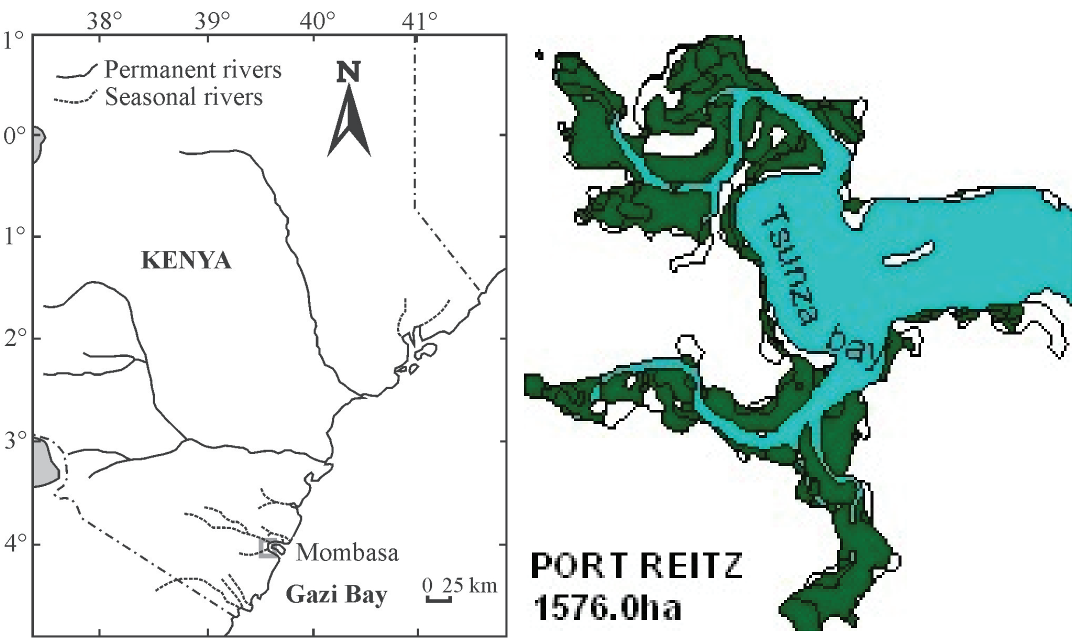

Figure 1. A map of the study area showing location of the two study sites. Each site had two sampling areas i.e. the reference forest and the degraded forest (Source: Authors).

hence only four quadrats per transect could fit, but three parallel transects were laid. Transects were laid 10 m apart to ensure independence of sampling units. Along each transect, 5 m^2 quadrats were made after every 100 m. Within the 5 m^2 quadrats, one 2 m × 2 m sub-quadrat was randomly placed for actual sampling.

Physico-chemical variables

In each sub-quadrat set-up as described above, a total of five sediment cores were randomly taken using a hand corer of diameter 6.4 cm to a depth of 15 cm during low spring tide. The samples were then sub sectioned (2 cm sections), immediately stored in cool boxes with ice and transported to the laboratory where they were frozen at -20 ^{0}C for various analyses. Three sediment cores were used for nutrients (NO_2^-, NO_3^-, NH_4^+, and PO_4^{3-}) and organic matter analysis, whereas the remaining two cores were used for grain size analysis. From one of the holes made by the removal of the sediment cores, interstitial salinity, temperature, dissolved oxygen and conductivity were determined using a universal multimeter (Hanna instruments). Before any analysis, corresponding segments from each core were pooled together and homogenized.

Pore water was extracted from 10 g of sediments in 40 mls 1M KCl, then flashed with white nitrogen gas (2 minutes) and mechanically shaken for 2 hours, to ensure adequate extraction. Each sample was then centrifuged using Van der Heyden, Heraeus Sepatech, Megafuge 1.0 R at a speed of 2000 × g.r.m. for 10 minutes. The supernatants were decanted then adequate amounts were put in volumetric flasks and diluted with distilled water. The resultant solutions were used for the determination of nutrients. Ammonium (NH_4^+) and phosphate (PO_4^{3-}) were determined according to methods described by Parsons *et al.* (1984), whereas nitrite (NO_3^-) and nitrate (NO_2^-) according to APHA (1995).

Sediment granulometry and organic content

Soil texture was assessed by sieving 100 g subsamples of dry sediment through eight different sieves corresponding to as many grain size classes (>0.38 μm, >0.63 μm, >125 μm, >250 μm, >500 μm, >1 mm, > 1.60 mm and >2.00 mm). The mass of the soil fractions in each class was then weighed and expressed as percentage of the original mass.

The organic content of the sediment was measured by baking 10 g of sediment for three days in a muffle furnace at 350°C. The organic fraction was estimated by calculating the weight lost of the sediment dry weight (24h, 80°C) and standardized as percentage.

Faunal colonization

For every 2 m × 2 m sub-quadrat above, all crab species were identified and counted using a binocular to assess the ratios among species and the sex ratios within the species (Skov *et al.*, 2002). In order to avoid underestimating those species not active during the direct binocular counts, three sub-quadrats (0.5 m × 0.5 m) were randomly placed in the 2 m × 2 m quadrat after the binocular counts in order to count the crab burrows (Skov *et al.*, 2002). Dichotomic identification keys by Cannicci *et al.* (1997) were used for species identification. Molluscan species were identified and counted within the 2 m × 2 m quadrat using keys in Richmond (1997). Molluscs species on trees falling within the sub-quadrat up to 1 m height from the ground were also identified and counted.

Statistical analyses

Multivariate methods were used to analyze changes in both abiotic and biotic assemblages in the treatments. Abiotic similarity matrix was computed using Euclidean distance on normalized data, while biotic similarity matrices were computed using Bray–Curtis distance on square root transformed data. A Principal Component Analysis (PCA) and Non-metric Multidimensional Scaling (NMDS) (Clarke, 1993; Field *et al.*, 1982) were used to visualize multivariate patterns on abiotic and biotic data respectively.

Two distinct distance-based permutational multivariate analysis of variance (PERMANOVA) designs (Anderson, 2005) were employed to test (at a significance level of p = 0.05), based on the null hypotheses of no differences in environmental factors and in faunal assemblages among treatments (impacted vs. primitively forested sites) and across sampling sites and treatments. Further, DistLM routine (using the "best fit" and "BIC" models) was employed to identify the abiotic factors able to explain the changes in biotic composition, whereas the Canonical Analysis of Principal coordinates (CAP) (Anderson and Robinson, 2003; Anderson and Willis, 2003) was used as a constrained ordination procedure to confirm the consistency in the variation in the biotic factors among treatments. In addition, a distance-based redundancy analysis (dbRDA) was employed for partial display on both the abiotic factors able to explain the changes in biotic composition. Multivariate analyses were performed using the PRIMER v.6.1 (Clarke and Gorley, 2006) and the PERMANOVA + for PRIMER routines v. 1.0 (Anderson *et al.*, 2008).

Results

Environmental factors

The environmental factors showed no defined trends between forested and impacted areas across the 2 sites as depicted by the PCA plot (Fig. 2). A 3-way PERMANOVA test with factors: treatment (orthogonal and fixed), site (orthogonal and fixed) and transect (nested in site and random), showed a strong variability among transects (Table 1). A DistLM analysis was used to search from all sampled parameters the variables that contributed more to the changes in biotic composition among treatment. This test isolated salinity followed by temperature and TDSO in order of importance (Fig. 3).

Biotic factors

There were differences in faunal composition between treatments across the 2 study sites (Fig. 4). A 3-way PERMANOVA test with factors: treatment (orthogonal and fixed), site (orthogonal and fixed) and transect (nested in site and random); indicated significant differences in the biotic composition between treatments regardless of the sites and transects (Table 2). Canonical Analysis of Principal coordinates (CAP) analysis showed a significant effect between the treatments (Table 3). The test (CAP Leave-one-out test) was able to reallocate the samples to their original group with 94% and 100% of success, attesting to the strong difference in faunal compo,-sition between the treatments across the 2 sites (Table 3). A dbRDA test showed that *Uca inversa*

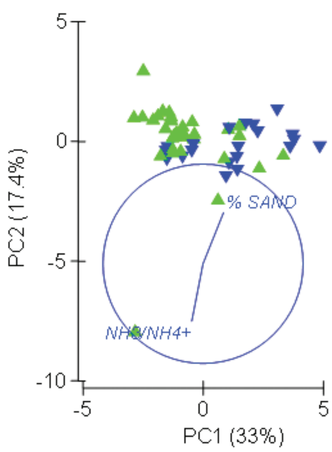

Figure 2. PCA ordination for environmental factors showing no visible differences between treatments regardless of sampling sites. Green symbols represent the forested sites, whereas blue symbols represent degraded sites.

Table 1. Results of the 3-way PERMANOVA testing the environmental factors between the treatments across the 2 study sites with transects (nested in site and random).

Source	df	SS	MS	Pseudo-F	P(perm)	perms	P(MC)
Site	1	32.809	32.809	2.1936	0.2005	29	0.0651
treat	1	44.57	44.57	2.2988	0.2326	8883	0.0873
TRANSECT(Site)	3	51.978	17.326	2.002	0.0356	9915	0.0087
Sitextreat	1	10.575	10.575	0.54543	0.6521	8935	0.7873
treatxTRANSECT(Site)	2	39.13	19.565	2.2607	0.0039	9910	0.0091
Res	45	389.45	8.6545				
Total	53	583					

(Hoffmann), *Cerithidea decollata* (Linnaeus), *Uca annulipes* (H. Milne Edwards) and *Perisesarma guttatum* (A. Milne Edwards) contributed more to the difference in faunal composition with *U. inversa* being typical of the impacted areas and *C. decollata, U. annulipes* and *P. guttatum* being more common in the forested areas (Fig. 5).

Table 2. Results of the 3-way PERMANOVA testing the differences in the biotic composition between treatments, sites and transects.

Source	df	SS	MS	Pseudo-F	P(perm)	perms	P(MC)
Site	1	1675.4	1675.4	1.2692	0.3067	180	0.3025
treat	1	31548	31548	24.173	0.0186	9504	**0.0008**
TRANSECT(Site)	4	5545.7	1386.4	1.1677	0.2865	9918	0.3055
Sitextreat	1	764.32	764.32	0.58564	0.675	9506	0.696
treatxTRANSECT (Site)	2	2620	1310	1.1033	0.3629	9945	0.3612
Res	44	52241	1187.3				
Total	53	1.0094E5					

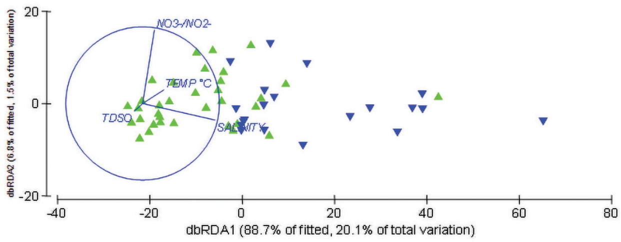

Figure 3. dbRDA showing the variation in the abiotic factors salinity, temperature and TDSO (in order of importance) as responsible for the changes in the biotic composition across the study sites.

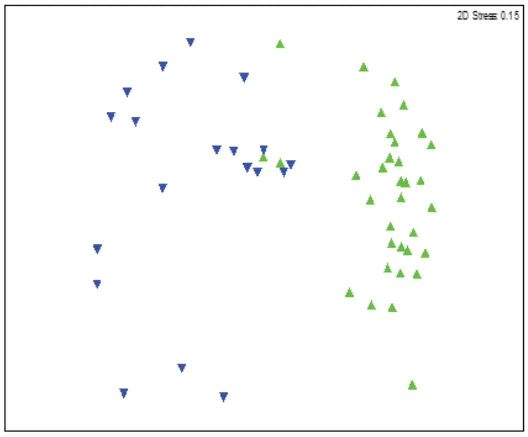

Figure 4. nMDS ordination of faunal assemblage showing visible differences among treatments regardless of the study sites. Green coloured triangles represent faunal samples drawn from reference sites whereas the blue triangles represent those from degraded sites.

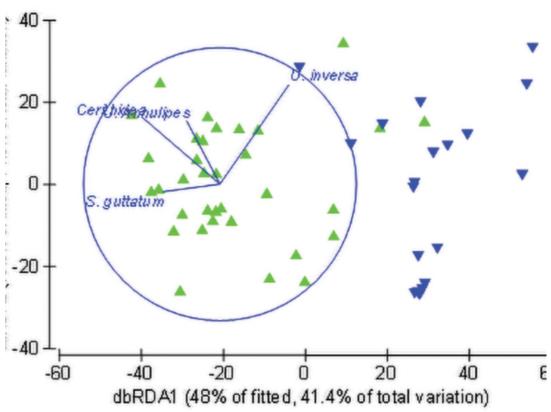

Figure 5. dbRDA plot of faunal assemblage showing that *U. inversa, C. decollata, U. annulipes* and *P. guttatum* contributed to the difference in faunal composition within the treatments. Green coloured triangles represent faunal samples drawn from reference sites whereas the blue triangles represent those from degraded sites.

Table 3. Results of a CAP Leave-one-out Allocation of observations to groups showing the consistency of the differences in faunal composition between the treatments across the study sites.

Orig. group	Classified			
	F	D	Total	%correct
F	32	2	34	94.118
D	0	20	20	100

Discussion

There was lack of variation in environmental parameters between the treatments (Table 1), suggesting that disturbance did cut across the entire study area. Previous studies have reported sedimentation levels of up to 3 m in the study sites (Kitheka, 2002) and since our coring depth was 15 cm, it is possible to find no variation in environmental variables between treatments as displayed in the PCA plot (Fig. 2). It may be useful in future to take deeper cores from the sites for both treatments and analyse for variations of selected physico-chemical parameters as a function of depth and treatment. However, for the purpose of this particular study, a 15 cm depth coring is sufficient to provide the information on environmental changes affecting most of the studied fauna since they are mostly epibenthic. Variability among transects depicts disturbance that was not uniform in local micro-areas, which may have led to different microenvironments within the sites. For instance, patchy sedimentation and shading level can affect the interstitial water temperature and salinity level due to evaporation differences in shaded and non shaded areas and even affecting total dissolved oxygen hence leading to great habitat modification thereby creating micro niches for different faunal groups. These factors i.e. salinity, temperature and TDSO could consequently impact the composition and density of mangrove-associated fauna as highlighted by the dbRDA plot (Fig. 3). Other studies on mangroves have found similar results and reported that sedimentation within mangrove habitats had resulted in negative functional and structural effects on benthic communities and was responsible for lower densities and biodiversity of macro-fauna (Ellis *et al.,* 2004; Alfaro, 2010).

Total crab densities recorded in this study (Fi. 6) were lower than those recorded in studies by Icely and Jones (1978); Skov and Hartnoll (2001) and Skov *et al.* (2002), who recorded crab densities ranging from 77-100 m^{-2} for fiddler crabs alone. However, these studies are not fully comparable since their studies were done in pristine mangroves whereas this particular study was conducted in a generally degraded mangrove area. The low crab density (Fig. 6) and significantly differing composition between the treatments (Table 2), attest to the negative impacts of sedimentation which triggered the mangrove dieback, once again emphasizing the intimate link between mangrove forest structure and species richness (Bosire *et al.,* 2004, 2008). The MDS plot (Fig. 4) indicates a clear difference in fauna composition between the treatments which had different characteristics, thus re-enforcing the role of habitat integrity in biodiversity conservation (Fondo and Marterns, 1998; Ellis *et al.,* 2004; Barbanera *et al.,* 2022). The reference sites supported more biodiversity and had certain species specifically occurring in these sites, probably due to the structural complexity they afford which made them functionally better (in terms of food, shelter, refuge from predators and shade from direct sunlight) than the impacted site (Ruwa, 1988; Fondo and Marterns, 1998; Ewel, *et al.,* 1998; Erasmus *et al.,* 2002; Bosire *et al.,* 2004; Barbanera *et al.,* 2022).

In this study, three molluscs species: *Cerithidea decollata* (Linnaeus), *Crassostrea cucullata* (Born) and *Littoraria Scabra* (Linnaeus) were recorded in both impacted and non-impacted sites. This similarity in composition in the treatments could be due to the mollusc's wide ecological amplitude (Plaziat, 1984) and thus higher tolerance to environmental perturbation (Powell, 1990). The densities of molluscs (Fig. 7) were low in the disturbed forest compared to the reference forest further attesting to the

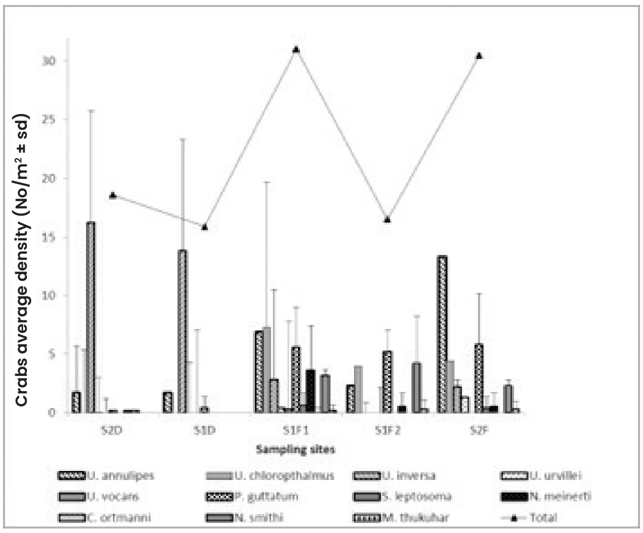

Figure 6. Average crab species density (number m^{-2}) and their corresponding standard deviation in the two study sites. (S1D, S1F1, SIF2, S2D, S2F).

importance of mangrove trees in supporting mangrove associated biodiversity. Even though this study did not record any *Terebralia palustris* (Linnaeus) which is the most important gastropod in terms of biomass in East African mangroves (Cannicci *et al.,* 2009), and is widely distributed in almost all Kenyan mangroves, there were visible traces of *T. palustris* shells on the mangrove floor across the sampling sites (*personal observation*). This suggested that this mollusc species had once existed in this mangrove before the massive sedimentation event that highly changed the sediment to sandy type, thereby leading to habitat modification, which resulted in its extinction in the local area. Studies conducted in the region on the impacts of sewage disposal on mangrove fauna found the gastropod nearly disappeared from impacted sites, suggesting a lower physiological tolerance of this gastropod to altered conditions (Cannicci *et al.,* 2009). The low density of the molluscs, especially *L. scabra* in the degraded area suggests the lack of optimal conditions for full recovery from the impacts of this event to the original densities or it could suggest a lower physiological tolerance of the molluscs to degradation. It is therefore likely that this species (*L. scabra*) may also disappear from the study site if the forest does not re-establish or in case of occurrence of another perturbation to the mangroves. The observed low tolerance to perturbation by some gastropod species suggests the possibility of using them as bioindicators. Studies have found that extinction of species (at least on a local scale) is a real possibility in case of habitat degradation and mainly due to habitat loss (Thomas *et al.,* 2004). Abrupt sedimentation, like other environmental stressors which could lead to severe habitat degradation, precipitating a pronounced shift in environmental factors, have great potential to cause cascades of species loss including actual species extinctions (Erasmus *et al.,* 2002; Malcolm *et al.,* 2002; Lovett *et al.,* 2005). In South Africa, models done to predict the impacts of climate change predicted local extinction for some species and reduced species diversity of study areas as a result of habitat degradation (Erasmus *et al.,* 2002). Depending on the tolerance level of a species to change in local conditions, a species could either go extinct, reduce in density or even migrate to other areas where migration is possible (Erasmus *et al.,* 2002; Case, 2006).

Compared to the impacted sites, the relatively healthy mangrove forest attracted high species composition and densities of both crabs and molluscs. However, despite lack of shading, hence the high temperature, salinity and general absence of the *A. marina* leaves which is the preferred food source for *C. ortmanni* and *N. meinerti,* these crab species remained in the degraded sites, even though they have the ability to move to the less impacted sites. Their fidelity to the *A.*

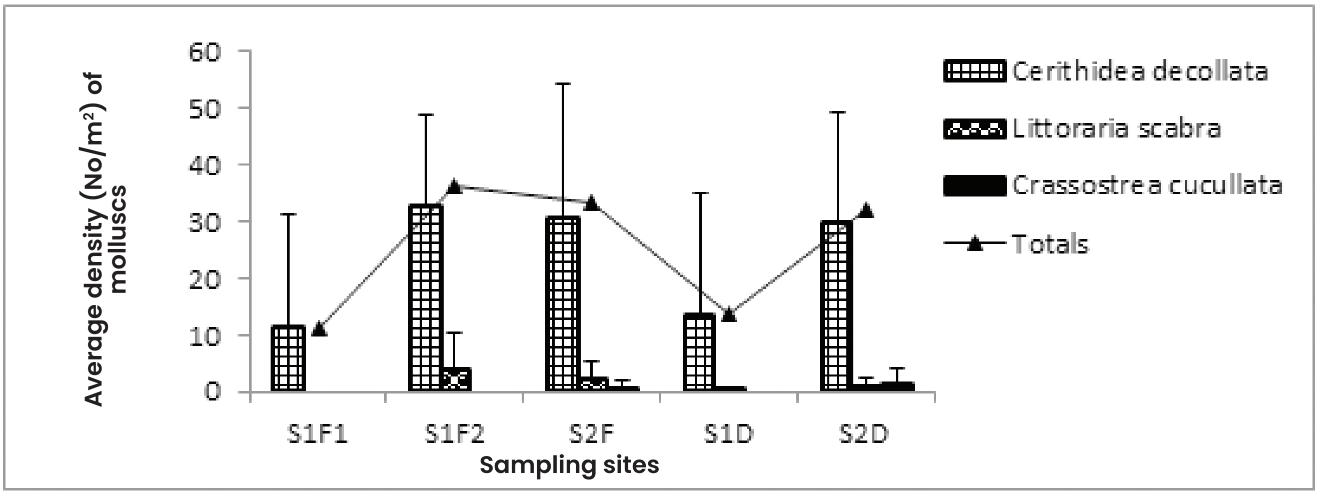

Figure 7. Average density (number/m²) and their corresponding standard deviation of Molluscs species at the different sampling sites.

marina zone despite the degradation could be explained by the fact that these crabs preferred *A. marina* leaves compared to *R. mucronata* leaves as their food (Ólafsson *et al.,* 2002) and the fact that sediments comprised higher percentage (70%) of their diet than leaves (Micheli, 1993; Ólafsson *et al.,* 2002; Skov and Hartnoll, 2002). It could therefore be thought to be energy wise non-profitable for these species to move to the less impacted sites where the leaves have the less desirable high tannin levels and the competition for the mangrove leaves from other crab species is higher. It seems that these crabs do not have much direct reliance to the mangrove tree. These crab species have been reported and observed to make burrows under terrestrial trees far from mangrove species. This suggests that in the case of pronounced mangrove die off (as in this case), the level of impact caused to mangrove associated fauna will depend on the degree of reliance of particular faunal group to the mangrove trees.

Some *Uca spp.* i.e., *U. inversa* and *U. annulipes* and molluscs were found to colonise the impacted site as well as the reference sites. In the reference sites, *Uca spp.* colonised mainly in areas which sedimentation type had changed to be sandy and with open canopy within the reference forest. The sandy sediment condition, combined with the open canopy in these reference forests resembles the conditions of the natural habitat for these *Uca* species i.e. the desert region of mangroves (the outer most side of mangroves which has either no mangrove or very sparse mangrove stands. The sediments are mainly sandy in this region). As for the molluscs, the function of shelter and attachment surface in the impacted sites was provided for by an invasive shrub *Suaeda maritima* (L. Dumort) which was colonizing the impacted site on places previously occupied by mangroves. On the other hand *Uca spp.* seemed not to strictly need the mangrove trees for either shelter or food, hence they were able to establish in both the impacted and reference forest. *U. inversa* which was responsible for the change in faunal composition, especially in the impacted area (Fig. 5) is known to thrive in generally high salinity (Gillikin, 2004) and the desert region of mangroves. This made *U. inversa* to easily establish in the entire study area regardless of treatment, whereas *C. decollata*, *U. annulipes* and *P. guttatum* have been known to establish in forested areas of mangroves (McGuinness 1994; Richmond 1997; Vannini *et al.,* 2006), hence explaining their density in the reference sites, as opposed to the impacted sites. The above situation attests to the ability of degradation to influence either species range expansion or constriction.

Abrupt and massive sedimentation due to extreme weather events and consequently mangrove dieback, may lead to habitat modification which in turn may either constrict or expand faunal range. At Mwache site we observed an expansion of *Uca* species beyond their normal habitat range. A previous study (Fondo and Martens, 1998) observed that the absence of mangroves did not seem to affect all faunal groups, especially infauna. This is in harmony with the finding of this study. However, it is worth noting that compared to a healthy mangrove forest, the density of the crabs and molluscs were very low in this study, suggesting lack of optimal conditions for complete establishment. A study conducted by Bosire *et al.* (2004) also found that the number of sediment-infauna taxa in both the reforested and natural sites of all the mangrove species was similar and higher than in the comparable bare sites. Their results suggested that the reforested sites are supporting more faunal recolonisation, and therefore becoming more akin to the natural mangrove sites in terms of the investigated functional indicators.

At the degraded sites, there was high growth of grass and an opportunistic shrub (*Suaeda maritima*) with S2 having higher cover of this opportunistic shrub. Frequently molluscs; *C. ortmanni* and *N. meinerti* were encountered around the *A. marina* stumps or under the opportunistic shrub. This shrub provided attachment substrate for molluscs and shelter for the *C. ortmanni* and *N. meinerti.* It seems, therefore, that the opportunistic shrubs can maintain some mangrove-associated biodiversity though in much lower densities and diversities (Stevens *et al.,* 2006). However the limited mangrove biodiversity maintained by the invasive species can act as an important precursor for quick recovery in case conditions change to support greater density and diversity. Therefore the opportunistic shrub acts as a reservoir of future colonization of species, even though such opportunistic shrubs don't provide the goods and services derived from mangroves to the ecosystem and the community. It seems, therefore that climate variability may trigger succession in degraded sites by inferior species without capacity to provide inherent ecosystem goods and services. This has ramifications on livelihoods of dependent communities e.g. in terms of wood provision, support to fisheries and coastal protection (Worm *et al.,* 2006; Semesi, 1998; Dahdouh-Guebas F *et al.,* 2000; Kairo, *et al.,* 2001). Previous studies have indicated that an increased number of species invasions over time coincided with loss of biodiversity and that invasion does not compensate for loss of native biodiversity and services since they compromise other species groups, mostly microbial and small invertebrates which have an equally important role in the ecosystem functioning and stability (Barbier, 2007; Duke *et al.,* 2007; Alongi and Carvalho, 2008).

Conclusion and recommendations

Mangrove mortality seems to have significantly shifted crab and mollusc species composition and reduced their densities, besides leading to probable loss of other mangrove-associated faunal species. Although the invasive flora invading the impacted sites may support different fauna and bring some degree of ecosystem functioning besides acting as a precursor for future recovery, they do not provide all the goods and services provided by the mangroves like wood products, coastal protection, nutrient filtering, sediment trapping and high organic matter production among others. This could be an example of the concept of 'cryptic ecological degradation', where the loss of mangroves in the disturbed sites has been masked by the expansion of the less important (less functional) opportunistic semi-terrestrial species (*Suaeda maritima*). These results confirm that sedimentation-triggered degradation will have far reaching effects by compromising the composition, density and diversity of mangrove fauna and associated biodiversity. In some cases, as was observed for *T. palustris,* there may be cascades which may trigger extinction of less tolerant species, with highly specialized niches and ecological compartmentalization. This study was conducted 10 yrs after impact and recovery of the mangroves was very limited. Human intervention by removal of physical impoundments to successive natural regeneration or actual restoration will be necessary (Bosire *et al.,* 2008). It will also be critical to link mangrove management downstream to land-use practices upstream and thus promote sustainable land-uses which minimize soil erosion, hence sedimentation downstream. This study should be conducted in other impacted areas to corroborate these findings and where possible different modeling scenarios undertaken to project future responses of mangrove associated biodiversity to such perturbations.

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Stock status of the dash-and-dot goatfish, *Parupeneus barberinus* (Lacepède, 1801) in Kenya's coastal marine waters

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Abstract

Demersal reef fisheries are important for the provision of food and livelihoods for the coastal communities. The fisheries are multispecies, exploited by artisanal fishers using a diverse range of gear types. Data collated from artisanal fishers along the Kenya coastline for the period 2017 to 2023 was used to assess the stock status of *Parupeneus barberinus* to inform the management of the fishery. Results revealed a higher proportion of *P. barberinus* caught were immature and large reproductive individuals were not conserved during the fishery. The fishing mortality estimate (F = 1.57 year^{-1}) and exploitation rate of 0.674, which is higher than the threshold of E = 0.5 year^{-1} indicate overexploitation. We recommend management to enforce monitoring and surveillance to ensure that legal gears with the right mesh / hook sizes are used for the protection of juveniles and sustainability of the fishery. There is a need to disseminate findings from this study to the stakeholders for awareness creation to ease the implementation of regulations in place.

Keywords: stock status, selectivity, mortality rates, exploitation

Introduction

Small-scale fisheries comprise majority of the global fisheries and are crucial in providing food and nutrition security, livelihoods, income and tourism services to coastal communities (Donner and Potere, 2007; Newton *et al.,* 2007; McClanahan *et al.,* 2013). Small-scale fisheries support about 6,500 fishermen in the coastal communities, excluding those engaged in the fish processing and marketing sectors and are the main contributors, accounting for about 93 – 98% of the marine catches in the Western Indian Ocean (WIO) region. Small-scale fisheries in the tropics are multi-species, exploited by multi-gears, making the management of the fisheries difficult. (Peterman, 2004). The fisheries predominantly dwell in the seagrass meadows and among the coral reefs (Donner and Potere, 2007).

Despite their crucial contribution, current scientific information on small-scale fisheries is not available, coupled with limited financial and institutional support complicate the management of the small-scale fisheries, especially those in the developing countries (Mahon, 1997). Even with the limited information, compliance to the regulations in place is poor owing to the fact that the resources are open access (Donner and Potere, 2007; Newton *et al.*, 2007). Additionally, the small-scale fisheries are overexploited and their habitats are degraded by the use of destructive fishing gears and effects of climate change (McClanahan, 2008).

Kenya's marine fisheries lie within the 640 km long coastline which extends from 1.75-4.65°S to 39.18-41.22°E and includes a narrow continental (nearshore) shelf which extends to about 60 km offshore at the Northern part and the 200 km offshore Exclusive Economic Zone (EEZ). The nearshore is largely characterized by fringing reefs running parallel to the shoreline. There are numerous resources of conservation concern in the coastline which include marine fish, coral reefs, seagrass beds, mangrove forests and a lot of cultural heritage (Kimani *et al.,* 2018).

The small-scale fisheries are conducted in the nearshore zone and yield about 80% of the marine production annually, with the demersal finfish contributing 50% of the marine catches. The main artisanal fishing areas include the fishing grounds of the Lamu Archipelago, the Malindi-Ungwana Bay, North Kenya Bank and Malindi Bank. Artisanal fishing activities are conducted by local fishers whose capacity is debilitated by the small non-motorized vessels that cannot reach the deep waters. The demersal fish comprise of the Scaridae, Nemipteridae, Siganidae, Lethrinidae, Haemulidae and Lutjanidae.

The dash-and-dot goatfish, *Parupeneus barberinus* is one of the most abundant species of the *Parupenues* genus (Myers, 1999), with the adults occurring in solitary or small groups inhabiting large sand patches and rubble areas of reef flats and lagoon reefs at a depth of about 100 m. Additionally, the juveniles occur in small groups, mixed with other species in seagrass habitats (Kuiter and Tonozuka, 2001). In Kenya marine waters, *P. barberinus* is abundant in the shallow seagrass meadows, contributing about 2.9% of the total catches in abundance (Musembi *et al.,* 2019), coral reefs and along the rocky shores which are easily accessed by artisanal fishers.

The species exhibit diurnal a feeding pattern in which they forage on invertebrates such as polychaete worms and crustaceans (Randall, 2004). *Parupeneus barberinus* exhibits gonochorism, although some immature individuals of sizes between 16.1 and 22.5 cm, FL are bisexual (Longernecker *et al.,* 2017), with mature individuals migrating shoreward to feed or spawn (Hoese *et al.,* 2006). The peak spawning period occurs between May and August for males while the spawning period for females is between May and June (Wahbeh and Ajiad, 1985). The species utilizes multiple habitats, shifting from mangroves/seagrasses to coral reefs (Honda *et al.,* 2013).

Globally, the species is distributed in Africa, Asia and Oceania continents, in 64 countries / islands as either an endemic, native or introduced species, where it occupies freshwater, salt water and sometimes brackish water (in the Indo-Pacific: Gulf of Aden and Oman, South on the East Coast of Africa to Mossel Bay, South Africa, East to the islands of Micronesia, Line Islands, Marquesas Islands, and Tuamotu Archipelago; and from Southern Japan to Australia and New Caledonia. The species has medium to high resilience and moderate vulnerability to fishing (Chueng *et al.,* 2005; Froese *et al.,* 2017). This study is meant to provide stock status information necessary for sustainable fishery of this species.

Stock status analysis can be done adopting the length-frequency approach to estimate mortality rates, which does not lead to misinterpretation of estimates, is easy to collect data and does not require complicated analytical tools (Pauly, 1983). Additionally, mortality estimates are indicators of fishing pressure in a locality for a specific fish stock. Length-frequency distribution is important for assessing the size structure of a particular fish population in nature and is used as the first gauge for gear selectivity (Bagenal, 1978). Size structure information is crucial for assessing the reproductive potential, growth, and stability of demersal reef fishes (Hixon *et al.,* 2014; Van Overzee and Rijnsdorp, 2015). The absence of smaller size classes is an indication of recruitment deficiency, while the lack of large size classes is an indication of high mortality of mature fish (Neumann and Allen, 2007). Length at first maturity (L_m) is also used to monitor whether representative juveniles in an exploited stock mature and spawn before they are caught (Beverton and Holt, 1959; Jennings *et al.,* 1998).

Population dynamics and the population's health status are proxies for providing information to guide the regulation of the fisheries. Many studies on small-scale fisheries focusing on various aspects have been conducted (Mwatha *et al.,* 1997; Fulanda *et al.,* 2009; Tuda *et al.,* 2018; Musembi *et al.,* 2019). However, there is no study on the stock status for *P. barberinus*. This study, therefore, seeks to provide baseline information on the stock status of *P. barberinus,* important for the management and regulation of its fishery. Specifically, to describe the size composition, estimating selectivity and assessing the stock status of *P. barberinus*.

Materials and methods

Study area

The study was conducted within the Kenya coastline which extends from 1°30′ S at the Somalia border to 5°25′ S at the Tanzania border (Fig. 1). The marine coastal area has an extensive cover of mangroves and an intertidal zone covered with seagrass meadows and coral reefs (McClanahan and Mangi, 2000). The marine environment is characterized by warm tropical conditions, with sea surface temperatures (SSTs) ranging between 24°C in August and 30°C in February (McClanahan, 1988; Obura, 2001). The Kenya coastal waters are influenced by the Inter-Tropical Convergence Zone (ITCZ) movement that acts on the waters to create the northeast monsoon (NEM) and southeast monsoon (SEM) seasons which prevail from November to March and April to October, respectively (McClanahan, 1988). The monsoon seasons influence fishing activities in the Kenya coast (Ochiewo, 2004).

Data collection and analysis

Fishery data

Data was collected between 2017 and 2023 from 18 fish landing sites distributed along the entire coastline through the catch assessment program conducted in the five coastal counties. Extractive method associated with fishing gears was used for data collection as it allows for direct measurement of the catch to give accurate size structure data for the artisanal catches (Weerarathne *et al.,* 2021). However, the method cannot be used for protected fisheries (Mallet and Pelletier, 2014). Data enumerators identified landed catches to species level and recorded the number, size (total length in cm), gear used, landing site, and date. Although all sampling was conducted during daylight hours, these include catches attributed to night-time fishing activities as data enumerators also intercepted fishers returning from their overnight fishing.

Data analysis

Size structure

The size composition of P. barberinus was assessed using bar plots and determining the mean sizes of the length frequencies of the fish sampled during the 2017-2023 fishing period in Minitab ® software (Minitab, 2021). To assess the size structure of the individuals caught during the fishing period, the lengths were compared with length at first maturity (L_m) and asymptotic length (L_∞) values obtained from Fishbase (Froese *et al.,* 2017).

The optimal size of capture, a level where highest yield from a cohort for each species is obtained was determined as the proportion of the catch between $0.9L_{opt}$ and $1.1L_{opt}$, then the proportion of all the catch with lengths greater than $1.1L_{opt}$ were

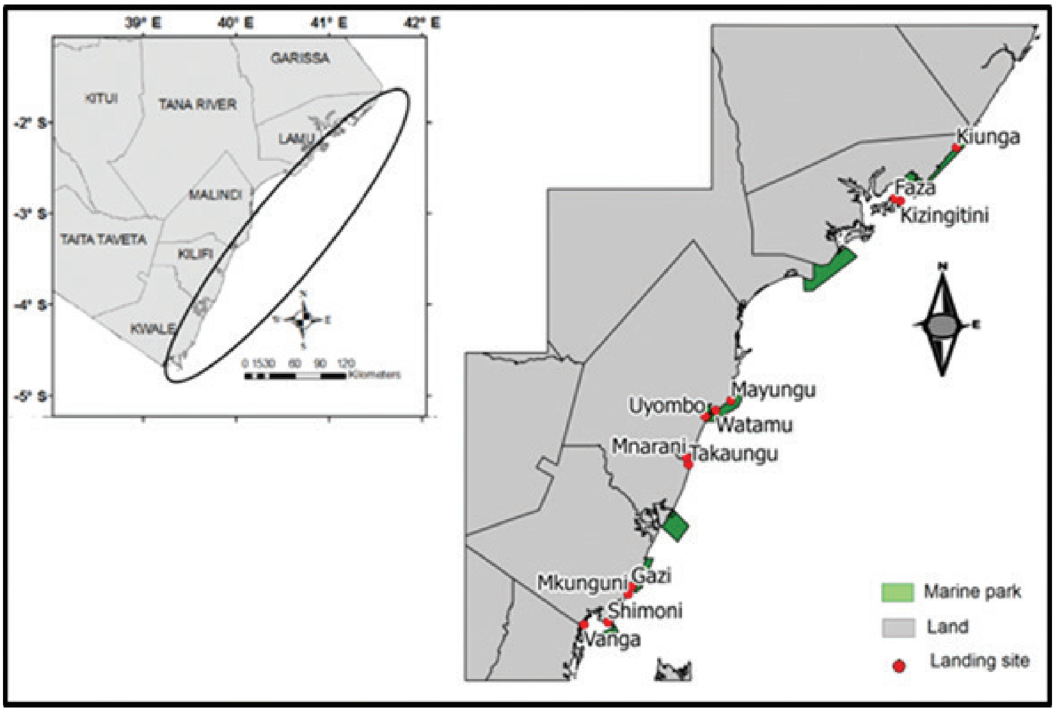

Figure 1. Map of Kenya showing some of the artisanal fisheries landing sites at the Kenya coast (Source: Authors).

considered as "mega-spawners" (P_{mega}) which indicate future recruitment and sustainability of the fishery. The "mega-spawners" should be allowed to live to have a sustainable fishery (Froese, 2004).

Historical length-weight relationship (LWR) parameters, a = 3.5 * 10^{-5} and b = 2.7 (Ontomwa *et al.,* 2018) for *P. barberinus* were input in the ELEFAN, LBI and LBSPR tools in Tropfish R to determine the stock status, mortality rates, spawning potential rate and conservation indicators.

Stock status

Growth parameters mortality and exploitation rates

The *Parupeneus barberinus* fishery was assessed using the length-based stock assessment TropFishR (Tropical fisheries analysis) package (version 1.6.3). The length-based stock assessment with TropfishR is based on the routine outlined by FAO (1998), which was compiled into R by Mildenberger *et al.* (2017). The assumptions of TropFishR are that: the data used is a representative of the whole catch; and the routine assumes a sigmoid selectivity commonly applicable for trawl-like fishing gears including gillnets and hook-based methods with various mesh and hook sizes, respectively. Further, the routine assume that there is constant recruitment, fishing and natural mortality, somatic growth and maturation over time, the density is independent on maturity and somatic growth, growth parameters (L_∞ and K) are predictors of natural mortality, somatic growth follows the logistic von Bertlanffy growth (VBG) function and that the stock under study is closed with no immigration or migration taking place. All these assumptions may limit the results of this study.

Prior to the assessment, the length data was organized into length-frequency clusters in Microsoft Excel® software and converted to comma-separated values (CSV) text file format, before uploading in TropFfishR. Length-frequency data was generated at an optimal bin size (OBS) determined from the maximum body size as: OBS = $0.23*L_{max}^{0.6}$ according to Wang *et al.* (2020). Then growth parameters (K, L_∞, and t_a), natural (M), total (Z) and fishing (F) mortality rates, and stock status were assessed using the ELectronic LEngth Frequency ANalysis with genetic algorithm (ELEFAN_GA) in TropFishR package (Mildenberger *et al.,* 2017). The TropFish package allows for the analysis of length-frequency data for data-poor fisheries and the ELEFAN_GA method allows for optimization hence reducing search (Mildenberger *et al.,* 2017).

The most important growth parameters considered in this study were the asymptotic length (L_∞), condition factor, K and t_a. Asymptotic length also referred to as L infinity (L_{inf}) is the length a fish would reach if they are allowed to grow indefinitely. K is the growth coefficient which expresses the rate at which asymptotic length is approached.

Length-frequency data was pooled by quarter then ELEFAN method was applied to estimate L_∞, K and t_a by restructuring and fitting growth curves through restructured data (Pauly, 1980). This method assumes that the length-frequency data are representative of the population, growth parameters are repeated each year, all samples have the same growth parameters and length frequency data obtained usually contain modes pertaining to one of two major cohorts per year.

Then the growth performance coefficient, *phi'*, which provides a metric for the correlation of L_∞ and K and essential for the comparison of growth parameters among species or analyses was estimated using the formula: $phi' = \log_{10}K + 2\log_{10}L_\infty$

Total mortality (Z) was deduced from the length "converted catch curves" derived by Ricker (1975). The assumptions made are that Z is same in all age groups used in the plot, all age groups used in the plot were recruited with the same, small and random abundance fluctuations, all age groups used in the plot are equally vulnerable to the fishing gear (s) used for fishing and the sample used is large and lengths cover enough age groups to effectively represent the average population structure for the fishing period.

Using L_∞, total mortality, was also estimated as: $Z = K*(L_{inf} * L_{mean}) / (L_{mean} * L_c)$, where L_{mean} is the mean length of all fishes caught at sizes equal or larger than L_c which is the smallest size in the catch in the life history Fishbase tool. Both L_{mean} and L_c were estimated from length-frequency data using the LBI tool in TropFishR. Exploitation ratio (E), a fraction of the number caught versus the total number of individuals dying as a result of fishing and other causes (Pauly, 1984), set at E = 0.5 as the default (Gullad, 1971). Exploitation rate was calculated from mortality rates as: $E = F / (F+M)$; where M is the natural mortality rate and F the rate of fishing mortality.

Then the F and E estimates were compared with those at maximum sustainable yield (F_{msy}, E_{msy}) estimated from L_c in Fishbase. However, E_{msy} tends to be unrealistically high especially for small fishes with high natural mortality, necessitating the use of another value which is slightly lower than E_{msy}, which is the exploitation giving the highest yield (E_{opt}). The exploitation giving the highest yield, E_{opt} corresponds to a point on the yield-per-recruit curve where the slope is $1/10^{th}$ of the value at the origin of the curve.

Natural mortality (M), the instantaneous rate at which juveniles and adults die due to other causes other than fishing, was computed by the equation: $M = -0.0152 - 0.279 \ln L\infty + 0.6543 \ln K + 0.463 \ln T$ (Pauly, 1980), where, L_∞ and K are growth parameters and T is the annual mean water temperature in which the stocks live. Fishing mortality (F) was calculated by subtracting natural mortality from total mortality, $F = Z – M$ (Beverton and Holt, 1956).

Conservation indicators

Conservation indicator points for *P. barberinus* fishery were estimated using the length-based indicator (LBI) tool in TropfishR and compared with the reference indicator reference points to assess the status of the fishery. Length based indicators provide information reflecting the conservation of large, mature fish with high fecundity (mega-spawners), and immature individuals and provide a size at which highest yield (MSY) is expected. These metrics are indicators of how the stock is performing in terms of yield optimization and conservation goals. The LBIs estimated were length at first capture (L_c), the average length of the first 25% of the catches ($L_{25\%}$), mean length of largest 5% of the catches ($L_{max5\%}$), optimal length (L_{opt}), mean length of largest 5% of the catches ($L_{max5\%}$), optimal length (L_{opt}), mean length of individuals with lengths greater than Lc (L_{mean}), length class with maximum biomass in the catch (L_{maxy}), length at which fishing mortality (F) equals natural mortality ($L_{F=M}$) and 95th percentile of the lengths ($L_{95\%}$). Then the indicators relative to their reference points were used to derive the stock status of the fishery.

To assess whether the conservation of large individuals was achieved, the following expressions were employed: $L_{max5\%} / L_{inf}$, $L_{95\%} / L_{inf}$, and L_{opt} + 10% (P_{mega}). On the other hand, the conservation of immature *P. barberinus* individuals was assessed using the following formulae: $L_{25\%} / L_{mat}$ and L_c / L_{mat}. To establish whether optimal yield was achieved during the fishery calculated using the following expressions were used; L_{mean} / L_{opt} and L_{maxy} / L_{opt}. Lastly, the sustainability (MSY) of *P. barberinus* fishery during the fishing period was assessed from the following expression: $L_{mean} / L_{F=M}$.

The LBI methods assume that the dataset is representative of the length distributions of the whole catch, that recruitment and natural mortality, somatic growth and maturation over time were constant within and over all the years of fishing when data was collected, density is independent maturity and somatic growth, that the natural mortality is equal for all length classes, the growth of individuals in length follows the logistic von Bertlanffy growth (VBG) function and that the stock (population) under study is closed (Cope and Punt 2009; ICES, 2018).

Relative yield per recruit (Y'/R) and spawning potential ratio (SPR)

Relative yield-per-recruit was estimated from the mean length at first capture (L_c), L_{inf}, M, K and E (Beverton and Holt, 1964). Spawning potential ratio (SPR), a proportion of the total reproductive production at equilibrium for a given level of fishing mortality divided by the productive production in the unfished state (Goodyear, 1993; Mace and Sissenwine, 1993), was assessed using the length-based spawning potential ratio (LB-SPR) tool in TropFishR package. The tool requires M/K and L_m/L_∞ ratios for the estimation of SPR. The length-frequency data was input in the tool and the target SPR was set at 40% a level considered as a conservative proxy for attaining maximum sustainable yield (Hordyk *et al.,* 2015). Additionally, the lower limit is set at 20%, a point when recruitment rates are compromised (Mace and Sissenwine, 1993; Prince *et al.,* 2015).

Results

Size structure

A total of 1,276 fish were sampled during the 2017- 2023 fishing period and were caught by ten different fishing gears. The gears include basket traps, beach seine, cast net, gill net, hand line, harpoons, ring net, rapala, reef seine and spear gun. Most of the *P. barberinus* individuals representing 68.9% and 14.5% of the total fish sampled were caught by basket traps and gillnet, respectively (Fig. 2). Length at first maturity (L_m) and asymptotic length (L_∞) for *P. barberinus* are 19.2 cm and 32.8 cm, TL (Froese *et al.,* 2017) respectively. Comparatively, the size of most of the *P. barberinus* individuals caught by majority of the gears were greater than L_m. However, majority of the *P. barberinus* individuals had sizes less than L_{inf} (Fig. 2).

Based on the pooled data across the years, 72.6% of the *P. barberinus* individuals were caught between September and January, with the later having the highest proportion accounting for 27.7% of the total fish sampled. Most of the *P. barberinus* caught during all the months had sizes greater than L_m with most of the fish having sizes less than L_{inf} except in December (Fig. 3).

Generally, the mean sizes of the individuals caught was 28.2 ± 7.7 cm, TL, with about 75.4% of the fish caught having sizes greater than L_{50} (23.0 cm, TL). A higher proportion accounting 48.1% of the fish were immature with sizes less than L_{mat}, while few individuals caught had optimal sizes. About 20.9% of the fish caught were mega-spawners and 29.8% of the individuals had the optimal size of capture (Fig. 4).

The annual mean sizes of *P. barberinus* ranged between 25.6 ± 4.1 cm, TL in 2020 and 30.5 ± 1.1 cm, TL in 2022 (Fig. 5). There was no significant variation in the mean size of fish caught during the 2017-2023 fishing period. The small variation in mean sizes is a reflection of the fish size composition in the fishing grounds.

The mean size (mean ± SD, cm) of *P. barberinus* individuals caught by the ten gear types used by the small-scale fishers during the fishing period is shown in Fig. 6. The mean sizes of *P. barberinus* caught using beach seine (a banned gear), cast net, and ring net during the 2017-2023 fishing period were lower than length at first maturity (L_m).

Stock status

Growth parameters

In ELEFAN, the length-frequency data was restructured by scoring the length bins based on their deviation from a moving average (MA)

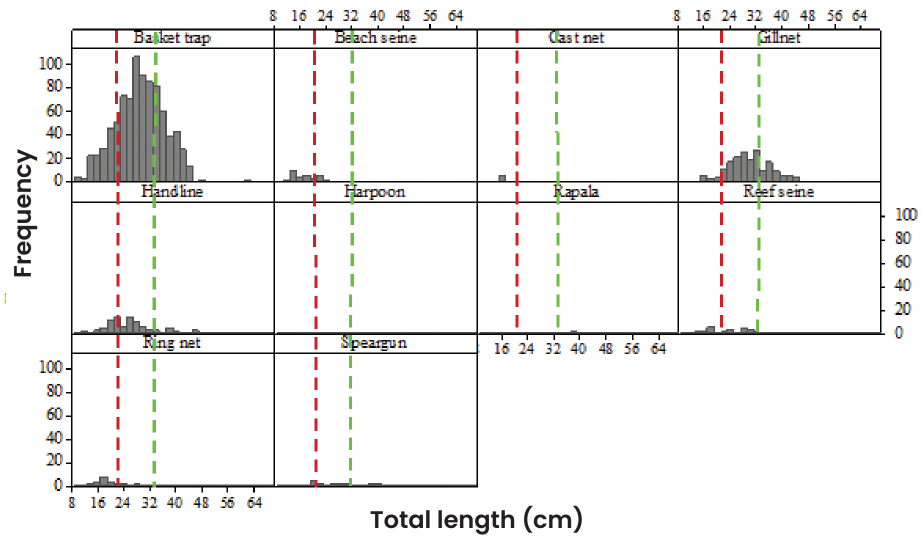

Figure 2. Size composition of the fish caught by basket traps, beach sein, cast nets, gillnet, handline, harpoon, rapala, reef seine, ring net and spear gun during 2017-2023 fishing period (red dashed line= length at first maturity, green-dashed line = asymptotic length).

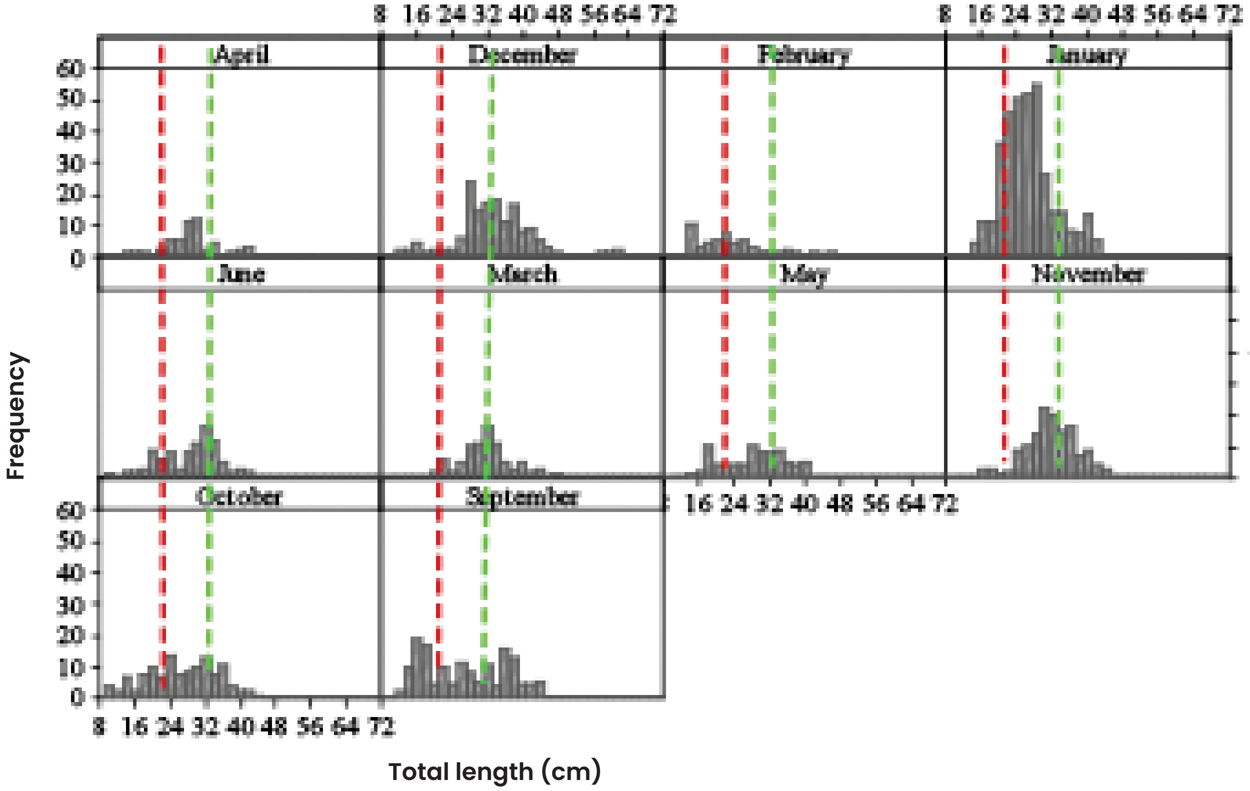

Figure 3. Size composition of the fish caught in different months during 2017-2023 fishing period (red dashed line= length at first maturity, green dashed line = asymptotic length).

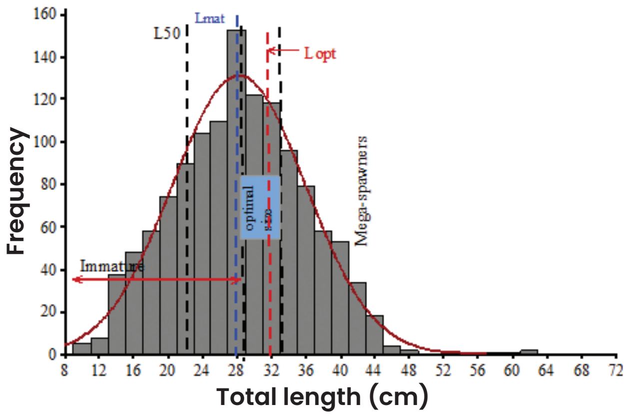

Figure 4. Size structure with the length at first maturity (L_{mat}), optimal length (L_{opt}), L_{50} and optimal size of *P. barberinus* caught during the 2017-2023 fishing period.

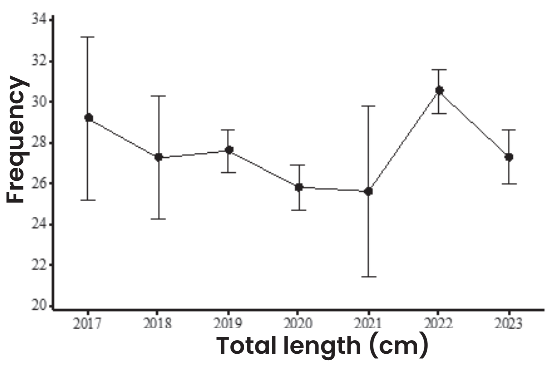

Figure 5. Annual mean size ± standard deviation (SD, cm) of the fish caught during the 2017-2023 fishing period.

across neighboring bins. The improved ELEFAN fit in terms of the average and best score value (fitness value) of the genetic algorithm used in ELEFAN_GA over the number of iterations (generations) is as shown in Annex 1. The estimated von Bertlanffy growth parameters (L_∞, *K, ta*), the growth performance coefficient

phi' = log10 *K* + 2 log10 L_∞, and the best score value (*Rn*) are shown in Table 1. The asymptotic length the fish can reach in an unfished situation is 55.5 cm.

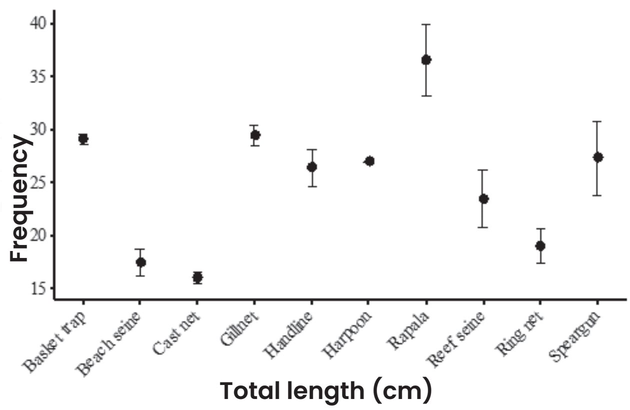

Figure 6. Mean size ± standard deviation (SD, cm) of the fish caught during the 2017-2023 fishing period by gear type.

Table 1. Growth parameters estimates obtained from ELEFAN.

L_{inf}	K	t_a	R_n	*phi '*
55.5	0.606	0.871	3.27	0.234

Mortality and exploitation rates

Estimated fishing mortality (F) was 1.57 year^{-1} representing 67.4% (E =0.674 year^{-1}) of the total mortality estimate (Z = 2.33 year^{-1}), while natural mortality estimate was 0.759 yr^{-1}. The fishing mortality is concentrated at sizes between 18.0 and 35.0 cm, TL (Fig. 7). Catch per length interval against the relative age is shown in Annex 1.

The estimated current fishing mortality (F = 1.57 year^{-1}) is slightly lower than the fishing mortality leading to maximum yield per recruit (F_{max} = 1.62 year^{-1}). However, the estimated F was higher than the fishing mortality at which yield per recruit equals 10% of the slope ($F_{0.1}$ =0.71 year^{-1}), representing a more conservative reference point than F_{max}. Additionally, the estimated fishing mortality was higher than fishing mortality where biomass equals to 50% of the unexploited biomass ($F_{0.5}$) estimate of 0.54 year^{-1} (Fig. 8 and Table 2).

Table 2. Mortality, exploitation and selectivity estimates for *Parupenues barberinus* fishery.

Z	M	F	E	L_{s50}	L_{s75}	F_{max}	$F_{0.1}$	$F_{0.5}$
2.33	0.759	1.57	0.674	27	30	1.62	0.71	0.54

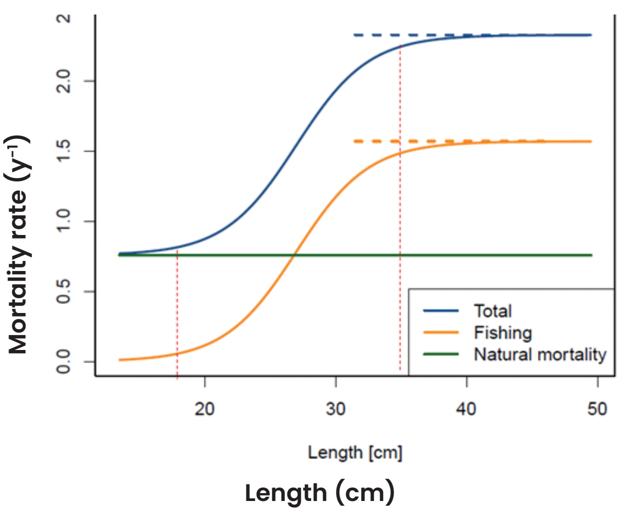

Figure 7. Estimated (total, fishing, and natural) mortality rates by length class (solid lines) and average levels for main exploited length classes (dashed lines).

The exploitation rates estimated from the life history tool are as shown in Table 3. The mortality estimates derived from the life history tool were too low compared to those obtained from the ELEFAN TropFishR tool. On the other hand, the exploitation rate (E = 0.674 year^{-1}) was slightly higher than the average exploitation where the maximum sustainable yield can be achieved (E_{MSY} = 0.71 year^{-1}) but lower than the exploitation where optimal yield can be achieved (E_{opt} = 0.628 year^{-1}).

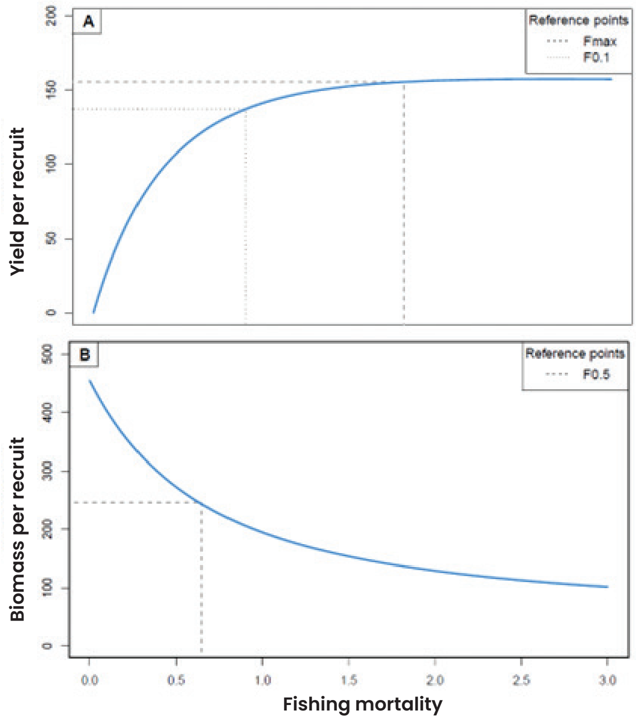

Figure 8. Yield per recruit (panel A) and biomass per recruit (panel B) against fishing mortality rates.

Conservation indicators for the fishery

The estimated LBIs are as represented in Table 4. The estimates varied across the years but L_{opt} was constant at 39.2 cm. The respective length-based estimated indicator ratios indicating the stock status generated as traffic light model is as shown in Table 5 with the green and red colors indicating how the stock performs for different properties. The indicator ratios reflect whether the conservation of large individuals and highly reproductive individuals mega-spawners (P_{mega}) and immature individuals, was achieved. The estimated LBIs for the conservation of large individuals and mega-spawners were below the expected reference values in the all years except in 2018 and 2022 when the $L_{max5\%}$ / L_{inf} was above the target level. The conservation of immature individuals was only achieved in 2022 when the esti-

Table 3. Exploitation and yield per recruit (Y'/R) estimates.

	Exploitation			Y'/R (/year)			
Year	Z	F	E	E_{MSY}	E_{opt}	F_{MSY}	F_{opt}
2018	0.21	-0.02	-0.1	0.65	0.56	0.43	0.3
2019	0.34	0.11	0.32	0.87	0.75	1.54	0.68
2020	0.35	0.12	0.34	0.75	0.66	0.69	0.44
2022	0.24	0.01	0.04	-	0.67	-	1.25
2023	0.17	-0.06	-0.35	0.57	0.5	0.3	0.23
Average	0.262	0.032	0.05	0.71	0.628	0.74	0.58

mated indicator values were above the expected target. The indicator values show that the sizes of fish caught cannot give the optimal yield for the fishery hence the stock is not sustainable (Table 5). Most of the indicator ratios were further from the target values, indicating there is more over-exploitation of the fishery (Fig. 9).

Selectivity and Spawning potential ratio (SPR)

Selectivity of the fishery during the fishing period is shown in Fig. 10. Fish caught in all the years measured less than length at first maturity with about 75% of the fish vulnerable to the fishing gears (caught) having lengths ranging from 20-30 cm. 50% of the catches had sizes less than 25 cm (Fig. 10).

Table 4. Estimated length based indicators (cm) for the years whose data was analyzed.

Year	L_c	$L_{25\%}$	L_{maxy}	$L_{F=M}$	L_{mean}	L_{opt}	$L_{95\%}$	$L_{max5\%}$
2018	19.5	22.5	34.5	29.8	29.5	39.2	43.5	45.1
2019	25.5	25.5	31.5	34.1	31.2	39.2	40.5	41.7
2020	22.5	22.5	28.5	31.9	28.7	39.2	37.5	41.1
2022	28.5	28.5	34.5	36.2	35.3	39.2	43.5	45.3
2023	16.5	22.5	34.5	27.6	29.0	39.2	40.5	43.4

Table 5. Annual length-based indicators (LBIs) relative to specific reference values (in parenthesis) for the conservation of large and immature individuals and obtaining optimal yield and maximum sustainable yield (MSY), (green and red cells indicate value is above or below reference value, respectively).

Conservation of large individuals				Conservation of immature individuals		Optimal yield		MSY
Year	$L_{max5\%}/L_\infty$ (>0.8)	$L_{95\%}/L_\infty$ (>0.8)	P_{mega} (>0.3)	$L_{25\%}/L_{mat}$ (>1)	L_c/L_{mat} (>1)	L_{mean}/L_{opt} (≈1)	L_{maxy}/L_{opt} (≈1)	$L_{mean}/L_{F=M}$ (≤1)
2018	0.81	0.78	0.07	0.83	0.72	0.75	0.88	0.99
2019	0.75	0.73	0.02	0.94	0.94	0.8	0.8	0.91
2020	0.74	0.68	0.02	0.83	0.83	0.73	0.73	0.9
2022	0.82	0.78	0.1	1.06	1.06	0.9	0.88	0.98
2023	0.78	0.73	0.05	0.83	0.61	0.74	0.88	1.05

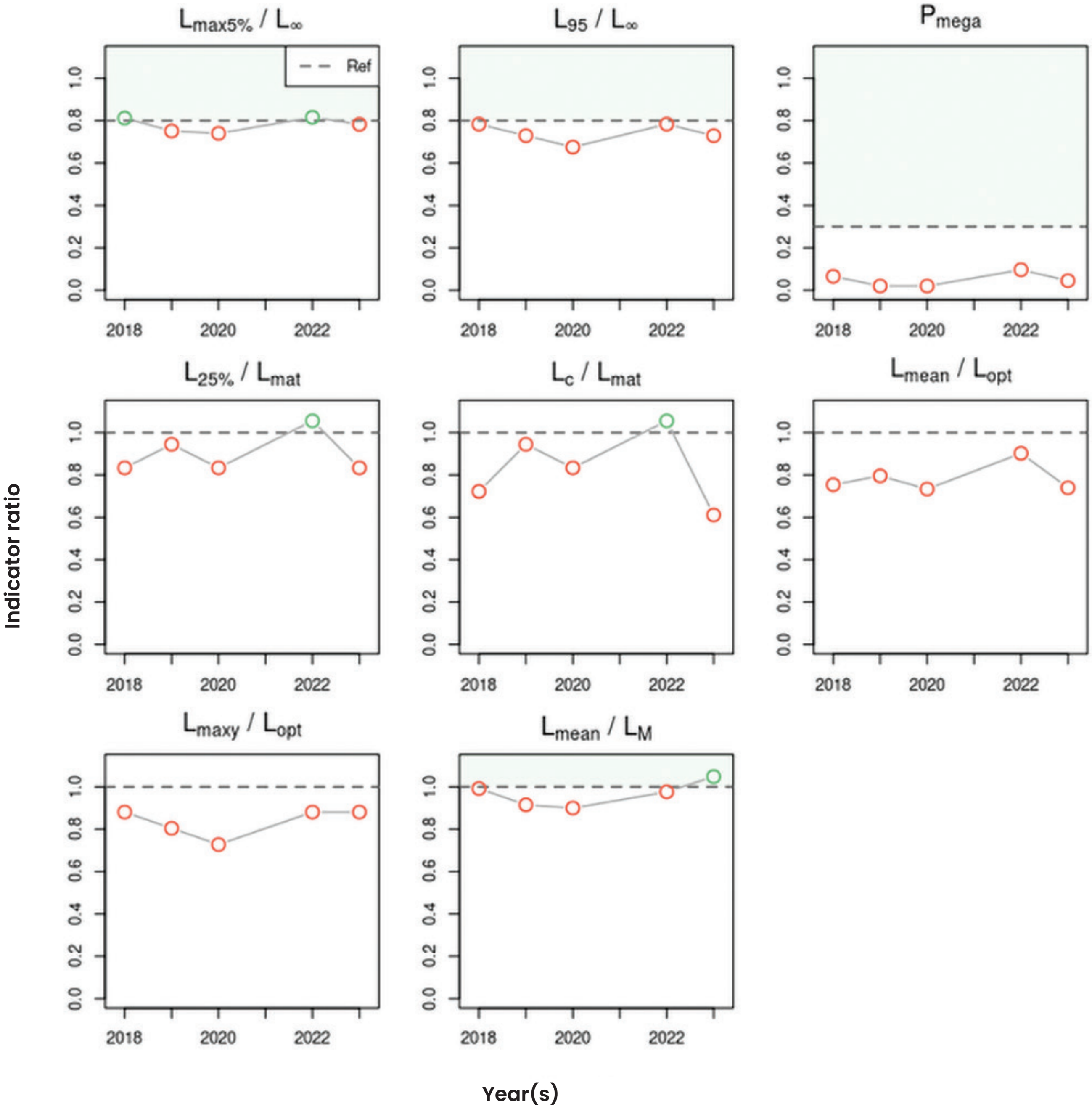

Figure 9. Graphical presentation of the indicator ratios over time, the reference point is represented by a horizontal dashed line. The further the points/lines are from the expected values the more evidence of overfishing, any value above the limit reference point is considered desirable.

The estimated LB-SPR, selectivity parameters (L_{s50} and L_{s95}) and the ratio of fishing relative to natural mortality is shown in Fig. 11. Selectivity at L_{s50} ranged between 19.3 cm in 2018 and 36.64 cm in 2022 while that at L_{s95} ranged between 25.9 cm and 53.7 cm for the same period. The SPR ranged between 10% in 2020 and 24% in 2023, however the target $SPR_{40\%}$ was not reached in all the years of the fishery.

Discussion

This study provides information on the stock status of *P. barberinus* caught by small-scale fishers during the 2017-2023 fishing period. Information provided on size composition, conservation indicators, mortality rates, selectivity and SPR are important for the regulation and management of the *P. barberinus* fishery. Most of the *P. barberinus* caught were immature and very few had optimal sizes indicating growth overfishing is prominent for the fishery.

The size structure results indicate there are very few mega-spawners and this indicate that older fish have been completely fished due to over-fishing, leading to the occurrence of small sized fish, hence the fishery will not be sustainable in the near future (Mangi and Roberts, 2006). The observed high level of immature *P. barberinus* individuals could be associated with the functional role of the seagrass habitats as a breeding ground, where the artisanal fishers capture fish (Musembi *et al.,* 2019). Additionally, from the LBI assessment estimates, the conservation of mega-spawners was not achieved during the fishing period, indicating the future of *P. barberinus* fishery is at threat of extinction. The immature fish were not conserved as the estimated indicators for the conservation of immature fish were below the expected threshold (>1). This is evident that growth over-fishing is taking place for the fishery. The conservation of immature *P. barberinus* individuals was not achieved during the fishing period. This is an indication that the main gears, i.e. basket traps and gillnets could be capturing immature fish. The length based asymptotic length obtained for this fishery, L_{inf} = 55.5 is lower than the value recorded in Fishbase, Froese *et al.* (2017), justifying the analytical tools and methodology used in this study.

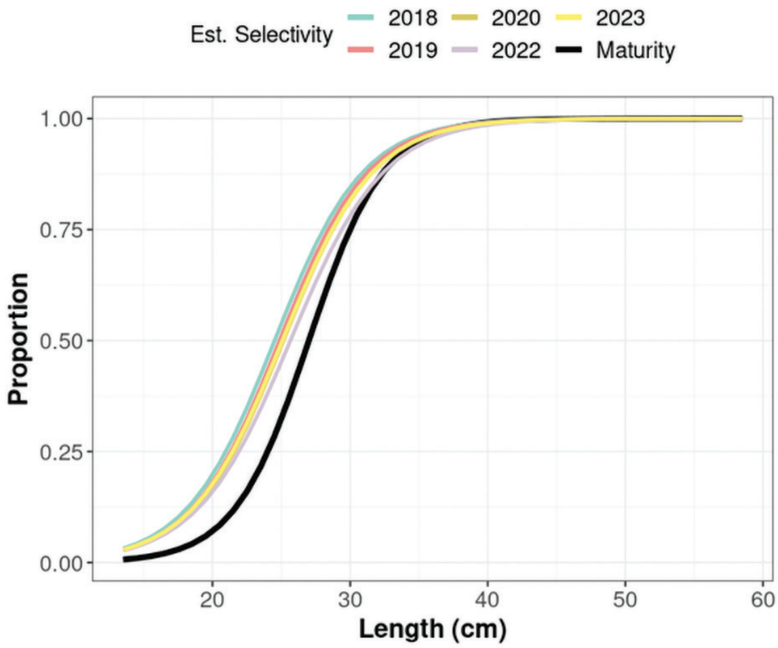

Figure 10. Estimated selectivity (coloured lines) and provided maturity (black line), curves indicate the proportion of the stock vulnerable to the gear (y-axis) at a given length (x-axis).

In any fishery which is optimally fished, the fishing mortality equals or closely approaches natural mortality, (E = 0.5 $year^{-1}$). The estimated current exploitation rate (E =0.674 $year^{-1}$) is much higher than the threshold value (E = 0.5 $year^{-1}$), an indication overex-

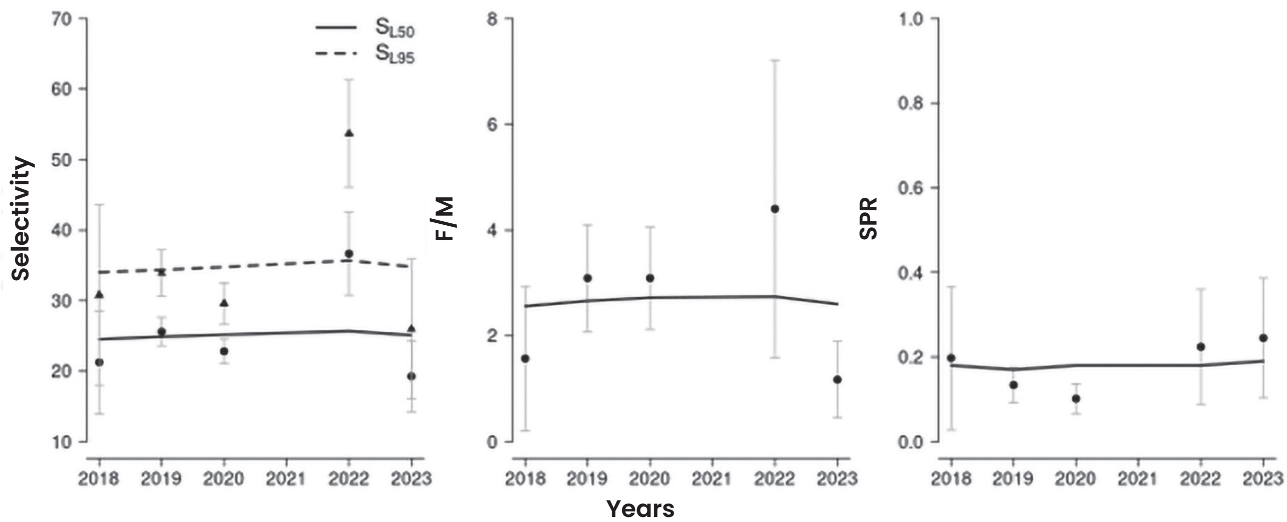

Figure 11. Annual selectivity parameters, fishing mortality relative to natural mortality and spawning potential ratio (SPR).

ploitation. However, the fact that the fishery was exploited using different gears with varying selectivity and sampling was not uniform across gears may influence the exploitation estimates (Tuda 2019).

The estimated fishing mortality relative to the fishing mortality estimate where biomass equals to 50% of the unexploited biomass ($F/F_{0.5}$ = 2.51 $year^{-1}$) and that of F/F_{max} was 0.969 indicating high fishing pressure on the *P. barberinus* fishery which may lead to a reduction in the population size and size at first maturity (Froese and Binohlan, 2000).

Selectivity results indicate the fishery capture immature individuals, an indication of unsustainability. The increased selectivity length in 2022 compared to other years could be due to improved monitoring and surveillance or as a result of high level of compliance to the gear restrictions in place during this period. The estimated F to M ratio was exceptionally higher SPR estimates indicating the exploitation rate does not have effect on the stock status os *P. barberinus*. The LB-SPR estimates of less than the reference limit (20%) and not reaching the target reference (40%) indicate the fishery is experiencing both growth and recruitment overfishing.

Conclusion and recommendations

This study describes the stock status of *P. barberinus* exploited by artisanal fishers in the Kenya marine waters, providing information on size structure, growth parameters, mortality and exploitation rates and assessment on the conservation of the fishery for its sustainability. The findings form a preliminary baseline of the fishery as there is no prior stock status study conducted for the specific fishery.

The results obtained were based on data not consistently collected, hence using data-poor methods to assess the status of the fishery. There is a need therefore, for data collection consistently over a long period to allow for the application of other assessment methods and comparison of the results. Beach seine and spear gun, which are banned gears, are still used in the *P. barberinus* fishery, where the mean sizes of individuals caught is lower than L_m. Additionally, the estimated LBIs for the conservation of immature individuals were not achieved for most of the years, indicating that immature fish are caught during the artisanal fishing. Therefore, we recommend management to enforce monitoring and surveillance to ensure illegal gears are not used for the protection of juveniles (Hicks and McClanahan, 2012). There is a need to disseminate findings from this study to the stakeholders for awareness creation to ease the implementation of regulations in place.

Acknowledgements

This work benefited from the Government funding through Kenya Marine and Fisheries Research Institute (KMFRI) in collaboration with Kenya Fisheries Service (KeFS), county fisheries and beach management units (BMUs). This work also benefited from the Kenya Marine Fisheries and Socio-Economic Development (KEMFSED), a World Bank project. Much thanks go to Dr. Tuda Paul, who tirelessly offered training on the use of length-based methods to assess the data poor fisheries. We are grateful to the Director of Kenya Marine and Fisheries Research Institute, Prof. James Njiru, for supporting the catch assessment surveys from which data was obtained. We thank KMFRI and KeFS, county fisheries officers and the BMU leaders for their coordination and collaborative efforrts during the data collection period. Much appreciation goes to the fishers for their cooperation and providing information during the data collection period.

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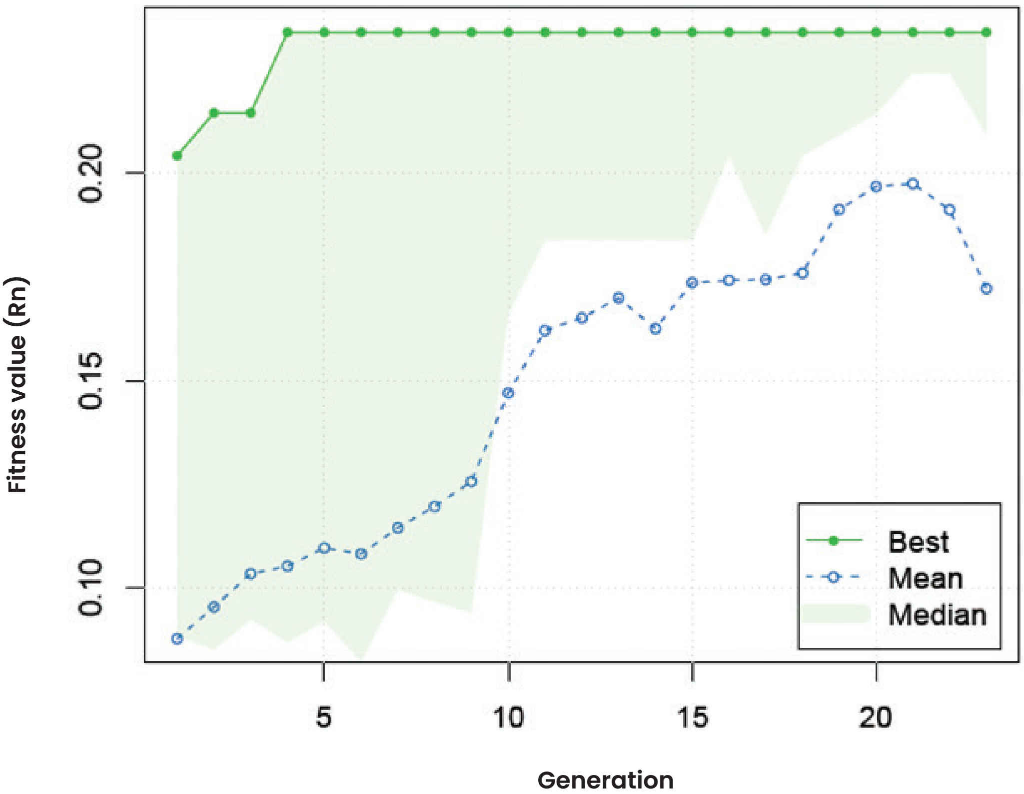
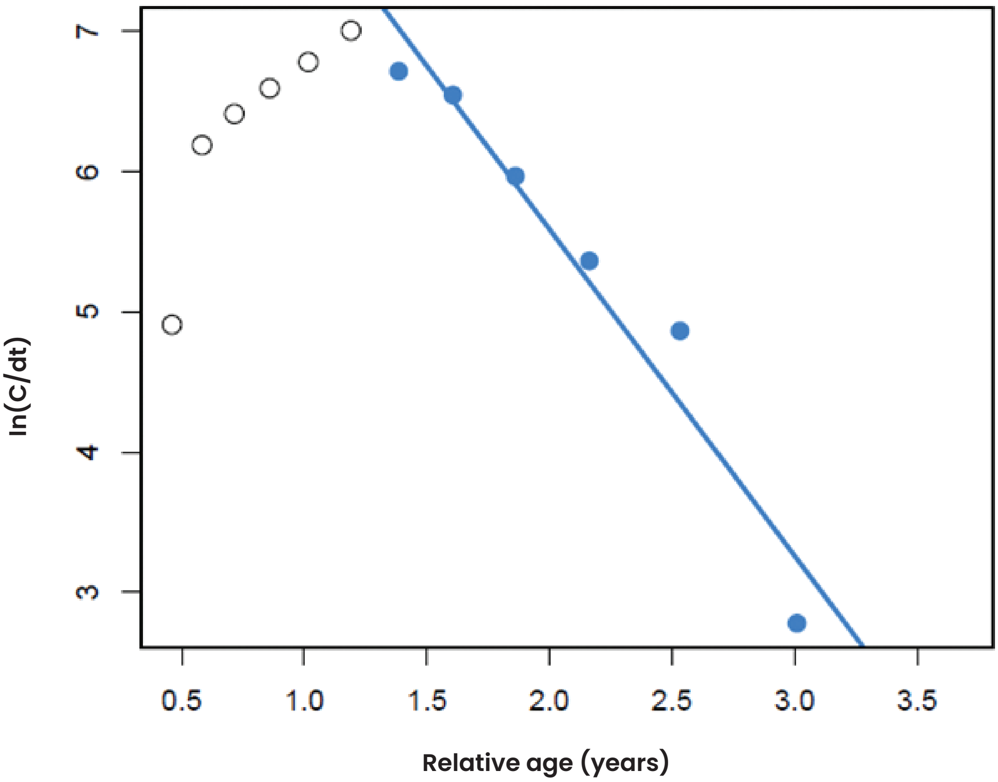


Annex 1. Score graph of ELEFAN with genetic algorithm. Fitness value (y axis) corresponds here to the score value of ELEFAN (Rn) and in the lingo of genetic algorithm 'Generation' (x axis) refers to the iteration.



Annex 2. Logarithm of catch per length interval against relative age. Blue points correspond to points used in the regression analysis (blue line) of the catch curve for the estimation of total mortality (Z), which corresponds to the slope of the displayed regression line.

Integration of remote sensing in watershed studies: A case study of Chawia & Fururu forested watersheds in Taita Hills, Kenya.

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Abstract

The ever-increasing demand for water due to population growth and the current environmental impacts due to climate change have resulted in the drying up of springs, and a reduction in their discharge volumes in Taita Hills. These impacts necessitated the evaluation and exploration of groundwater resources in Taita Hills. The main objective of the study was to evaluate the potential of integrating both Geographic Information Systems (GIS) and Remote Sensing (RS) in studying the status and spatial distribution of recent springs in the Chawia and Fururu forested watersheds. In this study, physical mapping of the springs was done by demarcating the location using Global Positioning System (GPS). The study identified and delineated the original watersheds in the Chawia and Fururu Forest fragments using GIS and RS using satellite data for watershed mapping.

Remote Sensing data from Landsat 7, 8 and Sentinel 2 were acquired, processed and analyzed. For watershed delineation, the data was examined using the Environmental Systems Research Institute (ESRI) ArcMap GIS hydrology tool, and image classification was done using the Maximum Likelihood algorithm, with classification accuracy verified using the confusion matrix approach. GIS image-processing Arc map program was used to ground truth data and process Digital Elevation Model (DEM) data. From the results, 91 springs were mapped and delineated in Chawia and Fururu forested watersheds. It was found that fifty three (53) springs were in Chawia, of which thirteen (13) were found to be inactive and thirty (30) were still active in Chawia compared to thirty eight (38) springs which were active in Fururu. The study provided information on the LU-LC classes in the study area, and how they influence the functions of the springs in providing water as well as informing environmental managers on watershed management. Six land use classes were identified, including built-up (66.3%), forestland (26.1%), agriculture (7.13%), water bodies (0.23%), grassland (0.04%), and bare land (0.01%). The study also showed that the Chawia forest cover has reduced from the year 1987 by (70%) of Vegetation Index to 2022 (60%) in and Fururu had increased by 10% from 70% in 1987 to 80% in 2022.

Keywords: springs, land use, cover change, watershed, remote sensing, Chawia, Fururu

Introduction

Water is regarded as life and the core of sustainable development.It is indeed very vital for socio-economic development, healthy ecosystems, and human survival. The demand for water around the world has been growing at more than twice the rate of population increase OVER the last century, and although there is no global water scarcity as such, there is an increasing number of regions that are grappling with chronic water shortage (Changwony *et al.*, 2017). This shortage is exacerbated by droughts, which damage surface water resources and generate long-term imbalances, hence reducing water supply and disrupting land cover and biodiversity. There are more than 1.3 billion cubic kilometers of water on earth (USGS, 2019), indicating that most of the planet is covered by water. However, much of water is available in forms unavailable to terrestrial and freshwater ecosystems (Jackson *et al.*, 2001). The rate and intensity at which the global freshwater crisis and the related environmental challenges have been underrated over decadesl, with more than 1 billion people on earth lacking reliable access to water. Addressing this challenge is very critical to the achievement of the United Nations Sustainable Development Goals (Bigas *et al.*, 2012).

According to the United Nations Inter-Action Council (2012), the water crisis' environmental effects are damaging natural water supplies as a result of population increase, which creates competition with nature. The report also shows that many springs and rivers do not make it to sea and there is widespread surface and groundwater contamination and human activities that make water unfit for use while springs are drying up (Bihgas *et al.*, 2012). With a population of 50 million, 32% of Kenyans rely on unimproved water sources, such as springs, ponds, shallow wells, and rivers, while 48% of Kenyans lack access to a steady supply of water (Kanoti *et al.*, 2019). Natural surface water sources in the country are not enough to supplement the vast population and the groundwater is a more important feature of the natural environment (Kagiri, 2005). Mountain springs are the forms in which groundwater provides water security for the rural population. They are the primary and reliable source of water in the hilly and mountainous areas of Taita Taveta County. The livelihood of the community depends on it for provision of clean water for agriculture, households use and beverages (Niraula *et al.*, 2020). Springs are indeed the terminal points of the water tower flow systems, and knowledge of their spatial distribution is essential for getting a better understanding of groundwater flow, vulnerable and water availability (Iván *et al.*, 2020). Chawia and Fururu are known to be among the many of the Taita Hills forest fragments, covering 86.0 ha and 5.0 ha, respectively (Hohenthal *et al.*, 2015).

Unequal and uneven allocation of water distribution and the spatial and temporal drying of springs, present a major problem for the sustainable development of these regions. Many people in Taita Hills live in rural areas, with their main socio-economic activity being farming, agricultural labor, and thus availability of water is essential to their livelihoods (Hohenthal *et al.*, 2015). Therefore, the current status of water suppy that is inadequate for irrigation and domestic usage poses a major problem to the local people in Taita Hills.

Remote sensing plays a vital role in conservation and watershed management and achievement of optimum planning and operation of water resources (Masud and Bastiaanssen, 2017). Satellite data provides readily available and alternative data required by hydrological models and avails spatial information for decision-makers (Ali *et al.*, 2023)). Remote sensing exhibits its presentation quality on worldwide dreary estimation ability including scene investigation, land use grouping, scene environmental change recognition, and landscape demonstration. Therefore, the geographical coverage of remote sensing data is advantageous over ground field data. Additionally, geometrical resolution has substantially advanced over the last decades. Thus it is possible today to investigate small-scale phenomena with satellite-based RS data. The present study aimed at providing much-needed hydrological information on the springs of Chawia and Fururu forested watersheds. It also aimed at providing information on the physical location and status of the springs within the watershed. The information derived from this study will inform the evaluation of watershed conditions through displaying the effects of human exercises to imagining those of elective situations in understanding the danger to water sources to the dynamic cycles; land use planning and backwoods restoration plots in Taita slopes.

Materials and methods

Study area

The Chawia and Fururu forest fragments are among the 12 forest fragments of Taita Hills located approximately 2,000 m above sea level (Fig. 1). The fragments are in Wundanyi around Ngerenyi in Taita Taveta County 86.0 ha (covering Chawia) and Fururu (5.0 ha) (Mkuzi, 2020). Ngerenyi is approximately 291 km (Chemuku, 2018) Southeast of Nairobi, and situated at 38°20'62E", 3°29'00"S while Fururu is located at 38°20'06.34"E, and 3°25'54.73"S in the verdant and humid Taita Hills (Wekesa *et al.*, 2020). The hills cover an area of 1,000 km² and are surrounded by semi-arid Acacia/Commiphora shrubland and dry savanna (Erdogan *et al.*, 2011). While the surrounding plains are at an elevation of 600 – 900 m above sea level , the Taita Hills rise abruptly in a series of ridges with the highest peak of Vuria at 2,208 m, although the average elevation of the hills is 1,500 m above sea level (Wekesa *et al.*, 2020).

Data collection

Physical mapping using remote sensing of satellite images

Remote sensing of satellite imagery data collection involved participatory mapping of springs through local knowledge gathered from the elderly people knowledgeable about historic springs and their localities. The springs were then geolocated using GPS device. This enabled the production of a precise map of recent and historic springs and wells, critical for analyzing spatial distribution, identification of former watersheds and determination of pathways consequential to drying up of springs and wells. The prescription of springs, is accessible with pictures and remarks on floristic elements and hints at former land usage in the direct neighborhood (i.e., special trees, like fig trees).

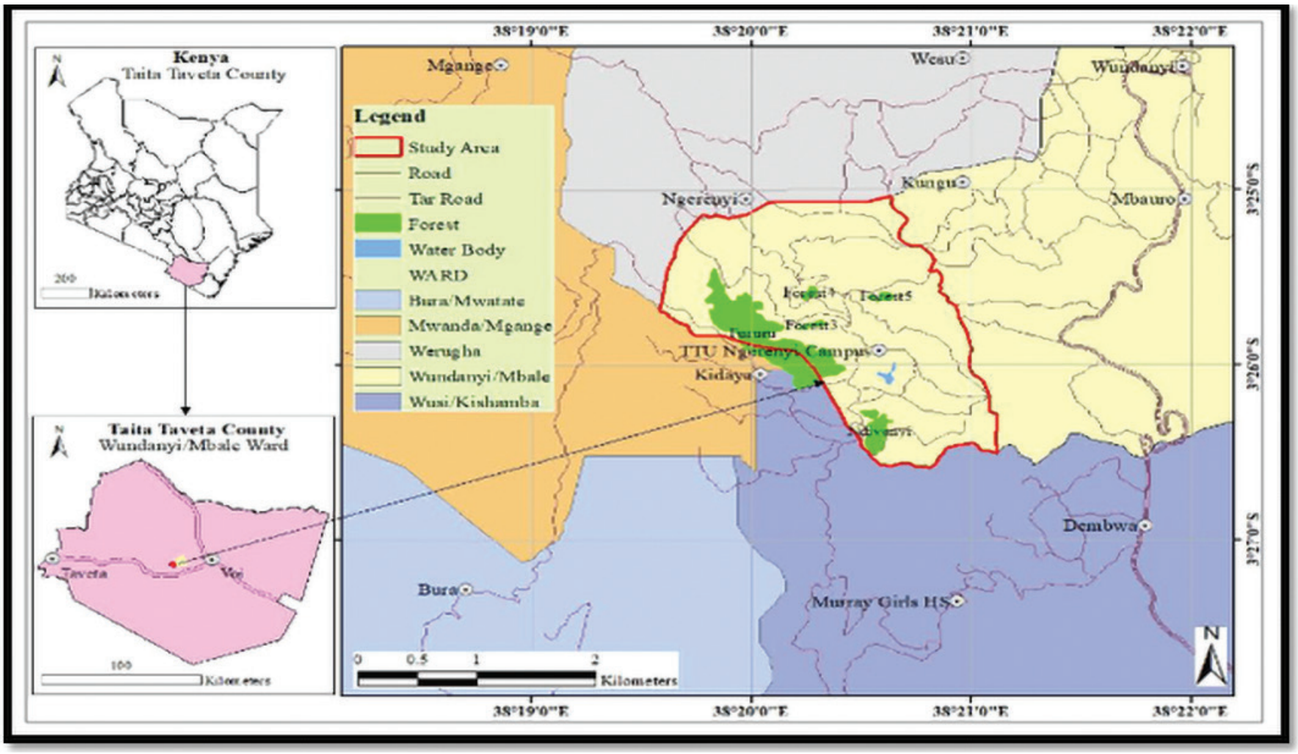


Figure 1. Site map showing Chawia and Fururu fragmented forests within the Taita Hills (Source: Author).

Watershed delineation and hydrological modelling

The study used Landsat images with a ten-year sequence between 1987 and 2019. Remotely sensed data from Landsat and sentinel-2 in digital elevation model (DEM) format was used to delineate the Chawia and Fururu watersheds. To analyze vegetation change, the use of satellite-based RS data was applied to provide a cost-effective means to develop LC coverages over large geographic regions as described by Mkuzi (2020). Satellite images such as Sentinel-2A, Landsat 8, 4-5 MSS and 1-5 MSS were acquired from the United States Geological Survey website. The Normalized Difference Vegetation Index (NDVI) quantifies vegetation by measuring the difference between Near-Infrared (NIR). Vegetation strongly reflects green and red light (which the vegetation absorbs/has a low reflectance). NDVI values range from -1 to +1. This index accounts for the converse reflectance properties of green vegetation in the near infrared (NIR) and red (R) parts of the solar spectrum and is defined as NDVI =(NIR-RED)/(NIR+RED). Negative values of NDVI corresponds to water. Values close to zero (-0.1 to 0.1) generally corresponds to barren areas of rock, sand, or snow. Tables 1 - 6 describe characteristics of Land sat images used in monitoring dynamics of land cover, images for various bands, and sentinel sensors. Low positive values represent shrubs and grasslands (approximately 0.2 to 0.4), while high values indicates dense natural/indigineous forest (0.5-1). NDVI calculation formula for Landsat 8 image, cloud cover of 10% = NIR-RED/NIR+RED; where RED is B4, 636-673 nm & NIR is B5, 851-879 nm. This applies for landsat 8 image from 2013 to 2022 using band (B5) and (B4) for computation of NDVI. B5 is NIR & B4 RED. Landsat 1-5 (NIRB04-REDB02)/(NIRB04+REDB02) NDVI calculation formula For Landsat 5 image,cloud cover 10% = NIR-RED/NIR+RED. This applies for landsat 7, 5 image from 1970 to 2013 using band (B4) and (B3) for computation of NDVI. B4 is NIR and B3 RED.

Sentinel-2 A

The combination of different optical wavelength of satellite data provides increased opportunities for more frequent cloud-free surface observations due to variable cloud cover as different satellites overpass time and dates (Li & Roy, 2017). In this study the Landsat-8 images, sentinel-2A and sentinel-2B together provided a summary of revisit intervals and the number of observations that are useful in terrestrial monitoring and assessment.The images came from sentinel-2, NDVI = (NIR-RED)/(NIR+RED) where RED is band B4 (664.5 nm) & NIR is band B8 (835.1 nm).

Table 1. Characteristics of Landsat and Sentinel images used in monitoring land cover change dynamics.

ID Scenes	Satellite sensor	Altitude	Spatial Resolution	Number of bands	Cloud cover level	Date
LM05_L1TP_166062_19870218	MSS	705km	60m	4	Low	1987/02/18
LT04_L1TP_166062_20091113	MSS	705km	60m	4	Low	2009/11/13
S2A_MSIL1C_20170126T073251	MSI	786km	30m	13	Low	2017/01/26
S2A_MSIL1C_20190327T073251	MSI	786km	30m	13	Low	2019/03/27
S2A_MSIL1C_20220209T072619	MSI	786km	30m	13	Low	2022/02/09

Table 2. Landsat 8 image has 11 bands.

Band Name	Bandwith (µm)	Resolution (m)
Band 1 coastal	0.43-0.45	30
Band 2 blue	0.45-0.51	30
Band 3 green	0.53-0.59	30
Band 4 red	0.64-0.67	30
Band 5 NIR	0.85-0.88	30
Band 6 SWIR 1	1.57-1.65	30
Band 7 SWIR 2	2.11-2.29	30
Band 8 pan	0.50-0.68	15
Band 9 Cirrus	1.36-1.38	30
Band 10 TIRS 1	10.6-11.19	100
Band 11 TIRS 2	11.5-12.51	100

Table 3. Landsat 7 image has 9 bands.

Band Name	Bandwith (µm)	Resolution (m)
Band 1blue	0.45-0.52	30
Band 2 green	0.52-0.60	30
Band 3 red	0.63-0.69	30
Band 4 NIR	0.77-0.90	30
Band 5 SWIR1	1.55-1.75	30
Band 7 SWIR2	2.09-2.35	30
Band 8 pan	0.52-0.90	15
Band 6 TIR	10.40-12.50	30

Table 4. Sentinel-2A – Sensor: MSI.

No.	Band name	Central wavelength (nm)	Bandwidth (nm)	Resolution (m)
1	Coastal aerosol	443.9	27	60
2	Blue	496.6	98	10
3	Green	560	45	10
4	Red	664.5	38	10
5	Vegetation Red Edge	703.9	19	20
6	Vegetation Red Edge	740.2	18	20
7	Vegetation Red Edge	782.5	28	20
8	NIR	835.1	145	10
8a	Narrow NIR	864.8	33	20
9	Water Vapour	945	26	60
10	SWIR – Cirrus	1373.5	75	60
11	SWIR	1613.7	143	20
12	SWIR	2202.4	242	20

Table 5. Sentinel-2B – Sensor: MSI.

No.	Band name	Central wavelength (nm)	Bandwidth (nm)	Resolution (m)
1	Coastal aerosol	442.3	45	60
2	Blue	492.1	98	10
3	Green	559	46	10
4	Red	665	39	10
5	Vegetation Red Edge	703.8	20	20
6	Vegetation Red Edge	739.1	18	20
7	Vegetation Red Edge	779.7	28	20
8	NIR	833	45	10
8a	Narrow NIR	864	32	20
9	Water Vapour	943.2	27	60
10	SWIR – Cirrus	1376.9	76	60
11	SWIR	1610.4	141	20
12	SWIR	2185.7	238	20

Land Use classification using Sentinel 2A Satellite Image

Sentinel 2 images are available since 2015 and with a resolution of 10 meters.

Table 6. List of main band combinations in Sentinel 2.

Combinations	R	G	B
Natural Colors	4	3	2
False color Infrared	8	4	3
False color Urban	12	11	4
Agriculture	11	8	2
Atmospheric penetration	12	11	8a
Healthy vegetation	8	11	2
Land/Water	8	11	4
Natural Colors with Atmospheric Removal	12	8	3
Shortwave Infrared	12	8	4
Vegetation Analysis	11	8	4

Data analysis

Satellite Image processing and analysis

In this study, the Arc GIS Desktop (Version 10.8) was used to perform the data analysis where supervised classification from Landsat/Sentinel_2 was done. The Image classification and processing, watershed delineation using DEM (SRTM) prepared Tiff format.

Confusion matrix/accuracy assessment

The ESRI accuracy evaluation technique was used to quantify how well pixels were sampled into the correct land cover classes. The ESRI ArcGIS software were used to perform this analysis, followed by the classification tab and the accuracy assessment tool. The ground truthing reference data was collected using a stratified random sampling method. Image data can be matched to actual ground-based features and materials through ground truthing, which also. facilitates the calibration of remote sensing data and supports the understanding and analysis of the detected information.

The ground truth points were superimposed on the LU-LC map, and the value was calculated (Sarkar, 2019). A confusion matrix was generated and placed such that class membership determined by image classification was along the y- axis. In this manner, correct values fell along the major diagonal of the matrix (Sarkar, 2018). Time series used herein is a statistical methodology appropriate for longitudinal research designs that involve single subjects that are measured repeatedly at regular intervals over time (Time-Series Study, 2010).

Time series analysis of the study area satellite images

This refers to the processes of removing distortions and anomalies within the images that might hinder image classification, hence affecting the analysis of the results. In the first stage, satellite images from Landsat 7 and 8 between 1987 to 2022 were used to analyze trends of deforestation in the area . This enabled the use of high-resolution Landsat satellite imagery to estimate annual deforestation and degradation simultaneously throughout the entire region for the years 1987–2022 by integrating knowledge-based decision tree classification, normalized difference fraction index, and spectral mixture analysis,

The date and month of data acquisition were all during the dry season allowing the acquisition of cloud-free images (Kaburi and Odera, 2014). Data was divided into bands covering various sceneries on the earth's surface. The image enhancement function was used to improve the image's visual quality to aid image interpretation by increasing visual distinctions between the image's features. Supervised Classification algorithms were used to adjust the contrast, brightness, picture sharpness, and color renderings of features in an image. Two methods of enhancements were applied in this study – brightness, and contrast by using histogram equalization to increase contrast over the whole image and edge enhancement to bring in contrast in linear features, such as river channels. While maintaining the original reflectance values, image enhancement techniques improve the image's visibility, contrast, and edge information (Kaburi and Odera, 2014).

RESULTS

Mapping the physical location of springs and current status

In this study, the physical mapping produced 91 springs visualized in Chawia and Fururu forest ecosystems (Fig. 2). Fifty three (53) springs were located in Chawia, with 13 of them being inactive while 30 were active. In comparison, the 38 springs situated in Fururu were all active.

Past watersheds were also delineated in Chawia and Fururu fragments and the LC-LU were determined as well. In this study the two forested watersheds that form part of the Taita hills forest patches and the study found that Fururu gained at least 10% between 1987 and 2022 as shown in Fig. 2 while Chawia lost at least 10% between 1987 and 2022 as shown in Fig. 3.

Land use land cover analysis from 1987 to 2022

Four different LC classes were determined both within and around the two forested watershed fragments for the period 1987-2022. In Chawia, moderate forest had the highest acreage in terms of cover, which showed a negative decrease from 191 ha (26.09%) to 125 ha (17.08%) between 1987 and 2022 respectively as shown in Table 6. Grasslands increased within the forest from 30 ha (9.93% to 98 ha (32.45%). There is evidence from the LC-LU maps that Chawia land cover decreased from 1987 to 2022 while Fururu land cover maps showed

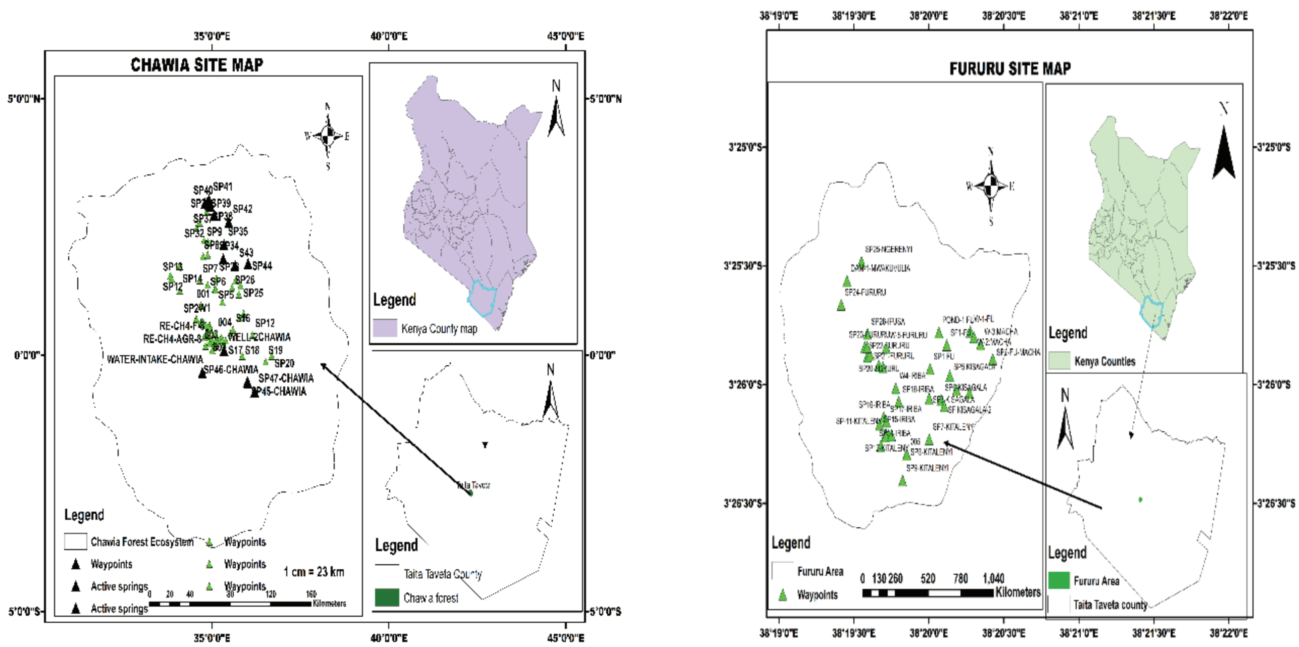


Figure 2. Physical location of the mapped springs in Chawia forest.

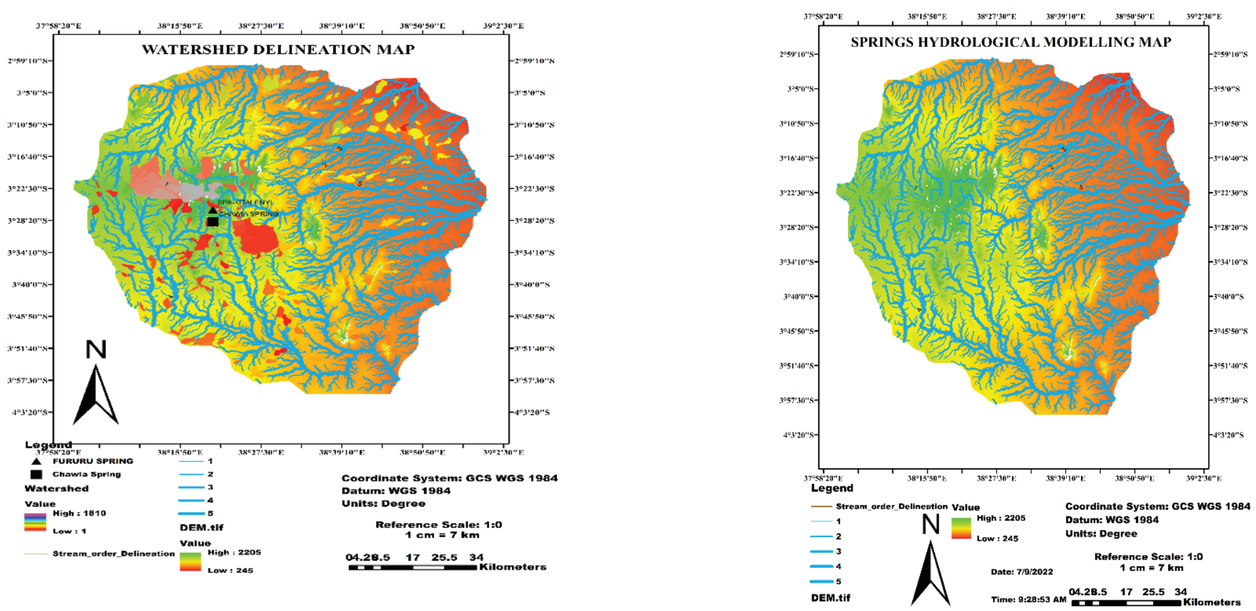


Figure 3. Delineated watersheds in Taita hills.

great increase in the same period as appended in Table 6. The maps show vegetation change and different forms and types. The changes in Chawia could have resulted from forest encroachment or even human disturbance (agriculture, and livestock) as shown in Fig. 4 and 5. From this study, five different LU types were determined namely dense rorest, moderate forest, grasslands, and shrubs in Chawia and Fururu forested watershed as outlined in Table 7.

The observed LU types were found to be impacting the forested watershed and thus reducing the number of springs in the study area, which are essential for human use and ecosystem regulation. The change in LU type caused these springs to dry up and that is the reason why the Chawia forested watershed is degraded and has lost a lot of cover whereas springs found in Fururu forested watershed were found to be active. This is due to the fact that the Fururu watershed is conserved and the forested area is still intact.

Percentage of change detection in land use land cover from 1987-2022

Figure 6 shows the highest NDVI value for each year in percentages. The value range of the NDVI is -1 to 1. Negative values of NDVI (values approaching -1) correspond to water. Values close to zero (-0.1 to 0.1) generally correspond to barren areas of rock, sand, or snow. Low, positive values represent shrub and grassland (approximately 0.2 to 0.4), while high values indicate temperate and tropical rainforests (values approaching 1).

In this study, the classification accuracy was 80.90%. The study areas were classified into six-land use and land cover classes namely; built up, agricultural, bare land, water bodies, grassland and forest land as defined in the classification scheme.

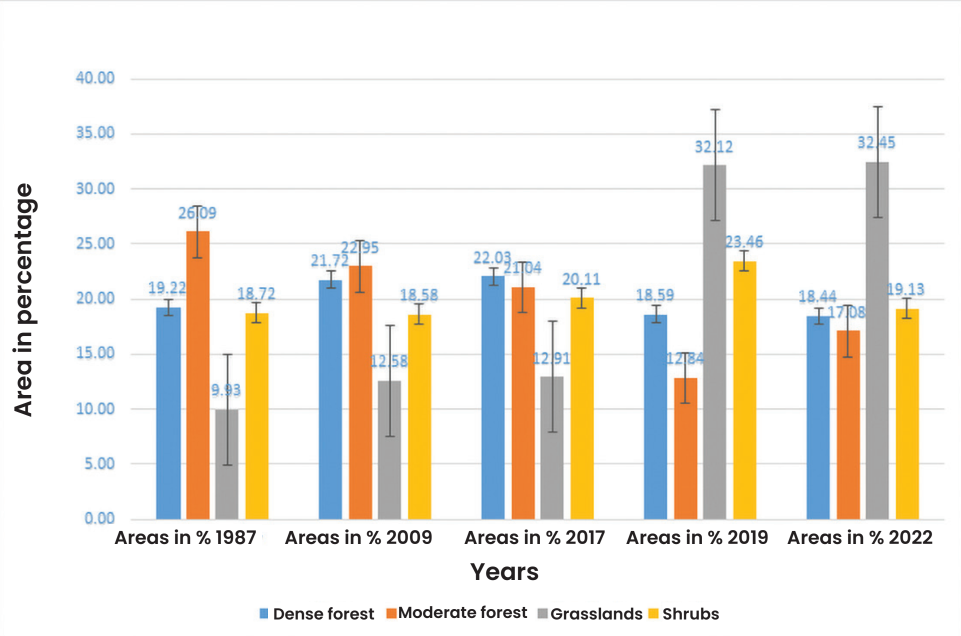


Figure 4: The phenological land cover changes in Chawia from 1987-2022

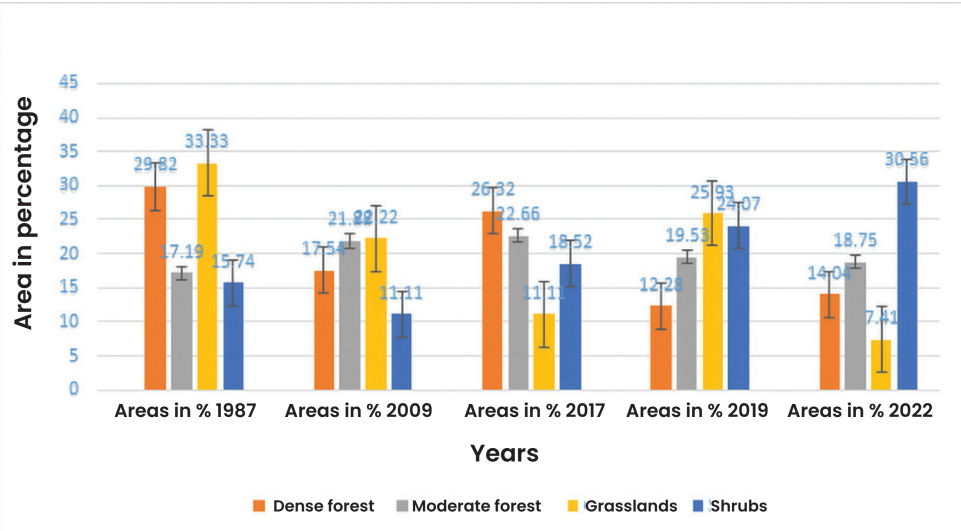


Figure 5. The phenological land cover changes in Chawia from 1987-2022.

Table 7. Land Cover change (Ha) from 1987 to 2022.

Land use type	Area in (ha) 1987	Area in (ha) 2009	Area in (ha)2017	Area in (ha) 2019	Area in (ha) 2022
Chawia					
Dense Forest	123	139	141	119	118
Moderate forest	191	168	154	94	125
Grasslands					
Shrubs	30	38	39	97	98
	134	133	144	168	137
Fururu					
Dense Forest	17	10	15	7	8
Moderate forest	22	28	29	25	24
Grasslands					
Shrubs	9	6	3	7	2
	17	12	20	26	33

Table 6 above where the most changes occurred large with increasing built up areas, forest land and agricultural land. From this study, the changes are attributed to large scale run off and erosion events that may be due to the decreased infiltration capacities associated with LU-LC changes. Chawia forested watershed experienced significant LU-LC changes between 2019 and 2022 while Fururu forested watershed experienced significant changes between 2009 and 2019 with the dominant changes happening within the dense forest and grasslands as shown in Fig. 4 and 5, respectively.

Some 91 springs were mapped and visualized in Chawia and Fururu forest ecosystems, where their respective watersheds were delineated and the hydrological, stream network and flow direction were developed based on the DEM method that was used. The results also showed that Chawia land cover has decreased over the years as follows: 123 ha (1987), 139 ha (2009), 141 ha (2017), 119 ha (2019), and 118 ha (2022). Whereas Fururu dense forest decreased from 17 ha in 1987, 10 ha (2009), 15 ha (2017), 7 ha, and 8 ha (2022).

From this study, six LC and LU classes were identified that is; Built up area dominating 66.3%, Forest land at 26.29%, Agriculture at 7.13%, Grass lands at 0.04%, water Bodies at 0.23% and Bare lands at 0.01%. Generally, the study indicate that the indigenous forest in the Taita Hills decreased by 66.3% due to the establishment of exotic plantations and more built up areas. Significant land use changes have taken place in Chawia and Fururu forested watersheds between 1987 and 2022 showing a relative matrix change within each land use/land cover class for different time scenes as shown in

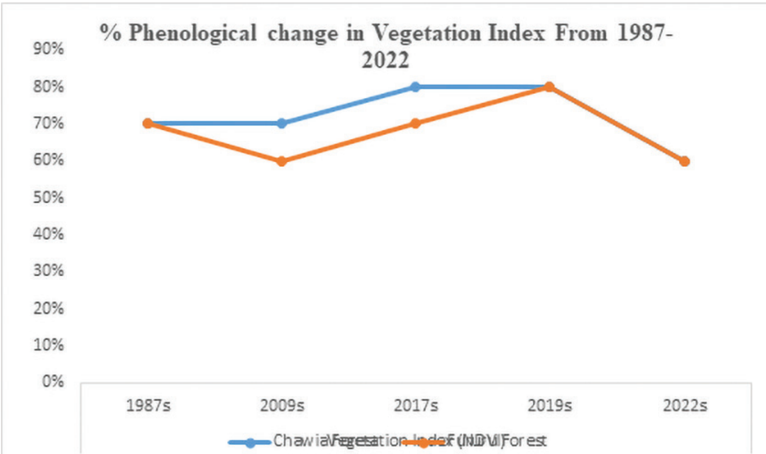


Figure 6. Normalized difference in vegetation Index (NVDI) in percentages.

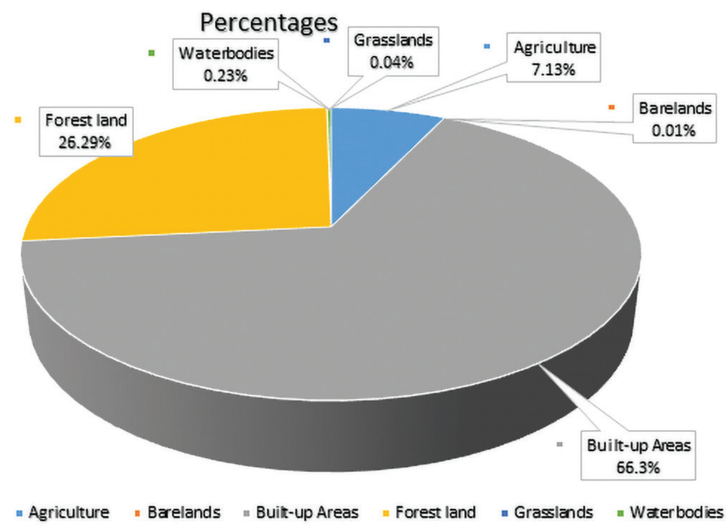


Figure 7. Land use status in Chawia and Fururu forest ecosystems.

Given that it offers guidance for the ensuing two decades and beyond, the Land Use Plan Map is long-term. Because it covers land usage across the Bowl, it is thorough. The following are its goals:

- Indicate the future distribution and general placement of land uses, including parks, mixed-use town centers, residential, commercial, and industrial development;
- Discuss the intended level of intensity, density, and overall nature of the land use designations shown on the map;
- Assist in guaranteeing that the expanding populace has sufficient housing, work, and leisure options;

Trends in forest cover change for dense forest, moderate forest, grassland, and shrubs forest areas varied among the forested watersheds (Table 6). The dense forest area in Chawia decreased between 2009 and 2022 while the moderate forest decreased between the year 2009 and 2019 before increasing in 2022 again. In Fururu, the dense forest area decreased between 1987 and 2009 before increasing in 2017; but decreased again in 2019 and 2022. The moderate forest area increased between 1987 and 2017 but reduced in 2019 and 2022 as shown in Tabel 6 and Fig. 4 and 5, respectively.

Land Cover Analysis from 1987 to 2022

Accuracy summary

As shown in Table 8, the overall accuracy of the data is 80.90%.

Table 8. Accuracy summary.

Accuracy summary					
Class name	**Reference**	**Classified**	**Number**	**Producers**	**Users**
Forestland	71	70	55	84.0%	86.3%
Grassland	21	19	17	90.96%	92.29%
Agriculture	16	19	15	96.4%	95.37%
Built-up	2	2	2	100%	100%
Totals	**110**	**110**	**89**		

Overall Classification Accuracy = 80.90%

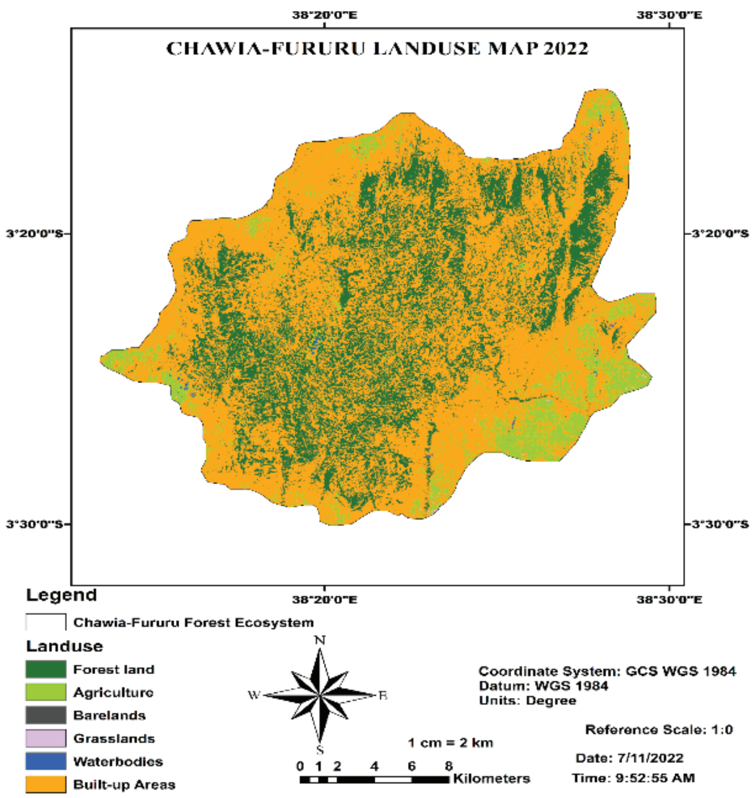
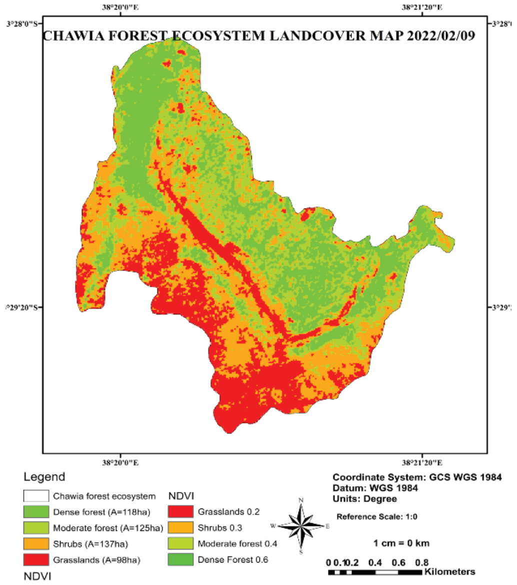


Figure 8. The Chawia-Fururu Land use status and characteristics in 2022.



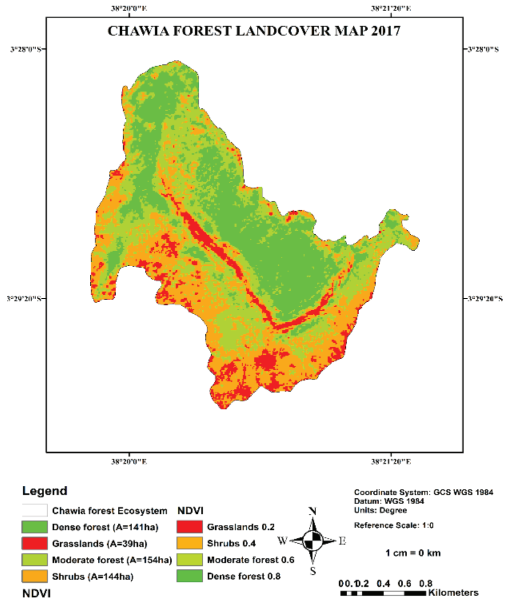
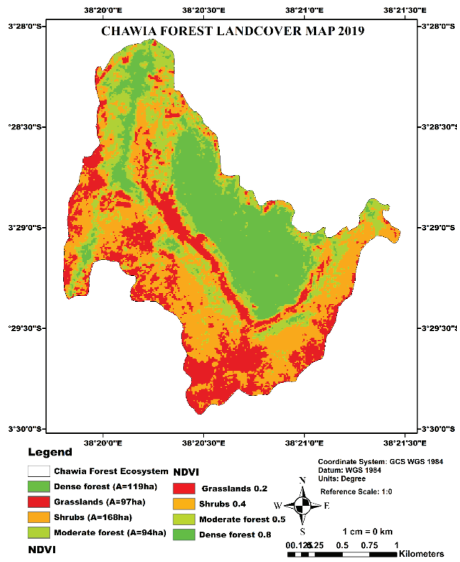


Figure 9. The Chawia land cover characteristics in 2022 and 2017.



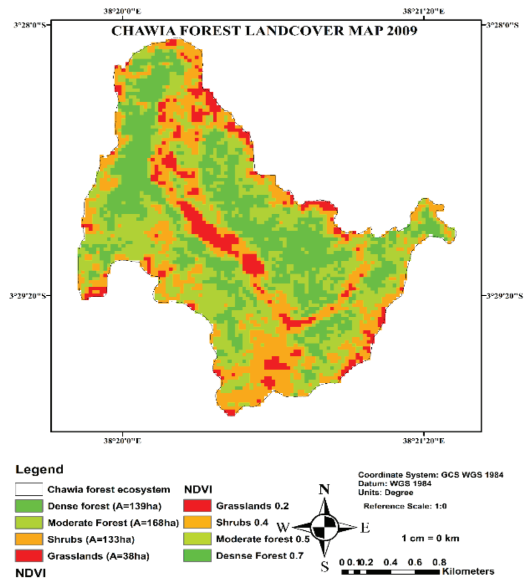


Figure 10. The Chawia Land cover characteristics in 2019 and 2009.

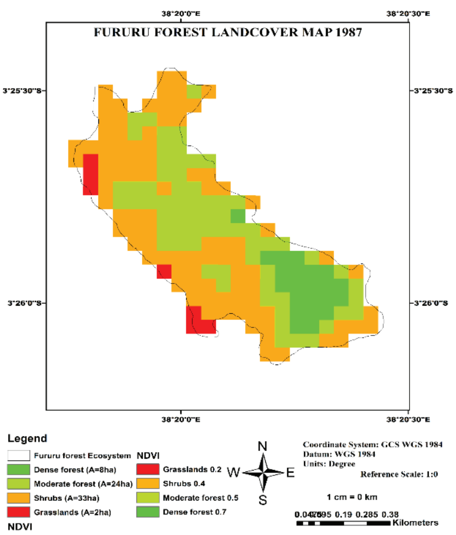


Figure 11.The Fururu Land cover characteristics in 1987.

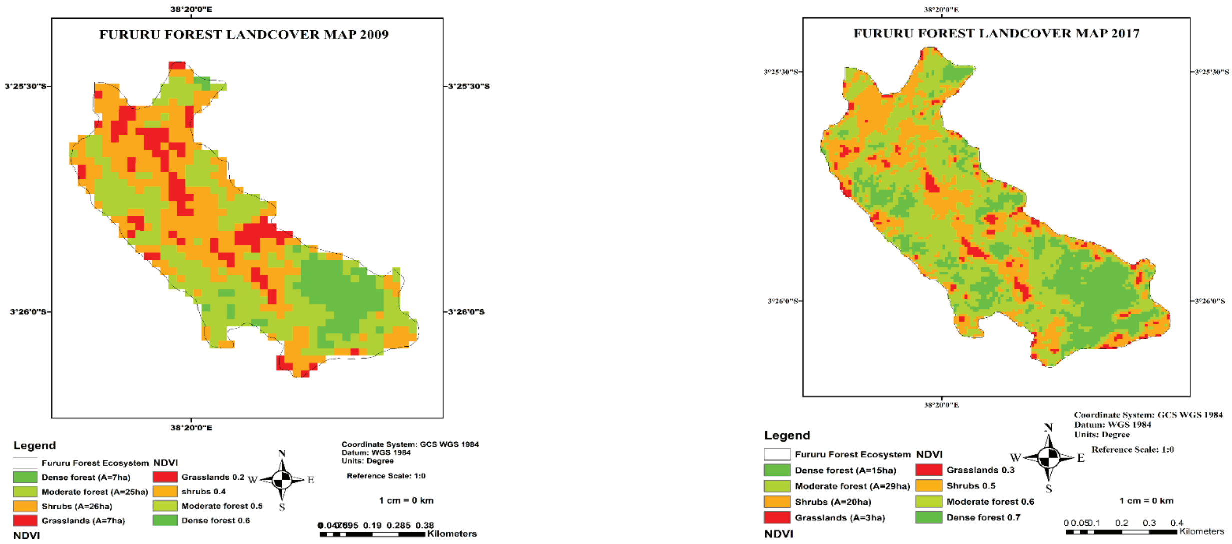


Figure 12. Fururu Land cover characteristics in 2009/2017.

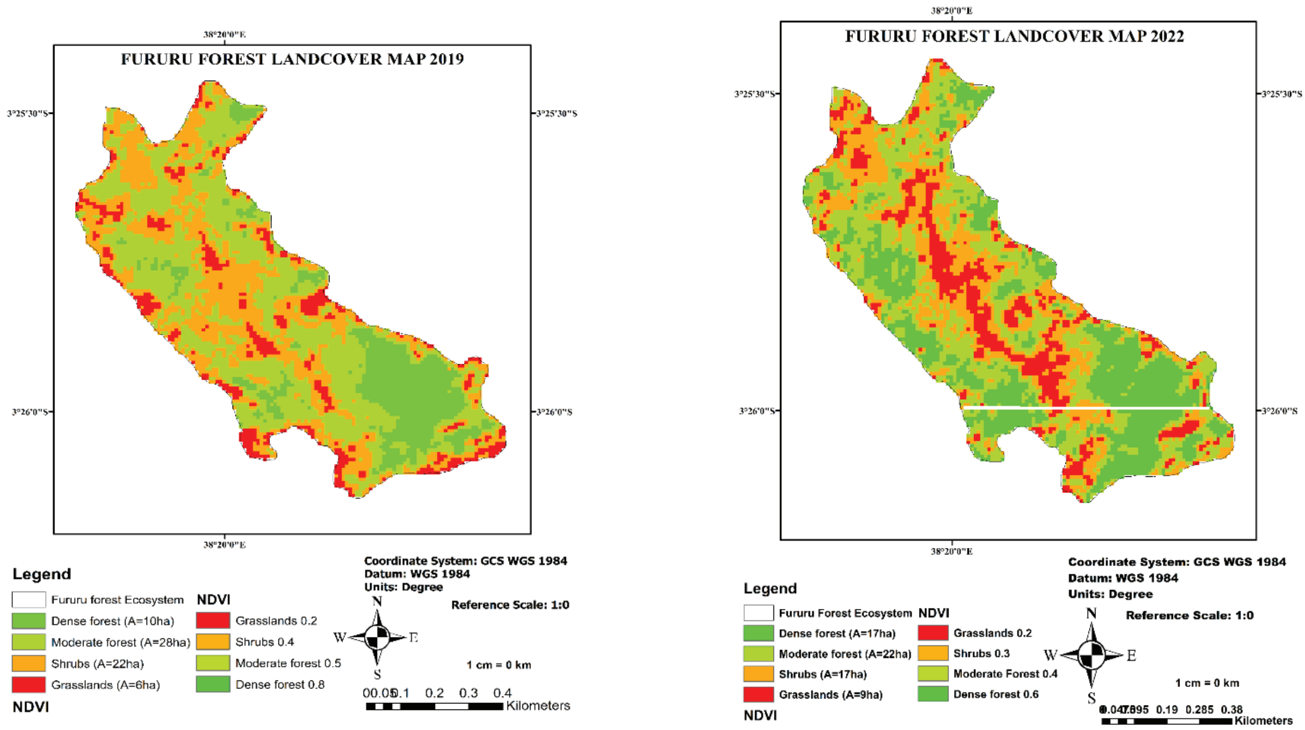


Figure 13. The Fururu Land cover characteristics in 2019/2022.

Table 9. Error matrix.

	Reference				
Classified	**Forestland**	**Grassland**	**Agriculture**	**Built-up**	**Total**
Forestland	55	14	1	0	70
Grassland	12	7	0	0	19
Agriculture	4	0	15	0	19
Built-up	0	0	0	2	2
Totals	71	21	16	2	110

Discussion

On the global scale, springs are a major source of water in the mountainous and hilly areas of the earth's surface and are important to terrestrial ecosystems. However springs are drying up at a rapid rate thus threatening livelihood globally (Dhakal *et al.,* 2020.). The Taita Hills' ability to supply water has been lessened due to deforestation of indigenous trees leading to decreased catchments' ability to retain water. Over the past 50 years, the water levels in numerous springs, rivers, and streams have plummeted, and some have almost entirely dried up. Local and historical knowledge shows that the exponential decrease in water levels peaked in the 1980s and 1990s (Thapa, 2021). Historically, particular areas in the steep upper zones of the the Chawia/Fururu forested watershed, used to remain rainy all year long (Hohenthal *et al*., 2015). Additionally, according to local accounts, residents once frequented the springs and rivers of the Taita Hills for fishing purposes. However, this is no longer the case, as the water quality and quantity have deteriorated, resulting in the absence of fish in these waters.

This study establishedthat most of the springs have dried up and thus the local communities cannot access the terrestrial water supply.

Ninety one (91) springs were mapped and visualized in Chawia and Fururu forest ecosystems. They were delineated and the hydrological, stream network and flow direction were developed based on the DEM method. The excessive exploitation and misuse of natural resources, along with environmental degradation, are placing significant pressure on water resources (Hohenthal *et al*., 2015). According to Hohenthal *et al*. (2015), indigenous forest cover has been reducing drastically since the 1960s due to population increase, expansion of intensive agriculture, planting of exotic tree species, and road construction. The drying up of the springs can be attributed to three major factors including anthropogenic factors, climate change, seisimic events and infrastructure development, such as building highways, hydropower tunnels, and cement irrigation canals as explained in similar situation by Dhakal *et al*. (2020). Water scarcity is also a result of unplanned urbanization and population growth, which increases consumption and increases reliance on springs and other water sources.

On forest management, satellite imagery has almost exclusively been used by GIS and geospatial practitioners. The emergence of new forest management solutions is creating new use cases for satellite imagery, addressing previously unanticipated needs, and ultimately driving value outside of GIS departments (Swift Geospatial, 2021). A study conducted by Uddin *et al*. (2015), aimed to assess and monitor natural resources, focusing on forests, within the Lorpa watershed in the Jumla district of Nepal. The research revealed that the cutting of trees, especially larger and older ones, remains a significant concern in the watershed.

Jasrotia *et al*. (2016), evaluated integrated remote sensing and GIS approach for delineation of groundwater potential zones in Devak and Rui watersheds of Jammu and Kashmir, India. Remote sensing, GIS, and fieldwork techniques were combined and used to delineate the groundwater sources map of Devak and Rui watersheds and the results from the study revealed that the excellent zone covers 13.5%, good zone 22.7%, moderate zone 15.8%, low zone 18.5% and run off zone 29.5% of the total study area. The results depicted the groundwater potential zone found to be helpful in better planning and management of groundwater resources in the study area(Jasrotia *et al*., 2016). In this study the Chawia and Fururu forested watersheds were delineated from data acquired from Sentinel_2 and Landsat8 satellites.

Globally, the majority of people on earth (approx 5 billion) live in cities. The urban population is predicted to exceed 6.5 billion within a decade. Terrestrial ecosystems will be impacted by urban growth, which will result in higher demands for the services they supply. The United Nations (UN) highlights the value of ecosystems and environmental services to people as natural products and services, on which social progress and economic growth directly depend, and which are currently disappearing globally at an alarming rate (Abad-Segura *et al*., 2020).

LU-LC classification was performed and although species-level classification was not possible, 10 optimum LC classes were mapped and contrasted in this study without affecting the precision of each class. Rangeland predominates throughout the study region; there are just a few patches of forest and agricultural land. Water, fuelwood, and other forest resources are in short supply, and the three nearby communities' rising demand further reduces their availability. The watershed is progressively being used at unsustainable levels for agricultural production, while overgrazing and overharvesting of fuelwood and lumber are contributing to the destruction of the environment(Uddin *et al*., 2015). Therefore in this study, it was similarly found that the four LC classes were determined and shrubland seemed to dominate the study area of Chawia watershed and there just a few patches of the dense forest in Chawia and Fururu as well but had an increase of the grassland forest.

As a result, therefore, the utilization of remotely sensed data and the integration of GIS and their techniques provide accurate and timely information for detecting and monitoring the land cover and land use. In this study, the classification accuracy was 80.90% where the study areas were classified into six-land use and Land cover classes namely built up, agriculture, bare land, water bodies, grassland and forest land as defined in the classification scheme. The results also showed that Chawia land cover has reduced by 10% from 123 ha in 1987 to 118 ha 2022. . This may be attributed to the increase in population and the increased built up areas in the study sites. Therefore, Chawia has lost 10% of its forest cover compared to reported global rates of a net annual loss of 4.7 million ha (Ritchie and Roser, 2021). The earth's cover has changed over the past 10,000 years shortly after the end of the great ice age up to the present. The loss of 10% cover for Chawia may be as a result of change in the land use activities where most people are encroaching towards the forest and participating more on agricultural activities that has made the forested ecosystem lose its cover whereas Fururu from this study gained a cover by 10% due to more conservation efforts.

According to the estimates of Winkler *et al*. (2021), at least 17% of the Earth's land surface moved between the six land types between 1960 and 2019. The total land change extent, which accounts for all individual change events (as well as areas of multiple change), is 43 million km^2, or almost a third of the world's land area. This indicates that, since 1960, an area of land that is roughly twice the size of Germany (720,000 km^2) has changed annually on average and it has been most evident in Africa and South America, regions of the tropics and sub tropics. They also found out that 0.8 million km^2 net loss of forest area globally, but an increase in world agriculture. However, in this study, land use changes were noticed to have shifted from forested land to agricultural and built up areas and the land use change has not been constant. It is also argued that in addition to globalized trade, climate change and its effects, such as extreme occurrences, droughts, and floods, are other significant drivers of land change dynamics that have increasingly affected the rate of land use change throughout the deceleration phase (Winkler *et al*., 2021). Droughts in West and East Africa have an impact on the utilization of agricultural land which in most parts of Kenya has affected agriculture and vegetation due to the rise in demand for land and poverty levels in Taita hills has made the local people to change their land use types which further contributes to vegetation change and index.

Conclusion and recommendations

Land use in Chawia and Fururu has been swamped by increased horticulture and brushing as a result of the rapid growth of the population, and this has forced the neighboring local area to encroach the slopes, creating actual erosion, soil disintegration, and lowering water tables in the slopes by ploughing the slopes and thus cutting down a lot of trees in the fragmented forests. Consequently, the incorporation of GIS and RS techniques advances watershed depiction and the land cover characterization from DEM information and from Landsat. The use of GIS and RS in Chawia and Fururu watersheds would assist in information securing on the hydrological foundation of the two watersheds, group the land uses, and land cover changes in the catchments. As a result, therefore, the utilization of remotely sensed data and the integration of GIS and their techniques provide accurate and timely information for detecting and monitoring the land cover and land use changes. From this study, there is need for urgent efforts to be done for Chawia forested watershed conservation to avoid its degradation and drying up of most springs. And the conservation efforts should be maintained for Fururu forested watershed in order to prevent drying up of the springs and reduction of the watershed size. As from the study results it is recommended that the Land Use Act should be enacted and enforced to put more conservation strategies to the forested areas of Chawia and more conservation efforts be done on Fururu forested watershed. The study also recommends that due to the higher rate of drying up springs, the Kenya Government and other stakeholders should develop more plans and strategies on the construction of more dams to act as water reservoirs to store water for irrigation and domestic use to meet the demand of the the increasing population in the forested areas of Taita Hills.

Acknowledgments

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Ethical statement

This study was carried out in accordance with the recommendations of the Pwani University ethics review committee (PUERC) with written informed consent from all subjects. All subjects gave written informed consent in accordance with the declaration of Pwani university committee.

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Short communication

The suitability of incentives in social research on artisanal fishing communities in coastal Kenya: A perspective

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Abstract

Artisanal fishing communities in coastal Kenya contribute the largest proportion of the country's total marine catch. This, coupled with nutritional value of fish, and the global focus on ensuring food security to all populations, makes coastal fishing communities excellent research subjects. Despite their critical contribution to satisfying the nutritional needs of numerous consumers – local and foreign, many of these coastal fishing communities are engulfed in severe poverty. Kenya Marine and Fisheries Research Institute (KMFRI) has undertaken socio-economics research among artisanal coastal fishing communities for over two decades and today it is clearly evident that research fatigue amongst these communities not only exists, intolerance of this fatigue is increasingly pronounced. Hence, given the existing researcher-researched relationship, these communities that are relied upon for professional output seem to be getting the short end of the stick. There is need to provide them with some form of immediate and tangible appreciation for the assistance (data and otherwise) they provide. Herein, we present an overview of the benefits and disadvantages of incentives in social research, the appropriateness of the incentive approach with respect to socio-economics research on Kenya's coastal fishing communities and a potential solution to alleviating artisanal fisherfolk poverty.

Keywords: artisanal fishing communities, deprivation, social research, incentives

Introduction

Many of the artisanal fishers found in Kenya's coastal region are rich in knowledge, but poor materially. These small-scale fishers suffer from abject poverty despite being custodians of a wealth of knowledge pertaining to their marine livelihood. The coastal region includes some of the poorest counties in Kenya, with Tana River, Kwale, and Kilifi ranking among the 14 counties with highest overall poverty and food poverty incidence. Tana River, Kwale and Kilifi counties show overall poverty headcount rates at 62.2, 47.4 and 46.4 percent respectively.

Most of the coastal population rely on coastal and marine ecosystems for employment, livelihoods and nutrition, however, population growth, narrow diversity of income sources and mostly open-access fisheries has led to increased overfishing and near-depletion of fish stocks in nearshore and territorial waters (Setlur, 2019). In an effort to address this plight, the marine division of the Socio-economics Directorate within the Kenya Marine and Fisheries Research Institute (KMFRI), is mandated to advise management on policies and strategies related to the use of Kenya's marine resources for community empowerment and sustainable development (KMFRI, 2024).

This division is focused on research associated with coastal communities' use of coastal and marine resources for their subsistence and commercial welfare. The focal point of this division's research is therefore the people (local communities) that rely on these resources: the division essentially engages in social research. The target group for the socio-economics research we conduct is primarily the artisanal fishing communities found along Kenya's coastline - from Kiunga in the North, all the way to Vanga in the South.

The most common instruments used in our cross-sectional socio-economics research are Questionnaires, Focus group discussions (FGD) and Key Informant Interviews (KII). These instruments are employed in a face-to-face setting, with the researcher posing the questions, and immediately recording whatever answers are provided by the respondent. For our research team, interviews using these instruments would on average take between forty-five to ninety minutes. For the overwhelming majority of fishing communities in which we conduct our research, the socio-economic status is dismal; as manifested in the form of decrepit mud-walled and thatched roof huts, lack of household assets such as chairs, radios or mattresses, low levels of education among household members and generally inadequate household income.

Given this context, we wish to put forward our perspective that the use of Incentives when conducting social research in such deprived communities, should be mandatory. The official position does not support the use of Incentives in social research, claiming that it contributes to collection of inaccurate data, especially through the promotion of social desirability bias amongst 'paid' respondents. We offer an alternative viewpoint, claiming that social research in deprived communities ought to leave the respondents materially better off once the activity is concluded. In the following sections we briefly explain what incentives in social research are, highlight their benefits and disadvantages, before setting forth our claim that these incentives when employed in research involving deprived communities are not only beneficial, but indeed necessary.

Types of incentives used in social research

Incentives are all forms of monetary or non-monetary inducement given to (potential) respondents (Singer, 2002; Singer and Ye, 2013). Non-monetary research incentives used during social research in the Kenyan context, include foodstuffs (e.g., packets of maize or wheat flour, long-life milk, sugar and cooking oil) or consumer durables such a blankets. Literature shows that prepaid incentives are given in advance to all those who are contacted, irrespective of whether they participate in the survey or not. Conditional incentives are given to respondents after participation (Pforr, 2016). However, prepaid incentives may be unlikely to work in a less developed country's scenario such as Kenya, given the widespread poverty and deprivation experienced by significant sections of the population. Besides appreciating respondent's time and effort, incentives aim to increase response rates (Groves and Couper, 1998).

Benefits of incentives

While each single survey is unique in terms of the collective variables involved, e.g., time of administering, geographical location, weather conditions and respondents participating, we can identify a few general advantages incentives can produce in a survey. It is generally assumed that incentives can increase response rates by persuading those who are not otherwise motivated to take part - i.e., the hard-to-persuade populations (Nicolaas *et al.,* 2019). Incentives allow for research respondents to be compensated for their time, expenses, inconvenience and for the degree of discomfort they may experience while participating in a research study (CUREC, 2020). Monetary incentives are often used to facilitate survey recruitment and motivate participation among individuals who might otherwise not respond (Singer and Bossarte, 2006; Singer and Couper, 2009). Several authors seem to conclude that incentives increase data quality, including by increasing accuracy (Singer *et al.,* 1998; Singer, Groves, & Corning, 1999). Some studies report significant positive effects of incentives on response quality, especially a reduction in item nonresponse (Olsen *et al.,* 2012; Ahlheim *et al.,* 2013).

Disadvantages of incentives

The most obvious disadvantage of using incentives in social research is that they may incline respondents to provide answers that either they believe the interviewer wants to hear or they consider as socially acceptable. This results in what is known as Social Desirability Bias, which negatively compromises the quality of responses. Particularly in very poor households, respondents may feel the need to 'repay' the incentive they have received and what better way to do so than 'to make the interviewer happy by saying what they want to hear'. The use of incentives can also be incompatible with treating the participants with respect and dignity. Incentives can influence potential participants to take part in research. Participants can be at risk of exploitation from accepting an unreasonable burden of risk or agreeing to do something they wouldn't otherwise agree to take on. They may also feel influenced to take on inconvenient or uncomfortable activities, or be motivated to volunteer repeatedly for research studies offering remuneration for participation. It has been argued that incentives may inappropriately commercialize the relationship between researchers and research participants, with implications for public trust. Participants from financially disadvantaged groups and those in resource-poor contexts may be at risk in such a situation. When compensating for loss of the interviewee's earnings, researchers could compromise the work by focusing on the recruitment of "cheaper" participants (CUREC, 2020).

Our perspective

Most of KMFRI's marine socio-economics research is conducted among coastal artisanal fishing communities. These communities, for the most part, share one characteristic: they suffer from (varying degrees of) poverty. This notwithstanding, it must be acknowledged that with the institutional developments that have over the years taken place within the Kenya's marine fisheries sub-sector – most especially the formation and subsequent development of the Beach Management Units (BMUs), significant strides have been made in addressing this scourge. However, these strides need to be greater. Poverty in these communities manifests itself in various ways, including: low incomes (and the associated marginal standard of living); inadequate infrastructure, and; fishing (and fishing-related) activities undertaken at an economically unprofitable scale.

KMFR's research has over the years been undertaken in key coastal fisheries centres, viz: Gazi, Msambweni, Shimoni, Vanga, Malindi, Ngomeni, Lamu and Faza. The respondents we focus on are primarily the artisanal fishers (and other local stakeholders) at these sites. On many occasions we interview the respondents at their homes – usually the fishers are too tired to engage in an interview once they arrive from sea. Hence arrangement is made to visit them later in the day once they have had an opportunity to rest. At many fisher households, the level of poverty is clearly visible. Often there may only be one chair available – which is usually offered to the 'guest' (researcher), but many a time you and the respondent simply have to sit on any available stones, fallen palm trunks or perhaps plastic water containers. More often than not the fisher's home is mud-walled, lacking electricity, cemented floors or piped water. However, the cooperation, warmth and hospitality of most respondents more than makes up for any material deficiencies in their homes.

In the contemporary world of research, community participation is widely recognized, encouraged and duly rewarded as a means of co-production of knowledge. Is it therefore justified for the communities that researchers work with here in Kenya to receive some form of compensation immediately after data collection, this notwithstanding the subsequent (future) benefits of the research. Skeptics may take the view that 'This incentive would just be enough for one day'- but can any of us really know a household's condition on that one day? For someone in severe need, making ends meet in fishing households is sometimes problematic and sometimes results in a family sometimes sleeping hungry. It therefore important to note that a financial 'incentive', 'reward', 'token', or however else one terms it, would go at least some way in defraying a household's food costs?

Our bone of contention is this: From an ethical (moral or humane) standpoint, is it inappropriate for a team of government researchers to arrive at a fishing village severely affected by the poor fish catches (and the associated socio-economic deprivation), spend close to an hour questioning each fisher (on matters including the difficulties brought about by climate change and dwindling fish catches), and thereafter simply thank the fishers for their co-operation and then leave the village. Over the past few years – and especially in 2020 during the Corona pandemic, there had been increasingly frequent encounters where respondents vocally question the benefit of our research to them. The Kibuyuni Seaweed farmers and Majoreni fishing community in Kenya's south coast are two such examples of communities that are increasingly dissatisfied and frustrated with researchers' repeated visits to their villages, asking them the same questions year in, year out', and yet failing to uplift their standard of living in any way whatsoever.

While we often console ourselves with the rationale that 'research benefits are not immediate, they take time', could it be that we are simply failing to see the trees for the forest? For many of the underprivileged respondents (households) we interview, securing the day's meal is their immediate concern. Thinking about next week becomes impossible if you don't know what your family will eat today. Is it not incumbent upon us as researchers, no - on us as human beings, to take care of our neighbour's immediate needs, rather than paint them a picture of a rosy but distant future? We believe that in the long-run, a culture of incentivizing respondent communities will engender a sense of being appreciated, which would in most probability enhance the communities' willingness to participate in research activities, and in so doing, improve the quality of data generated from these communities.

The suitability of research incentives will always be context-specific, depending on the needs and desires of the particular community where the research is undertaken. What is needed is a framework that justifies and encourages the use of incentives among the participating communities. We do not expect any radical, overnight paradigm shift in the way social research is conducted in Kenya. What we would like to see is the start of some form of institutional dialogue on how our research can move from the 100% extractive model, to a more respondent-focused approach, one that leaves the participating community in a tangibly better position after the interview than they were before it. How exactly this can be achieved requires the input of all concerned. Participatory stakeholder dialogue is the key. The Kenyan (developing country) context is far removed from that of the developed world where standards of living are much higher. For poor fishing communities the hand-to-mouth existence is simply the order of the day. But for us as Government, and being aware of this situation, is it not up to us to immediately do something about it? There is need to re-evaluate the existing research paradigm with particular respect to working with deprived communities in our country. Researchers need to remember that they are the main beneficiaries in any social research context. Immediate and adequate compensation to respondents from deprived communities needs to become the standard. While some may take the view that provision of respondent incentives is a certain way to creating dependency among the participating communities, we are of the view that this is an issue concerted consultation with stakeholders would resolve.

How can the impoverished artisanal fishing communities be helped?

On a practical level, a potential solution to the poverty afflicting Kenya's artisanal marine fishing communities may well involve developing the Artisanal Marine Fisheries Market System (AMFMS). The AMFMS (as in any other market system) comprises of three key elements: the Core function (in this context the supply of fish by artisanal fishers); Supporting functions (i.e. those that assist artisanal fisherfolk in their fishing livelihoods, e.g., credit facilities, cold storage and transport services), and; Rules (the formal (laws, regulations and standards) and informal (values, relationships and social norms) controls that provide a key input in defining incentives and behaviour in the AMFMS). Market Systems Development (MSD) is an approach that seeks to benefit lower income groups by unlocking key problems and opportunities they face in the market systems they engage in. The approach aims to improve the long-term efficiency and inclusivity of the systems that matter most to poor women and men. Thinking about 'systems' means focusing on the underlying reasons, the root causes (The Springfield Centre, 2015; DevLearn, 2022).

Unlike conventional approaches to poverty alleviation, where projects provide what is missing in impoverished communities, the MSD concept seeks to identify the root cause of the existing problem within a community, to determine who in the community can solve the problem, why they are not solving the problem and then proceeds to leverage the community's capacities and incentives to facilitate interventions aimed at scalable and sustained change (economic growth). MSD programs acknowledge that in order to achieve a change in the market that is both sustainable and scalable then they need to facilitate any change through those that exist in the market system. They only invest in systemic (widespread) changes that may achieve this.

Essentially, if one market actor is incentivized to change their behaviour, others may follow. This creates a multiplier effect and allows positive changes in the market to reach more people (SEEP, 2021). Improving the way our artisanal fisherfolk engagement in the market is an effective way of reducing their poverty and other limitations (DevLearn, 2022). Essentially, MSD provides a coherent, rigorous approach to understanding and intervening in market systems so that they function more efficiently and sustainably for poor women and men (The Springfield Centre, 2015). The poor (fisherfolk) participate in markets either as producers, consumers or providers of labour. The central idea is that they are dependent on market systems for their livelihoods. Therefore, changing those market systems to work more effectively and sustainably for the poor will improve their livelihoods and consequently reduce poverty. The involvement of poor people in economic growth is the best way to get them out, and keep them out, of poverty (Tschumi and Hagan, 2008). While the MSD concept has been applied in Kenya's Agri-input, Dairy and Water sectors, it has been conspicuously absent from the artisanal marine fisheries sub-sector. The concept may indeed be worth exploring with respect to alleviating the poverty gripping Kenya's artisanal coastal fisherfolk.

Conclusion and recommendations

The world is indeed changing and communities all over the world are increasingly recognizing their rights and entitlements. The research fraternity ought to be at the forefront in uplifting the lives of the destitute communities they work with.While our point of view on the use of incentives is based on our research experience with Kenya's artisanal fishing communities, we firmly believe that employing incentives can (and should) be applied to social research in any context where socio-economic deprivation is evident. We believe that appreciating research respondents in an appropriate manner will always enhance the research activity at hand. Let us stop exploiting our impoverished fishing communities (research subjects): they are actually very knowledgeable, resourceful and resilient. Rewarding them promptly every time they provide valuable research data must become the norm. We therefore need to start an open, honest conversation with all stakeholders on the modalities of just how social research incentives in Kenya can be institutionalized. Solutions to any problem begin with dialogue, so let's start talking. This is our perspective.

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