Short Note [Nota Corta]

EFFECTS OF BUFFEL GRASS (*Pennisetum ciliare*) AND GUINEA GRASS (*Megathyrsus maximus*) ECOTYPES ON GROUND COVER AND SELECT SOIL PROPERTIES IN SEMI-ARID KENYA †

[EFECTO DE LOS ECOTIPOS DE PASTO BUFFEL (*Pennisetum ciliare*) Y PASTO GUINEA (*Megathyrsus maximus*) SOBRE LA COBERTURA DEL SUELO Y DETERMINADAS PROPIEDADES DEL SUELO EN LA ZONA SEMIÁRIDA DE KENIA]

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SUMMARY

Background: Healthy soils are the key to the sustainability of dryland ecosystems. In semi-arid Kenya, indigenous rangeland grasses have been widely used to rehabilitate degraded lands with the aim of enhancing grass cover as well as enhancing soil quality and other ecosystem services. **Objective:** To assess the effects on ground or soil cover and soil physical and chemical properties of four indigenous grass ecotypes of two common rangeland grass species (*Pennisetum. ciliare* and *Megathyrsus maximus*) (Jacq.) B. K. Simon & S. W. L. Jacobs (Syn. *Panicum maximum* Jacq.), used for fodder and rangeland rehabilitation in semi-arid Kenya, four years after their establishment. **Methodology:** A field experiment was carried out in semi-arid southeastern Kenya comprising 4 grass ecotypes namely *P. ciliare* KLF, *P. ciliare* MGD, *M. maximus* ISY and *M. maximus* TVT). These were grown in a rhodic-ferralsol for determination of ground cover attributes and selected soil properties after 4 years. Soil samples were collected up to a depth of 30 cm in the established pastures and analyzed for bulk density, moisture content, pH, soil organic carbon (SOC), Total Nitrogen (TN) and elemental composition [Phosphorus (P), Potassium (K), Calcium (Ca) and Magnesium (Mg)]. Soil micronutrient status [Manganese (Mn), Copper (Cu), Iron (Fe), Zinc (Zn), Sodium (Na)] were also determined. **Results*:*** Inferences were made in comparison with conditions before the establishment of the grasses and comparison among the different grass ecotypes. Overall grass cover ranged between 52 and 85 % among the grass ecotypes, reflecting the importance of indigenous grasses in improving ground cover and rangeland rehabilitation. An improvement in SOC, N, K, Cu, Fe and Zn contents was observed. A decline was however observed in soil P, Mn and Na contents. Divergent responses were observed among the grass ecotypes in terms of soil attributes. **Implications*:*** The growing of indigenous grasses has the capacity and potential to improve soil conditions in the short term (< 5 years) and hence the productivity of semi-arid grasslands. Evidence is provided to guide decisions on the suitability of grasses for improving soil attributes in addition to enhancing forage productivity in semi-arid rangelands. **Conclusion:** The grass ecotypes enhanced the ground cover and improved certain soil properties over the 4-year period. In particular, there was an improvement in the soil organic contents, TN, Ca, Mg and K status of the soil.
Keywords: Carbon; grassland; nitrogen; pasture; perennial grasses; range rehabilitation; restoration.

RESUMEN

Antecedentes: Los suelos saludables son la clave para la sostenibilidad de los ecosistemas de tierras áridas. En la Kenia semiárida, los pastos y pastizales indígenas se han utilizado ampliamente para rehabilitar tierras degradadas con

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el objetivo de mejorar la cubierta de pastos, así como la calidad del suelo y otros servicios ecosistémicos. **Objetivo:** Evaluar los efectos sobre el suelo y la cubierta y propiedades físicas y químicas del suelo de cuatro ecotipos de pastos indígenas de dos especies comunes de pastos de pastizales (*Pennisetum. ciliare* y *Megathyrsus maximus*) (Jacq.) B. K. Simon y S. W. L. Jacobs (Syn. *Panicum maximum* Jacq.), utilizados para forraje y rehabilitación de pastizales en la Kenia semiárida, cuatro años después de su establecimiento. **Metodología**: Se llevó a cabo un experimento de campo en el sureste semiárido de Kenia que comprendió 4 ecotipos de pastos, a saber, *P. ciliare* KLF, *P. ciliare* MGD, *M. maximus* ISY y *M. maximus* TVT). Estos se cultivaron en un ferralsol ródico para determinar los atributos de la cobertura vegetal y ciertas propiedades del suelo después de 4 años. Se recolectaron muestras de suelo hasta una profundidad de 30 cm en los pastos establecidos y se analizaron para determinar la densidad aparente, el contenido de humedad, el pH, el carbono orgánico del suelo (COS), el nitrógeno total (NT) y la composición elemental [fósforo (P), potasio (K), calcio (Ca) y magnesio (Mg)]. También se determinó el estado de micronutrientes del suelo [manganeso (Mn), cobre (Cu), hierro (Fe), zinc (Zn), sodio (Na)]. **Resultados**: Se realizaron inferencias en comparación con las condiciones antes del establecimiento de los pastos y la comparación entre los diferentes ecotipos de pastos. La cobertura general de pastos osciló entre 52 y 85 % entre los ecotipos de pastos, lo que refleja la importancia de los pastos autóctonos en la mejora de la cobertura del suelo y la rehabilitación de los pastizales. Se observó una mejora en los contenidos de COS, N, K, Cu, Fe y Zn. Sin embargo, se observó una disminución en los contenidos de P, Mn y Na del suelo. Se observaron respuestas divergentes entre los ecotipos de pastos en términos de atributos del suelo. **Implicaciones:** El crecimiento de pastos autóctonos tiene la capacidad y el potencial de mejorar las condiciones del suelo a corto plazo (< 5 años) y, por lo tanto, la productividad de los pastizales semiáridos. Se proporciona evidencia para guiar las decisiones sobre la idoneidad de los pastos para mejorar los atributos del suelo, además de mejorar la productividad del forraje en pastizales semiáridos. **Conclusión:** Los ecotipos de pastos mejoraron la cobertura del suelo y mejoraron ciertas propiedades del suelo durante el período de 4 años. En particular, se observó una mejora en el contenido orgánico del suelo, así como en el estado de TN, Ca, Mg y K.

Palabras clave: Carbono; pastizales; nitrógeno; pastos; gramíneas perennes; rehabilitación de pastizales; restauración.

INTRODUCTION

The arid and semi-arid lands comprise of over 80% of the total land mass of Kenya. These regions face varied challenges including rangeland degradation often manifested in soil and biological productivity. Primarily these are brought about by factors such as climatic variability, inappropriate land use, vegetation removal and overgrazing (Mulinge *et al.*, 2016) among many other drivers. Sustainable land management practices such as rangeland rehabilitation through the growing of perennial grasses to reverse these degradation trends are therefore necessary to enhance the ecological productivity of these regions.

Grasses are some of the most abundant vegetation types globally. Perennial grasses, due to their productivity, longevity and persistence play a crucial role in the sustainability of grassland ecosystems. Buffel grass (*Pennisetum ciliare (L.)* and Guinea grass *Megathyrsus maximus* (Jacq.) B. K. Simon & S. W. L. Jacobs (Syn. *Panicum maximum* Jacq.), are two perennial grass species that are of immense importance in semi-arid dryland ecosystems in the tropics. In addition to providing biomass as feed for livestock, which is their primary role, grasses play other diverse ecosystem roles such as erosion control, carbon sequestration and nutrient cycling, among many other roles (Zhao *et al*, 2020). Perennial grasses when introduced or incorporated into other crop production systems are also an emerging technology in moisture retention, nutrient use efficiency, improving soil quality, weed and pest control (Schlautman *et al.*, 2021). In Kenya, the growing and cultivation of these grasses is an opportunity that has been taken by communities in semi-arid regions as an adaptive measure to climate variability and to increase resilience (Lugusa, 2015). The importance of perennial the two grasses has also majorly been highlighted in rehabilitation and the restoration of degraded semi-arid landscapes and fodder production (Kidake *et al.*, 2016; Mganga *et al.*, 2019).

The long-term and short-term effects of perennial grasses on ground cover and soil attributes have widely been explored in natural grassland ecosystems. In such areas, where grazing is common, processes such as overgrazing, when considered as process of repeated removal grass biomass, have been cited as major causes of alteration of soil physical properties, among them bulk density, porosity and aggregate stability (Mganga, 2010a). Similarly, in managed grasslands, practices such as mowing, grazing and nutrient management are major drivers of ground cover and soil quality (Boitt *et al.*, 2018). The rehabilitation of degraded landscapes in semi-arid Kenya using perennial grasses has shown the potential to alter both the physical and chemical properties of soils (Mureithi *et al.*, 2014b). In a study involving areas maintained under a herbaceous layer, the researchers found a higher total organic carbon, nitrogen and exchangeable cations compared to degraded bare sites. Saleem *et al.* (2020), suggested that perennial grasses when used as cover crops may help improve soil nutrients, soil organic matter as well as soil organic carbon and soil health in general. For instance, the introduction of

Urochloa (Syn. *Bracharia*) grasses in semi-arid Kenya has demonstrated the ability to improve soil aggregate stability and soil organic carbon (Gichangi *et al.*, 2016). This is crucial considering that soils in semi-arid regions are low in soil organic carbon, are fragile in nature and are prone to erosion (Mganga, 2010a; Oduor *et al.*, 2018). Furthermore, areas where pastures are continuously removed through grazing and defoliation exhibit a decline in soil nutrients and a subsequent decline in range condition (Mureithi *et al.*, 2014a). This is partly attributed to the removal of aboveground biomass and organic matter, which is the major input of nutrients into the soil and the improvement of soil health (Rumpel *et al.*, 2015).

Farmers and livestock keepers in semi-arid Kenya have adopted fodder establishment and cultivation using adapted indigenous grass species for enhanced feed security (Lugusa, 2015). Indeed, there are secondary benefits resulting from such initiatives, especially with regard to soil health (Lu *et al.*, 2020; Mganga, 2010a; Mganga 2019) and the environment in general. Understanding how soils respond to grass establishment and different grass species can guide on choice of appropriate species for restoration of degraded areas and fodder production. Perennial grasses vary in their morphological, structural and inherent characteristics and thus influence the soil environment differently (Mganga *et al*., 2019). Few investigations have been reported on the effects of pasture establishment and management on soil properties in semi-arid Kenya. With increasing pasture cultivation, further studies are required to understand soil quality indicators for better management and to inform the increasing adoption of pasture cultivation. Furthermore, in the recent past, there have been efforts dedicated to the development and promotion of climate-smart adapted rangeland grass varieties for adoption (Kirwa, 2019). These grasses are currently being evaluated for seed production that will be used to boost range restoration efforts and fodder production under arid and semi-arid conditions. Despite these efforts, little has been documented about within species variability, particularly on the effects on ground cover and soil fertility attributes.

A study was conducted with four indigenous grass ecotypes of two common rangeland grass species (*Pennisetum ciliare* and *Megathyrsus maximus*), used for fodder and rangeland restoration in semi-arid Kenya. These ecotypes were *Pennisetum ciliare* KLF, *Pennisetum ciliare* MGD, *Megathyrsus maximus* TVT and *Megathyrsus maximus* ISY. The objective was to assess the effects of the rangeland grass ecotypes on ground or soil cover and soil physical and chemical properties, four (4) years after their establishment. The results are expected to provide evidence and guide decisions on the suitability of grasses for improving soil attributes in addition to enhancing forage productivity.

MATERIALS AND METHODS

Site description

The experiment was set up at the Kenya Agricultural and Livestock Research Organization (KALRO) Kiboko Research Station experimental farm (coordinates 02° 127 S, 37° 437 E), found in Makueni County, Southeastern Kenya (Figure 1). The experimental site is characterized by a semi-arid climate, with an annual rainfall of approximately 600 mm distributed in a bimodal manner. Long rains are received between March and May and short rains are received between October and December peaking in April and November respectively. Temperatures average 24.1º C (Binacchi *et al.*, 2022). The weather conditions during the study period are as indicated in Figure 1, where rainfall received varied across months and years. The wettest year was the year of establishment (2019/2020) with a total of 2,469.7 mm of rain received. The driest year was 2022/2023 when only 338.6 mm of rainfall was received. As expected, some months did not receive any precipitation at all in some years. The mean minimum temperature was 16.4 ºC while the mean maximum temperature over the 4 years period was 31.2 ºC.

The soils are mainly Acri-rhodic ferralsols arising from undifferentiated basement system rocks (CIMMYT, 2013). They are well-drained, deep, reddish-brown to red and support different types of crops including dryland cereals and grain crops. The vegetation of the surrounding environment is mainly a bushed grassland with a variety of tree and shrub species such as *Acacia* and *Commiphora* species, with a grass understory. The common grass species include Buffel grass (*Pennisetum ciliare*), Guinea grass (*Megathyrsus maximus*), Maasai love grass (*Eragrostis superba*), Bush rye (*Enteropogon macrostachyus*) and Red oat grass (*Themeda triandra*).

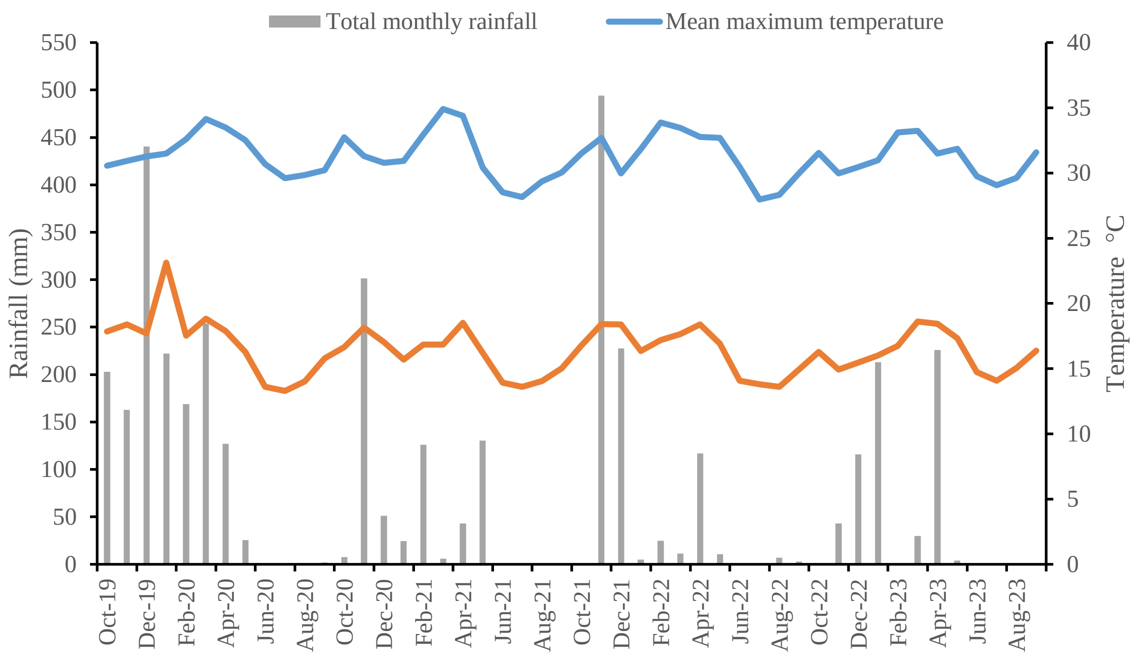

Figure 1. Total monthly rainfall and mean monthly temperature over a 4 years (2019-2023), from the time of grass establishment to sampling at KALRO Kiboko.

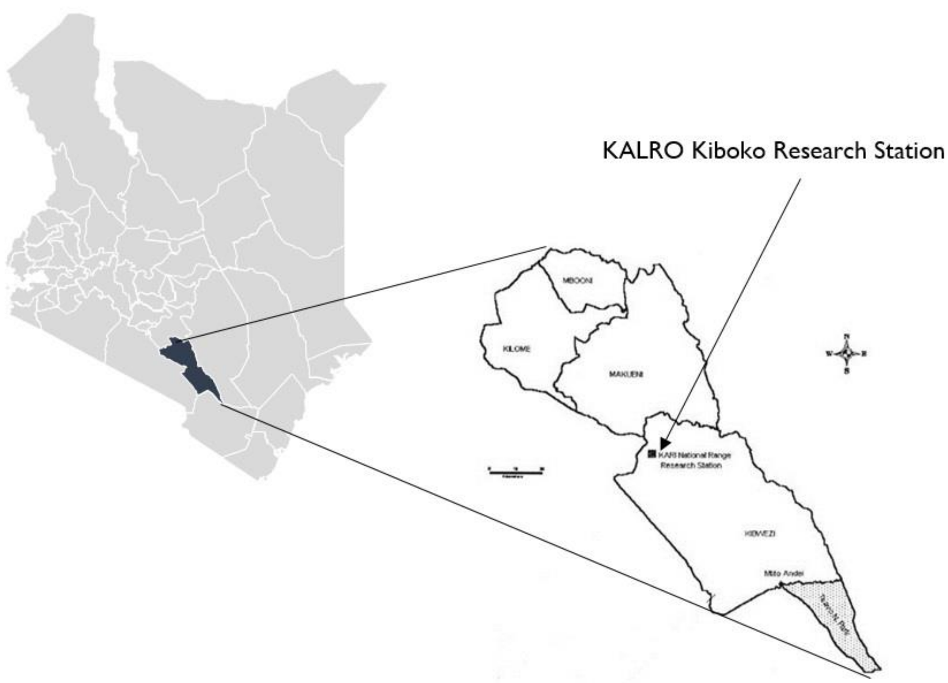

Figure 2. Map of Kenya showing Makueni County and the location of the study site. (Modified from Lubajo and Karuku, 2022)

Experimental design, planting and crop management

A plot measuring 54 m by 18 m was ploughed by use of a disk plough to a depth of 30 cm and then harrowed to a fine tilth on a relatively flat land in October 2019. The experimental design was a randomized complete block design (RCBD) involving four (4) grass ecotypes: *Pennisetum ciliare* KLF, *Pennisetum ciliare* MGD, *Megathyrsus maximus* KLF and *Megathyrsus* *maximus* ISY replicated 3 times. Plots measuring 10.5 m^2 were demarcated with a plot-to-plot distance of 1 meter and a spacing of 2 m between blocks. The selection of the grass ecotypes used in the study was based on an earlier preliminary evaluation by Kirwa (2019), which showed superior attributes for grasses used in rangeland restoration and grazing. This was mainly for *Pennisetum ciliare* . No previous work had been done on the *M. maximus* ecotypes. Prior to ploughing soil samples were taken randomly from the experimental field and a composite soil sample taken for laboratory analysis of chemical properties.

The source of the grasses was different sites in the southern rangelands of Kenya where an expedition was earlier carried out to collect gerplasm for variety development. Vegetative root splits of the grass ecotypes were uprooted from the KALRO Kiboko farm where collections of different grasses are maintained, *ex-situ* by seasonal mowing and weed management. These were then transplanted directly to the prepared plots by hand in November 2019. Each vegetative split had at least 2-5 daughter tillers with developed roots and precautions were taken to ensure they were of similar size depending on the ecotype. The grasses were planted in shallow holes of 10 cm deep with a plant-to-plant distance of 50 cm and a row-to-row distance of 50 cm. At planting time, the grasses received 50 kg ha^{-1} of N. The grasses were maintained under rain-fed conditions as is the case with most crop production in semi-arid Kenya. Regular mowing of the plots at a stubble height of 10 cm was done at the end of each season by a hand scythe, and clipped materials were removed from the plots. Weeding was done manually by removing undesirable plants over the four years whenever they emerged.

Data collection

Collection of weather data

Weather data was collected from a meteorological station located 500 meters from the experimental plots within the station.

Estimation of ground cover

Ground cover by the planted grass ecotypes was visually estimated by placing a 1 m^2 quadrat horizontally in the middle of the plot and observations made vertically from above, at the peak of the wet and dry seasons for 4 years (2020-2023). Wet season data was collected in January, which corresponds to the peak of the reliable short rains season. Dry season data was collected in August which is the peak of the dry season in the study site. Any plant materials, including the grasses, live and dead leaves that protect the soil surface or potentially prevent raindrops from hitting the ground directly (McIvor and Gardener, 1995) were recorded in terms of cover percentage. To minimize bias, 3 people made independent observations and the mean of the values presented were taken as the cover percentage of the respective plot.

Determination of soil physical properties and chemical properties

Soil samples were collected in October 2023, 4 years since establishment of the grasses for determination of physical and chemical properties. Undisturbed core samples were collected at a depth of 30 cm below the soil surface, by use of a 98.12 cm^3 metallic rings at the centre of each plot, in between two plants. This was done at two depths, within 0-15 cm and 15-30 cm. These were then used to determine bulk density and soil water content. Bulk density was determined through the technique described by Blake and Hartge, (1986). Soil water content was gravimetrically determined by standard laboratory procedures described by Hinga *et al.* (1980).

Soil samples for the determination of chemical properties were taken within each plot using a soil augur (5.5 cm diameter, 15 cm length) at two depths i.e. 0-15 cm and 15-30 cm. The soil samples were placed in separate sample zip lock bags, sealed and taken to the soil laboratory at the National Agricultural Research Laboratories (NARL), Nairobi. At the laboratory, the air-dried soil samples were cleaned of inorganic materials and roots and then analyzed for chemical properties. The main chemical properties determined included soil pH, total organic carbon (TOC), Total Nitrogen (TN), Phosphorus (P), Potassium (K), Calcium (Ca) and Magnesium (Mg). Micronutrients - Manganese (Mn, Copper (Cu), Zinc (Zn), Iron (Fe) and sodium (Na) were also determined.

Total nitrogen was determined by the micro-Kjehdal method (Bremner, 1996) and available P by the Mehlich 1 method (Mehlich, 1953). Exchangeable cations (Ca, K and Mg) were extracted with 1M NH_4OAc; Ca and Mg contents were then determined in the leachate by atomic absorption spectroscopy (AAS) and K by flame photometry. Organic carbon (OC) was determined using the wet oxidation method (Nelson and Sommers, 1996) and organic matter was calculated by multiplying the % OC by 1.724. Soil pH-H_2O was determined with a pH meter (with glass electrodes) at a 1:25 soil to water(salt)ratio, while electrical conductivity was measured at 1:2.5 (soil to water ratio) extract using a conductivity meter. Micronutrients (manganese (Mn), copper (Cu), iron (Fe), zinc (Zn) and sodium (Na) were also determined through atomic absorption spectroscopy.

Data analysis

The effects of grass ecotype and year on cover were analyzed by two-way Analysis of variance. Effects of grass ecotype and soil depth on soil physical and chemical properties at the end of the experiment were analyzed by a two-way analysis of variance (ANOVA) using the General Linear Model (GLM) in Genstat software version 23. Treatment effects were considered significant at $p \leq 0.05$, and Tukey tests were done to separate the means whenever significant differences were detected. For changes in soil chemical properties, a simple *t*-test was done for comparison of results obtained prior to establishment and four years later. Furthermore, Pearson correlation analysis was then done to determine the relationships between the different soil attributes under the grass ecotypes.

RESULTS

Effects of the grass ecotypes on ground cover

The ground cover varied among the grass ecotypes and over the different years with significant differences noted among grass ecotypes ($p < 0.001$) and year ($p < 0.001$) (Figure 3). The interaction of grass ecotype and year was also highly significant ($p < 0.001$). The overall mean cover was 69.71 % with the highest cover observed in *P. ciliare* KLF (83.72 %) in 2021. The lowest cover was found in *M. maximus* ISY in 2023. Averaged across years, *P. ciliare* KLF had the highest cover at (76.39 %).

Soil physical properties under four grass ecotypes in semi-arid Kenya

Bulk density and soil water content

Bulk density (BD) did not vary significantly among the grass ecotypes ($p = 0.173$) with values of between 1.25 -1.50 g/cm^3 obtained within the top 30 cm of soil (Table 1). The mean BD for the upper horizon was 1.37 g/cm^3 while the lower horizon had a mean value of 1.48 g/cm^3. As for soil water content, values of between 70-82 % were recorded within the soils under the grass ecotypes, with the higher values attained within the top soil layer of 0-15 cm.

Soil chemical properties under four rangeland grass ecotypes in semi-arid Kenya

pH and macronutrients

Changes in soil attributes between the time of establishment and after 4 years were observed in select soil salient properties in the study. pH values of the soil among the grass ecotypes at different soil depths ranged between 7.1-7.9, though did not vary significantly, with the top 15 cm of soil having a higher pH than the 15-30 cm layer. An overall marginal decrease (-2 %) was observed within the top 30 cm between the time of establishment and after 4 years. The TOC varied significantly among the grass ecotypes with values ranging between 1.55 and 2.76 % obtained at the end of the experiment. Compared to the initial status of TOC, changes were apparent at both depths with an increase of 95 % and 128 % at the 0-15 and 15-30 cm depths, respectively. The TN in the soil of the grass ecotypes did not vary significantly ($p = 0.528$), with values ranging between 0.15 and 0.50% realized. For phosphorus (P) content, differences in available soil P among the grass ecotypes were statistically significant ($p < 0.001$). Values ranging between 12 and 30 ppm were observed. Similar observations of significance among the grass ecotypes were recorded for K content in the *P. ciliare* MGD plots. Ca and Mg content in the soils did not vary among the grass ecotypes (Table 2).

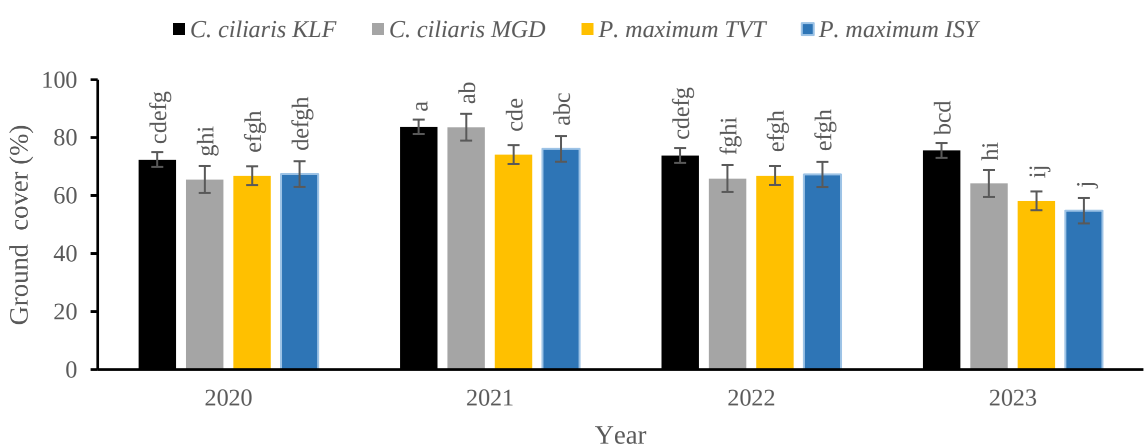

Figure 3. Effects of grass ecotype on percent ground cover averaged per year during the study period. Different lower case letter denote significant differences (Tukey α = 0.05).

Table 1. Bulk density and soil moisture content determined under the 4 grass ecotypes site in the top 30 cm at two depths at the end of the study period

Treatments		Soil property	
Grass ecotype	Soil depth (cm)	Bulk density (g/cm^3)	Moisture content (%)
P. ciliare KLF	0-15	1.25 b	81.63 a
	15-30	1.45 ab	76.28 ab
P. ciliare MGD	0-15	1.44 ab	81.26 a
	15-30	1.48 a	73.62 ab
M. maximus TVT	0-15	1.37 ab	81.59 a
	15-30	1.50 a	70.50 b
M. maximus ISY	0-15	1.41 ab	81.36 a
	15-30	1.49 a	78.13 ab
LSD		0.132	5.072
CV (%)		5.4	3.8
P-value		0.336	0.158

LSD: Least significant difference; CV: Coefficient of variation. *Means with a different lowercase letter(s) within the same column denote significant differences (*Tukey α = 0.05).

Table 2. Influence of grass ecotype and soil depth on soil chemical properties after 4 years of crop management.

Factors/treatments		Soil chemical properties						
Grass ecotype	Soil depth (cm)	Soil pH	Total Organic Carbon (%)	Total Nitrogen (%)	Phosphorus (ppm)	Potassium (Meq %)	Calcium (Meq %)	Magnesium (meq %)
Before experiment								
	0-15	7.66	1.1	0.12	23	0.68	2.2	1.82
	15-30	7.71	0.76	0.09	13	0.66	2.2	2.21
After experiment								
P. ciliare KLF	0-15	7.54 abc	2.45 ab	0.25	18.67 ab	0.72 b	4.00 ab	3.05
	15-30	7.85 ab	1.74 bc	0.17	16.80 ab	0.83 b	4.33 ab	3.06
P. ciliare MGD	0-15	7.12 c	1.68 c	0.17	12.60 b	1.70 a	3.00 b	3.64
	15-30	7.51 abc	1.55 c	0.16	30.33 a	0.73 b	3.70 ab	3.13
M. maximus TVT	0-15	7.39 bc	1.69 c	0.50	28.47 a	0.75 b	4.40 ab	3.01
	15-30	7.91 a	1.62 c	0.16	17.73 ab	0.70 b	4.08 ab	3.06
M. maximus ISY	0-15	7.30 c	2.76 a	0.24	28.10 a	0.81 b	5.33 a	3.09
	15-30	7.53 abc	1.90 bc	0.23	25.20 ab	0.62 b	2.68 ab	3.08
LSD		0.286	0.451	0.388	8.274	0.378	1.358	0.621
CV (%)		2.2	13.4	94.1	21.2	15.6	19.4	11.3
P-value		0.467	0.041	0.519	< 0.001	< 0.001	0.032	0.505

LSD: Least significant difference; CV: Coefficient of variation; Meq: Milliequivalents.
Different small letter(s) after the number within the same column denote significant differences at p $\leq$ 0.05.
CV – Coefficient of variation

Micronutrients

After 4 years, the micronutrient content of the soils within the experimental plots was affected with an increase observed in copper, iron and zinc contents. However, a decline was recorded in manganese and sodium. Differences among treatments were significant for only Iron (p = 0.004). For the other micronutrients (Mn, Cu, Zn and Na), the effects were not significant in this study (Table 3).

Relationship among soil properties under grass ecotypes in semi-arid Kenya

Varied relationships were observed among the different soil properties in the study (Table 4). Significant correlations were observed only between TOC and moisture content (p = 0.031), Ca (p = 0.036) and Fe (p = 0.002). The other significant correlation was between K and Mg (p = 0.014). Significant negative correlations were also observed between pH and moisture content (p = 0.029), K (p = 0.034), Mg (p = 0.022), Fe (p = 0.024) and Zn (p = 0.009).

Table 3. Effect of grass ecotype and depth on micronutrient content of the soil.

Factors/treatment		Micronutrients				
Grass ecotype	Soil depth (cm)	Manganese (meq)	Copper (ppm)	Iron (ppm)	Zinc (ppm)	Sodium (meq)
Before experiment						
	0-15	0.33	2.0	13.7	4.33	0.52
	15-30	0.33	2.57	10.0	0.96	0.70
After experiment						
P. ciliare KLF	0-15	0.24	3.88 ab	23.24 b	3.84	0.29
	15-30	0.24	4.24 a	25.55 b	3.17	0.33
P. ciliare MGD	0-15	0.25	3.84 ab	28.79 b	5.52	0.26
	15-30	0.24	4.02 ab	33.73 a	5.22	0.22
M. maximus TVT	0-15	0.24	3.51 ab	17.22 b	5.22	0.31
	15-30	0.19	3.21 b	16.75 b	2.72	0.31
M. maximus ISY	0-15	0.21	3.5 ab	42.09 a	5.14	0.37
	15-30	0.20	3.65 ab	22.78 b	3.25	0.29
LSD		0.08	0.61	7.78	2.354	0.211
CV (%)		20	9.3	18.3	31.5	40.6
P-value		0.765	0.422	0.004	0.477	0.828

LSD: Least significant difference; CV: Coefficient of variation. *Different small letter(s) after the number within the same column denote significant differences at p* ≤ 0.05.

DISCUSSION

Weather conditions during the study period

Precipitation data from the study site shows high variability in rainfall within and among years, a common phenomenon and characteristic in semi-arid Kenya (Mnene, 2006). The mean annual rainfall for the three years (2020, 2021, 2023) was 789.85 mm which was higher than the long-term mean of 534 mm reported by Ndathi (2012) and the value of 575 mm reported by Kirwa (2019) for the same study site. For this study, 2019/20 was the wettest period a situation also reported by Wainwright *et al.* (2021). The rains peak in November and in March for the October–January and March–May growing seasons followed by a long dry period. These precipitation episodes heavily drive primary production patterns within the region and arid and semi-arid regions at large. This variability in precipitation patterns has a bearing on ground cover and soil properties. The mean monthly temperature reported was 23.8 ºC.

Effects of grass ecotypes on ground cover

As expected, all the grass ecotypes at the peak of the seasons demonstrated their capacity to cover the ground surface as indicated by the over 50 % values obtained. This was mainly attributed to the high aerial leaf production and higher canopy diameter of the grasses used in the study, especially at the peak of the seasons when measurements were taken. The high values found in the study could be explained by the adaptability of the grasses to the environmental conditions of the region (Mganga *et al.*, 2019), favorable climatic conditions and enhanced soil moisture which resulted in continued growth over the years. Other than seasonal harvest, the ecotypes did not experience any other disturbances. The probable effect of litterfall on the ground surface as a result of leaf senescence also contributed to the high values. The overall high cover percentage could also indicate the cumulative effects of herbage on ground cover over time due to natural processes in vegetation, results supported by other grazing management studies by Sanjari *et al.* (2016).

The observation of high ground cover also indicates the preference of these grass species for rangelands rehabilitation in Kenya. *Megathyrsus maximus* has widely been used in stabilizing terraces that control soil erosion in sloppy lands in semi-arid eastern Kenya as well as feed for livestock (Kinama *et al.,* 2007). On the other hand, *P. ciliare* is also a widely used species in combating desertification in semi-arid Kenya (Mganga *et al*., 2013), and the success of these initiatives is mainly manifested in increased ground cover by introduced grass species (Mganga, 2010a). Most perennial grasses establish themselves and are capable of colonizing areas where they are introduced enhancing ground cover (Mnene, 2006). An enhanced grass cover on the land reduces the effects of rain by dissipating the kinetic energy of raindrops on the soil surface (Zuazo and Pleguezuielo, 2008) and channelling more water to the root base into the rhizosphere (Mganga *et al*., 2013). Grass cover also reduces the erodibility of the soil surface and consequently improves other soil hydrological responses (Mganga *et al*., 2010b). In this study, *P. ciliare* KLF due to its rhizomatous and stoloniferous

Table 4. Correlation matrix among soil properties under 4 grass ecotypes in semi-arid Kenya.

	BD	MC	PH	TN	TOC	P	K	Ca	Mg	Mn	Cu	Fe	Zn	Na
BD	-													
MC	-0.529**	-												
PH	0.205	-0.446*	-											
TN	-0.357	0.235	-0.178	-										
TOC	-0.444*	.441*	-0.231	0.158	-									
P	0.093	0.019	-0.070	0.165	0.154	-								
K	0.014	0.297	-0.435*	-0.118	-0.194	-0.471*	-							
Ca	-0.092	0.122	0.036	0.157	.430*	0.171	-0.388	-						
Mg	0.027	0.174	-0.464*	-0.116	-0.045	-0.310	0.497*	-0.219	-					
Mn	-0.385	0.325	-0.143	0.076	-0.090	-0.134	0.245	0.070	0.050	-				
Cu	-0.122	0.173	0.040	-0.369	-0.201	-0.107	0.109	-0.034	0.078	0.353	-			
Fe	-0.129	0.314	-0.458*	-0.089	0.601**	0.019	0.149	0.130	0.340	-0.140	-0.026	-		
Zn	0.128	0.246	-0.522**	0.069	0.108	0.139	0.375	-0.040	0.186	-0.017	-0.139	0.229	-	
Na	-0.065	0.222	0.138	0.391	0.153	-0.191	-0.122	0.281	-0.082	-0.193	-0.188	0.219	0.139	-

***Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed).*
BD- Bulk Density; MC- Moisture Content; TN – Total Nitrogen; TOC – Total Organic Carbon; P – Phosphorus; K – Potassium; Ca – Calcium; Mg – Magnesium; Mn – Manganese; Cu – Copper; Fe – Iron; zn – Zinc; Na – Sodium.

growth habit, exhibited a higher ground cover compared to the other grass ecotypes which were bunch grasses and can be a favorable species for soil erosion control.

Over the 4-year period, cover was highest during the 2nd year of crop establishment (2021) and lowest in the 4th year. Generally, in range grasses establishment and reseeding, the first year or season can be regarded as the year of establishment and it is not anticipated to have much ground cover. Under optimal or favorable conditions, the productivity of pastures increases and hence parameters such as cover are likely to increase (Mnene, 2006) as found in this study during the second year. The grasses established well as a result of the high precipitation received, though unusually high in the 2019-2020 period (Nicholson *et al*., 2022) favoring their growth and development. Adequate soil moisture has a positive effect on rangeland grasses (Koech, 2015)

Effects of grass ecotypes on soil physical properties

Bulk density and soil moisture

The bulk density did not differ significantly among the grass ecotypes (p = 0.173). Bulk density is normally influenced by various grass management factors (Murphy *et al,* 2004) including the presence of crop cover. As expected, bulk density was higher with increasing soil depth across treatments. Deeper soil layers normally contain less organic matter, pore spaces and are carry the weight of the soil above, hence a higher bulk density (Athira *et al.*, 2019). Deeper layers also have more clay content hence fine pores which tend to compact the soil (Mbayaki and Karuku, 2022).

The soils under the grasses showed a higher moisture content, but this did not vary among the different ecotypes or depth. Perennial grasses, especially those with good ground cover prevent run-off allowing the water to infiltrate the soil. It should be noted that it had rained earlier in the week, a few days before the sampling, though not intense hence the high values obtained especially in the top soil layer. It is also probable that the low bulk density in the top soil, high root volumes that greatly influence soil structure resulted in higher infiltration in the top soil layer (Yu *et al.,* 2015). The high plant cover as earlier shown in this study (Figure 2), and litter accumulation on the soil surface could have contributed to reduced soil temperature and thus less evaporative losses and enhanced infiltration. The use of grass cover crops in degraded environments has been identified as a key strategy for improving some soil hydrological properties including moisture content (Mganga *et al.,* 2010).

Effects of grass ecotype on soil chemical properties

Soil pH

Differences among the soil pH values (7.33 to 7.66) were not significant among the grass ecotypes within the top 15 cm of soil at the time of sampling. This is in line with a similar 3-year study by Adjolohoun *et al.* (2013) involving *Megathyrsus maximus* ecotypes who also reported no variation in soil pH. However, the pH range of 7.1 - 7.9 indicates that the soils under the grass ecotypes were slightly alkaline which can have implications on the acquisition of some nutrients particularly the micronutrients, decomposition and other plant-soil feedback processes (Barrow and Hartemink, 2023).

Total Organic Carbon and Total Nitrogen

An increase in total soil organic carbon (TOC) was observed between 2019 and the time of sampling in 2023, four years after establishment of the grasses. The overall mean increase in organic carbon translated to approximately 52 %. This is attributed to the addition of organic matter in the soil from plant materials over time and subsequent decomposition. It is possible that older leaves in the form leaf senescence and other decomposable plant residues on the ground surface over time contributed to the addition of organic matter into the soil, observations also reported by Sanaullah *et al.* (2010). This corresponds to results reported by Hassan *et al.* (2024) who reported marginal changes in soil C and N in a tall 3-year study in a Chinese grassland, even though the changes were not significant. Root biomass production and decomposition has also been cited as a factor contributing to increased soil organic carbon and has been reported to contribute to an increase in SOC mainly through rhizodeposition (Yang *et al.*, 2023).

Differences among grass ecotypes were significant ($p < 0.001$), with plots with *M. maximus* ISY having the highest soil organic carbon compared to the rest of the grasses. This ecotype was mostly observed to lodge at later stages of plant development hence the possibility that most of the plant material would eventually fall to the ground surface. The grasses varied morphologically and genetically, thus the likely difference in OC composition in plant parts. Nevertheless, values determined for soil organic carbon were still low as per laboratory results. One possible explanation is that the experimental site was under annual crop production for a long time before the establishment of the grasses. Annual cropping systems have been observed to significantly reduce top soil organic carbon over longer periods (Shang *et al.*, 2024). Additionally, the evaluation period of 4 years, was probably too short for any large changes in SOC to be realized

The overall mean percent increase in TOC with an increase in depth was even higher (133 %) at the 15-30 cm depth compared to the top 0-15 cm depth (95 %). Increased carbon inputs into surface soils over time can in some cases lead to higher amounts of soil organic carbon in deeper horizons (Hicks *et al.*, 2023), where 70 % of soil organic carbon stocks are found. In cultivated forage grasses, mowing has the potential to increase organic matter decomposition due to addition of biomass but at the same time contrarily decrease organic matter due to herbage removal (Mayel *et al.*, 2021). The reduction in organic content with depth as found in this study has also been observed under grazing treatments in semi-arid Kenya, reflecting the effects of removal of plant cover on soil organic content (Kamiri *et al.*, 2022). Organic matter additions or removals may likely depend on other factors such as rainfall, temperature, frequency of mowing, machinery involved in mowing or clipping and grazing among others.

Plants require nitrogen for growth and development and it is an essential nutrient in plant nutrition. In grasslands, the sources of nitrogen are mainly organic matter from plants through decomposition, mineralization, remobilization, direct fertilizer inputs, nitrogen-fixing plants, atmospheric deposition and animal excreta (Burke *et al.*, 2002; Carbonelli *et al.*, 2021). Nitrogen is also lost from the soil through leaching, denitrification, volatilization and uptake by plants (Ghosh *et al.*, 2017). In this study, an increase in Nitrogen was realized in the soil from the initial 0.12 and 0.09 to an overall mean of 0.29 and 0.19 within the top 0-15 cm and 15-30 cm respectively, reflecting a more than doubling in this case. These values are however still low for these soils, which is a common occurrence with soils of semi-arid grassland ecosystems due to their textural nature and this can have negative implications on productivity. These low values have also been reported in enclosure-managed systems in semi-arid where indigenous grasses are used (Mureithi *et al.*, 2014a). Since little OM was left in the farms due to mowing and removing mowed material, it is anticipated that the amount of N would also be low. Organic matter has been cited as the main cause of N variability in common Kenyan soils (Karuku and Mochoge, 2018). Over the growing seasons, losses of N are apparent and a balance is required mainly through N additions to maintain adequate quantities for increased productivity of pastures. No fertilizer amendments to increase soil N were incorporated over the study period as reflected in obtained values after 4 years. In pastures, management practices such as grazing and mowing clearly affect soil nitrogen content in the soils. Wang *et al.* (2022), in a study on some temperate grasses, found mowing and grazing to significantly affect N concentration in plant tissues and eventually the availability in the soil. Some suggested interventions to increase soil N include the use of animal manure in pasture systems (Washaya and Washaya, 2023), especially in resource-poor sub-Saharan Africa where inorganic fertilizers are beyond the reach of a majority (Raimi *et al.*, 2017).

Phosphorus, Potassium, Calcium and Magnesium

In the tropics, phosphorus is a major limiting nutrient in soils (Sattarri *et al.*, 2016). It is an important element involved in energy generation, photosynthesis, seed formation, germination, respiration among many other roles (Muindi, 2019). Potassium, Calcium and Magnesium are also critical for their different roles in plant growth and development. In this study, there was an overall slight increase in P content within the whole rooting zone (30 cm) from 18 ppm to 21 ppm. However, there was a decrease in the top 15 cm indicating a potential phosphorus depletion under these grasses within this horizon. This depletion can be correlated to the seasonal removal or harvest of plant biomass (Boitt *et al.*, 2018). Differences between the grasses under study were significant (p = 0.038) though variability with depth was insignificant (p = 0.776). Increases in the amount of K (25 %), Ca (80 %) and Mg (56 %) were also observed in the soils under the grass ecotypes after 4 years. Differences among grass ecotypes were significant (p <0.05) for K but not for Mg and Ca content. Adjolohoun *et al.* (2013) reported similar results in a West African savannah where some *Megathyrsus maximus* ecotypes significantly removed nutrients such as P and K from the soil more efficiently than others. It is quite evident that these grass ecotypes influenced the concentration of these elements in the soil mainly through the deposition of organic matter in the soil.

Manganese, Copper, Iron, Zinc and Sodium

Micronutrients in plants, though required in small quantities, play strategic roles in the growth and development of plants. Few studies seem to report on the micronutrient aspects in forage systems in drylands. Attention has been given to macronutrients and their concentration in vegetative parts. Different factors affect micronutrient availability, uptake and distribution in plants and soils. Some of these include plant genotype, moisture supply, pH and temperature among others. Generally, the soil in this study site had low concentrations of micronutrients mainly attributable to the high soil pH. As earlier observed, soil pH in this study was high (mean of 7.6 before the study and 7.3 at the time of sampling). Soil pH predominantly determines availability of micronutrients, with cations Cu, Mn, Fe and Zn being less available at high pH (Rengel, 2015). After the 4 years, the concentration of Cu, Fe and Zn increased, while a decrease in Mn and Na was observed between the two sampling periods. No significant differences were observed in the soils under the different grass ecotypes. It is worth noting that the concentrations of most of these micronutrients are adequate to support plant growth and development. However, continuous repeated harvests are likely to result in Na and Mn depletion.

Relationship among soil properties

In grassland soils, there are relationships among soil properties that heavily influence crop development, performance and productivity. In this study, significant correlations were observed among some soil properties. For instance, total organic carbon positively correlated with soil moisture content. It is expected that soils with high organic matter content will definitely have a higher moisture-holding capacity. Potassium and magnesium were also positively correlated. In plants, there are synergistic effects between the two elements that drive several physiological processes such as photosynthesis (Xie *et al.,* 2021). The absence of one will therefore have a possible negative effect on the other. Other significant positive correlations observed were between iron and soil carbon. Generally, iron plays a key role in stabilizing soil organic carbon in soil (Song *et al.*, 2022) hence, its availability is key to carbon storage aspects. Some negative correlations were also observed. These include bulk density and organic carbon as well as moisture content. It is a widely held assertion that soils with a high organic carbon content have more pore spaces hence the bulk density is likely to be low. As soils become more compacted, bulk density increases, and consequently organic carbon and nitrogen and even availability of some micronutrients such as Potassium may reduce. Such relationships have also been observed by Singh *et al.* (2020) in different Indian soils.

One notable significant negative relationship was observed between pH and micronutrients. Soil pH has been described as a master variable influencing nutrient availability in soils (Rengel, 2015). At high pH as was the case with the soils in this study, micronutrients are likely to be unavailable to the plants (Dhaliwal *et al.*, 2021). Other correlations observed in the study include the positive correlation of C and N has also been reported by (Mureithi *et al.*, 2014b) in in semi-arid northwestern Kenya under pasture enclosure systems where native rangeland grasses dominate.

CONCLUSIONS AND RECOMMENDATIONS

It is evident that soil properties were affected by the planting of the grasses albeit with no significant differences among grass ecotypes used in the study. In particular, there was an improvement in the soil organic contents and total nitrogen of the soils, 4 years after planting of the grasses. The restoration of degraded rangeland environments by use of rangeland grasses can go a long way in improving soil properties though it may take a longer period for significant outcomes to be realized. However, it is also apparent that the selection of species or ecotype influences soil properties even though in this study variation among species was not significant for most of the spoil properties investigated.

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Data availability. All data is presented in the present paper.

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