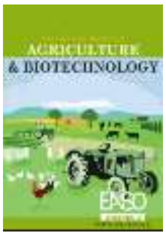

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Effects of Soil Type and Watering Regime on Performance of C4 Grass Ecotypes in A Simulated Semi-Arid Environment in Kenya

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ABSTRACT

Perennial grasses form the bulk of nutrition for livestock in semi-arid grassland ecosystems in addition to the provision of other ecosystem services such as carbon storage. A study was undertaken to evaluate the performance of ecotypes of two common perennial semi-arid grasses (*Panicum maximum* and *Cenchrus ciliaris*) under different soil types and watering regimes. Four indigenous perennial grass ecotypes namely *Panicum maximum* ISY, *Panicum maximum* TVT, *Cenchrus ciliaris* KLF and *Cenchrus ciliaris* MGD grown in three different soil types (ferralsols, fluvisols, and gleysols) and subjected to varied watering regimes (enhanced, depressed and normal) in greenhouse study. Interactively, soil types and watering regimes strongly influenced the morphological attributes among the grass ecotypes. Shoot and root biomass production among ecotypes was significantly ($p < 0.05$) higher in fluvisols subjected to enhanced watering and lower in gleysols under depressed watering. Shoot biomass of the different grass ecotypes was higher in fluvisols by between 7-34 % and 10-35 % compared to those grown in ferralsols and gleysols respectively. Similar trends were observed in rood biomass. Enhanced watering resulted in enhanced growth irrespective of the soil type. Depressed water regimes contributed significantly ($p < 0.05$) to a decline in biomass. Root biomass of the grass ecotypes was higher by between 50-89 % in fluvisols compared to ferralsols and between 41-163 % in gleysols respectively. Root: shoot ratios ranged from 0.41 - 1.73 in in the grass ecotypes with soil types and watering strongly driving biomass allocation patterns. These findings suggest that soil types and watering are key drivers of the productivity of the grass ecotypes, and precipitation variability is likely to have a strong influence on the productivity of semi-arid perennial grasses. Establishing appropriate grasses in suitable soils and with adequate moisture can enhance the success of fodder production and rangeland restoration initiatives for increased resilience.

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INTRODUCTION

Cenchrus ciliaris and *Panicum maximum* are two C4 grasses found in tropical and subtropical dryland ecosystems. They are a key source of livestock feed for resident communities, pastoralists and agro-pastoralists. In addition, their importance in arid and semi-arid Kenya has mainly been highlighted in the rehabilitation of denuded environments (Mganga et al., 2022). The productivity of these grasses is controlled by several factors, including precipitation, soil type, nutrients, management interventions such as grazing and defoliation, species characteristics, and their interactive effects (Rehling et al., 2021; Irving, 2015; Liu et al., 2021).

Soils are the main components of plant anchorage, water and nutrient transport in plants, among other processes (Schoonover & Crim, 2015). Semi-arid environments have different soil types with diverse physical and chemical characteristics that influence whole-plant productivity (Bansal et al., 2014; Mnene, 2006; Silver et al., 2021). They are majorly characterized by low nutrient content, low organic matter and poor water-holding capacity (Thomas et al., 2006). Soils rich in organic matter not only have high soil fertility but also other favorable soil physical properties such as texture and related environmental processes such as water infiltration (Schoonover & Crim, 2015). In contrast, nutrient-deficient soils, lacking essential nutrients and macronutrients negatively affect plant performance and biomass production (Schjoerring et al., 2019). Most Kenyan soils are deficient in nutrients resulting in low crop yields and productivity over the years (Omwakwe et al., 2022).

In water-limited environments, rainfall and moisture availability are key drivers of primary production where precipitation gradients vary from place to place and through seasons (House & Hall, 2001). Optimal rainfall is therefore certain to result in increased biomass and compensate for reduced biomass caused by deficit rainfall in dry seasons (Zhang et al., 2020). Depressed rainfall, on the other hand, leads to soil water stress and an eventual reduction in gross primary and net ecosystem production through the downregulation of photosynthesis and plant senescence (Ritter et al., 2020). Variable precipitation has been predicted under different climate change scenarios in sub-Saharan Africa (Mugo et al., 2020; Tierney et al., 2015), and this is likely to dictate future plant productivity. Even under irrigated pasture production, watering is likely to influence not only the morphometric properties, but also yields at the time of harvest (Koech, 2016), and this may vary with species.

In semi-arid Kenya, the growing of indigenous fodder grasses is emerging as a key strategy to rehabilitate degraded lands, provide feed for livestock and a means to cope with climate variability (Lugusa et al., 2016; Omollo, 2017). However, efforts to promote grass re-establishment and cultivation have faced various challenges including inappropriate species, moisture limitations, poor soils and climate variability (Mganga et al., 2010; Mnene, 2006) among others. Additionally, within these grasses, there exists a wide ecotypic variability and diversity that has not been exploited. The national genebank and research institutions maintain local indigenous range grass accessions in their conservation units and field genebanks, usually selected from wild populations. Research efforts are ongoing to develop varieties from these collections, adapted to different ecological conditions within arid and semi-arid lands (Kirwa, 2019). This will be critical for increasing and sustaining livestock productivity and maintaining healthy ecosystems.

Few studies have examined the performance of perennial grasses in semi-arid Kenyan environments, taking into account varying precipitation regimes and soil types. The morphology and biomass production and allocation patterns in perennial grasses can be key to understanding environmental changes in grassland ecosystems, assessing rangeland functioning and responses to climatic fluctuations, and comparing trends among species (Poorter et al, 2015; Zhang et al., 2020). Therefore, the objective of this study was to determine how soil types and watering regimes interactively affect (i) key phenotypic attributes, (ii) above- and below-ground biomass allocation, and (iii) root-shoot ratios in selected ecotypes of *Cenchrus ciliaris* and *Panicum maximum* grasses.

MATERIALS AND METHODS

Experimental plants – the grass ecotypes

A pot experiment was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) Kiboko Research Station, located 02° 127 S, 37° 437 E 160 Km south East of Nairobi, in semi-arid South Eastern Kenya. Four (4) grass ecotypes (*Cenchrus ciliaris* KLF, *Cenchrus ciliaris* MGD, *Panicum maximum* TVT and *Panicum maximum* ISY) were planted in pots in a naturally-ventilated greenhouse covered with a transparent 200-micron poly sheet from November 2020 to September 202. The grass ecotypes, previously collected in 2014 from different parts of semi-arid Kenya are conserved and maintained ex-situ at KALRO Kiboko farm in semi-arid South Eastern Kenya. These ecotypes were selected based on an earlier evaluation at the Centre which they expressed superior and unique traits such as biomass yield, ground cover, growth habit and persistence. These are some of the key attributes used when selecting grasses for range restoration and fodder production in semi-arid environments (Mganga et al., 2021). The grass tufts or rooted tillers of ecotypes were uprooted by the use of a hand hoe from the field for use in the greenhouse study. The height of the ecotypes was between 20-30 cm for *C. ciliaris* and 20-40 cm for *P. maximum* ecotypes and had between 3-4 attached daughter tillers.

Experimental set-up and grass establishment

The experimental setup was a completely randomized design in a 3 by 3 by 4 full-factorial experiment, with combinations of four grass ecotypes (*C. ciliaris* KLF, *C. ciliaris* MGD, *P. maximum* TVT, *P. maximum* ISY), 3 soil types (ferralsols, fluvisols, and gleysols); 3 simulated rainfall regimes (normal, depressed and enhanced,), replicated 3 times. The total number of pots was therefore 108. The three (3) different soil types were obtained up to a depth of 25 cm at different locations within the 15,000-hectare farm and used as the growth media. The sites were selected based on the descriptions by Wamari et al. (2011) of the soils of the study region. Each of the soils was sieved to remove unwanted materials such as stones, gravel, and other inorganic particles. A composite soil sample of about 500 grams from each soil was taken for determination of soil physiochemical properties by use of appropriate procedures as described in Hinga et al. (1980). This was done at the National Agricultural Research Laboratories (NARL), Nairobi.

The uprooted grasses were grown in 20-litre cylindrical plastic buckets filled with different soil types with a top diameter of 30 cm. There was a 5 cm space at the top to allow for watering. These buckets were perforated with small 5 mm holes at the bottom to permit drainage. The buckets were then placed on a flat ground surface containing volcanic pumice in the greenhouse. Planting was done in November to synchronize with the usual growing period in semi-arid southeastern Kenya. The experiment was carried out for two full crop growth cycles up to seed maturity and harvest.

Watering regimes and crop management

All pots were irrigated to field capacity using a watering can until the grass ecotypes were fully established and acclimatized for 30 days. A standardization cut was then done by clipping the grasses 5 cm from the soil surface before the watering treatments began a week later. Three watering regimes were derived for this study based on the surface area of the pots as determined by Keya (1997) and approximate seasonal rainfall means in southeastern Kenya (Mnene, 2006). These were '*normal*' watering, which represented the approximate seasonal mean rainfall received at the study site. The second was '*depressed*' watering, which involved applying 30 % less water than normal watering. The third regime was '*enhanced*' watering, which involved applying 30 % excess water than the normal rainfall treatment. The calculated total cumulative amount of water applied over the season was therefore 12.75, 17.4 and 22.36 litres for '*depressed*', '*normal*' and '*enhanced*' watering regimes, respectively. The selection of these watering regimes was representative of the potential magnitudes of rainfall variability in semi-arid regions of East Africa (Mugo et al., 2020; Tierney et al., 2015). Watering treatments were spaced and varied based on seasonal trends and approximate storm days to mimic the weather conditions in southeastern Kenya (Mnene, 2006). Weeding was regularly done by hand to remove unwanted plants from pots whenever and if they emerged. Pots were regularly reshuffled weekly in the greenhouse to prevent any shade or insolation effects.

Growth measurements and data collection

Plant height, leaf length, leaf width and tiller numbers were the plant phenotypic traits recorded. Plant height, leaf length and width were measured by a meter rule at the anthesis stage of crop development while tillers were physically counted per plant. Leaf length and width were used to derive the leaf area of the most recently matured leaf, i.e. the second leaf down from the flag leaf, by use of the equation by Kemp, (1960). The grasses were then clipped for shoot and root biomass determination during the 10th week of the experiment. For shoot biomass determination, the grasses were clipped at the soil surface and then any soil and dirt were washed off with running water. For root biomass determination, the removal of roots from the pots followed the floatation principle as described in Mckell et al. (1961), where all the soil containing the roots from each pot was separately emptied into a large 50-litre basin filled with water. Soil aggregates were dislodged from the roots and running water was used to clean the remaining soil material. Fine roots which are less dense than soil, floated on the water surface and were removed manually. The roots were then washed over a set of sieves of 2 mm, 1 mm, and 0.5 mm in the laboratory. This was done by use of running tap water to clean any residual soil material as described in Frasier et al. (2016). No separation was done to differentiate between dead and live roots. Both samples (root and shoots) were first air-dried for 24 hours and then oven-heated at 65 ºC to a constant weight and final weights recorded.

All results are given on a dry matter basis. Root-shoot ratios of the grass ecotypes under the different treatments were then computed by dividing the root biomass yield by the respective shoot biomass harvest.

Data and statistical analysis

All statistical analyses were conducted using the Genstat software Version 23 (VSN International) where data was first checked for normality under the Shapiro-Wilk test. Data transformation was carried out using natural logarithms especially for root-shoot ratios since it did not conform to conditions of normal distribution. Analysis of variance (ANOVA) using the general linear model (GLM) was used to determine the effects of soil type and watering treatments on phenotypic traits, biomass and root-shoot ratios of the grass ecotypes.

Analysis was done separately for each of the ecotypes to understand individual ecotypic responses. The least significant differences (LSD) was used to test for statistical differences among the treatment means at $p < 0.05$ level of significance. When differences were detected, Tukey tests were used to separate them.

RESULTS

Comparison of physiochemical properties of soils for growing the grass ecotypes

The soils used in the pot experiment varied in terms of macronutrient and micronutrient composition as well as pH, texture and particle size distribution (Table 1). The pH did not vary, as all the soils were moderately alkaline. Gleysols had the highest clay content and a lower particle density compared to the other soil types even though the sand content was inferior

Table 1: Chemical and physical properties (organic carbon, macronutrient, micronutrient, pH and particle size) of the soils used in the pot experiment

Soil type	C (%)	N (%)	K (Ppm)	P (Olsen, ppm)	pH	Ca (Meq %)	Mg (Meq %)	Mn (Meq %)	Cu (ppm)	Fe (ppm)	Zn (ppm)	Na (Meq %)	Particle Density (g cm^3)	Sand (%)	Silt (%)	Clay (%)	Texture grade
Fluvisols	3.22	0.32	1.04	42.00	7.75	16.2	3.92	0.01	0.39	trace	0.69	0.24	2.45	70	4	26	SCL
Ferralsols	1.52	0.15	1.04	18.40	7.64	2.8	3.98	0.12	1.60	8.92	7.27	0.22	2.43	70	2	28	SCL
Gleysols	3.28	0.33	1.60	16.00	8.31	20.6	5.33	0.01	0.39	trace	trace	0.46	2.35	40	4	48	C

C – carbon; N – Nitrogen; K –Potassium; P – Phosphorus, Ca – Calcium; Mg – Magnesium; Mn – Manganese; Cu – Copper; Fe – Iron; Zn – Zinc; Na- Sodium;
SCL – Sandy clay loam; C – Clay
ppm – parts per million; Meq – Milliequivalents;

Effects of soil type and watering on phenotypic traits of the grass ecotypes

In this study, plant morphological characteristics were positively responsive to enhanced watering, in the different soils, particularly in more pronounced in fluvisols compared to the other soil types. Leaf length, leaf area and number of tillers were all significantly ($p < 0.05$) affected by soil type and watering regimes. Overall trends showed that fluvisols, under the different watering regimes produced significantly taller plants, with a higher number of tillers and larger leaves compared to those grown in ferralsols and gleysols. Table 2 shows the results of a two-way ANOVA on the effects of soil types and watering regimes on the grass ecotypes.

Table 2: Results (p-values) of Two-way ANOVA on the effects of soil type (S), watering regime (W) and their interaction (S*W) on plant height, leaf length, leaf width, leaf area and the number of tillers in four C4 grass ecotypes (n=3).

			***C. ciliaris* MGD**		***C. ciliaris* KLF**		***P. maximum* ISY**		***P. maximum* TVT**	
Parameter	**Treatment**	***DF***	***F-value***	***P-value***	***F-value***	***P-value***	***F-value***	***P-value***	***F-value***	***P-value***
Plant height	S	2	122.15	< 0.001	121.07	< 0.001	273.06	< 0.001	114.21	< 0.001
	W	2	52.72	< 0.001	63.42	< 0.001	117.06	< 0.001	159.5	< 0.001
	S*W	4	3.38	0.031	5.06	0.007	19.59	< 0.001	23.92	< 0.001
Leaf length	S	2	40.24	< 0.001	49.99	< 0.001	46.22	< 0.001	30.52	< 0.001
	W	2	119.97	< 0.001	49.51	< 0.001	66.34	< 0.001	49.72	< 0.001
	S*W	4	31.47	< 0.001	4.56	0.01	36.01	< 0.001	4.02	0.017
Leaf width	S	2	0.17	0.848	3	0.075	8.23	0.003	3.02	0.074
	W	2	6.17	0.009	1.29	0.301	0.86	0.438	3.7	0.045
	S*W	4	8.17	< 0.001	1.07	0.399	1.14	0.371	1.37	0.282
Leaf area	S	2	15.22	< 0.001	13.18	< 0.001	13.02	< 0.001	35.68	< 0.001
	W	2	58.42	< 0.001	19.44	< 0.001	10.79	< 0.001	49.84	< 0.001
	S*W	4	22.95	< 0.001	2.26	0.103	2.29	0.1	7.95	< 0.001
Number of tillers	S	2	185.41	< 0.001	126.63	< 0.001	206.73	< 0.001	210.04	< 0.001
	W	2	44.45	< 0.001	41.51	< 0.001	83.84	< 0.001	40.96	< 0.001
	S*W	4	4.72	0.009	2.91	0.051	5.46	0.005	2.66	0.066

Effects of soil types and watering regimes on shoot and root biomass

The effects of soil type and watering on shoot biomass of the grass ecotypes were highly significant ($p < 0.001$), with the highest mean yield of 101.93g DM/plant obtained in *P. maximum* ISY. Among the two *C. ciliaris* ecotypes, the MGD ecotype had a higher shoot biomass at 76.30 g DM/plant. Both had been grown in fluvisols and subjected to enhanced watering. The lowest shoot biomass was recorded in the *C. ciliaris* MGD (38.40g DM/plant) grown in gleysols under normal watering. Overall, depressed watering, irrespective of the soil type produced the lowest shoot biomass (Figure 1).

The effects of soil type and watering on root biomass of the grass ecotypes were also highly significant ($p < 0.01$). Values of between 20.87 and 89.60 g DM/plant were obtained in *P. maximum* ecotypes while for *C. ciliaris*, the range was between 39.80 and 116.17 g DM/plant (Figure 2). The highest root biomass was reported in *C. ciliaris* MGD grown in fluvisols under enhanced watering while the lowest in *P. maximum* TVT grown in gleysols under depressed watering. Higher root biomass yields were found in *C. ciliaris* ecotypes compared to *P. maximum* ecotypes

Figure 1: Mean shoot biomass production among four grass ecotypes as influenced by soil type and watering regime. Coloured bars followed by different lowercase letters indicate significant differences at P < 0.05. (n=3)

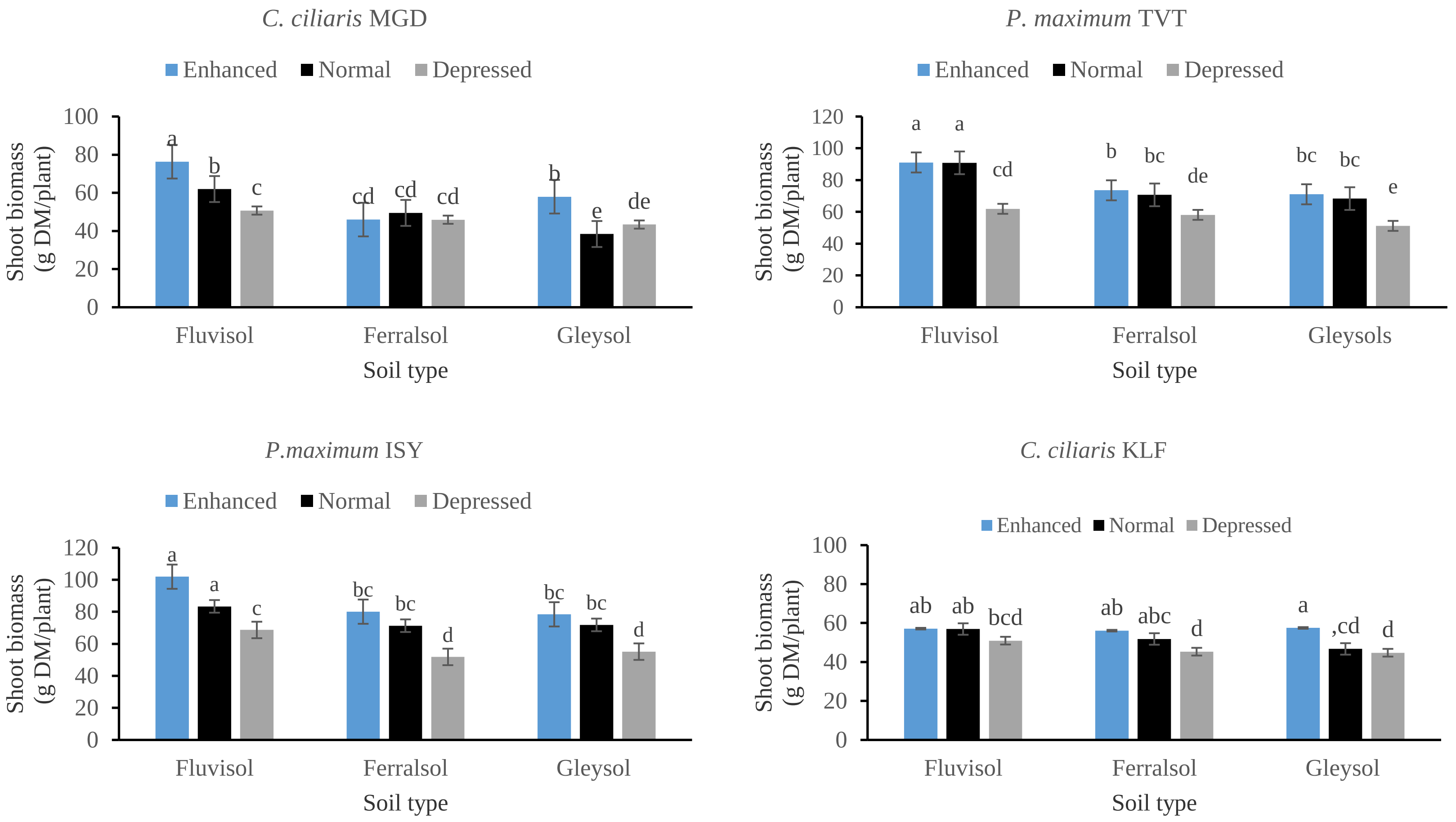
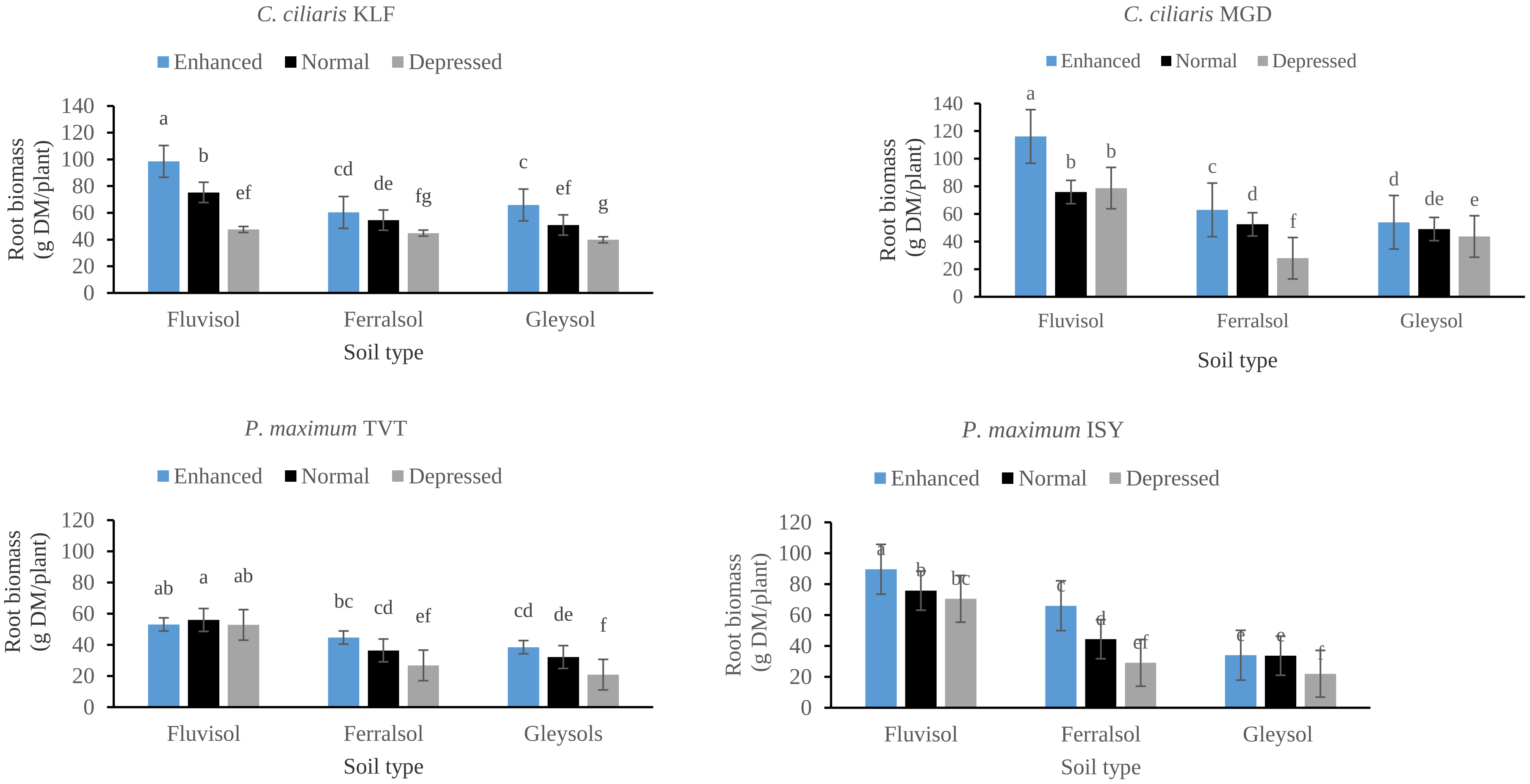


Figure 2: Mean root biomass production among four grass ecotypes as influenced by soil type and watering regime. Coloured bars followed by different lowercase letters indicate significant differences at $p < 0.05$



Effects of soil types and watering on Root-shoot (R: S) ratios

Root shoot ratios differed significantly ($p < 0.001$) in the different soil types and watering regimes (Table 3). Values of between 0.40 and 1.73 were obtained with the highest root-shoot ratio obtained in *C. ciliaris* KLF (1.73) grasses grown in fluvisols under enhanced watering. The lowest root-shoot ratio was found in *P. maximum ISY* ecotypes grown in gleysols under depressed watering at 0.40

Table 3: Mean root-shoot ratios of four grass ecotypes as influenced by soil type and watering regime. Means followed by different lowercase letters within the same column denote significant differences at p < 0.05

Treatments		***Grass ecotype***			
Soil type	**Watering regime**	***C. ciliaris* MGD**	***C. ciliaris* KLF**	***P. maximum* ISY**	***P. maximum* TVT**
Fluvisols	Enhanced	1.52 a	1.73 a	0.88 ab	0.57 bc
	Normal	1.23 bcd	1.32 b	0.91 ab	0.62 b
	Depressed	1.56 a	0.93 cd	0.99 a	0.85 a
Ferralsol	Enhanced	1.37 ab	1.08 cd	0.82 b	0.57 bc
	Normal	1.06 cde	1.05 cd	0.62 c	0.52 bcd
	Depressed	0.61 f	0.99 cd	0.56 cd	0.46 cd
Gleysols	Enhanced	0.93 e	1.15 bc	0.43 e	0.54 bc
	Normal	1.28 bc	1.09 cd	0.47 de	0.47 cd
	Depressed	1.01 de	0.89 d	0.40 e	0.41 d
Grand Mean		1.17	1.14	0.68	0.56
P-value	n	< 0.001	< 0.001	< 0.001	< 0.001
LSD		0.142	0.133	0.076	0.067
CV (%)		7	6.8	6.5	7

DISCUSSION

This study sought to determine the interactive effects of different soil types and watering regimes on morphological traits, biomass allocation in shoots and roots, and root-shoot ratios of selected range grass ecotypes. The results revealed that indeed, soil types and precipitation regimes influence the performance of grasses, even though the effect differed for each grass ecotype.

Comparison of physical and chemical characteristics of the cultivation soil

Soils used in this study were collected from different parts of the ranch with different land use histories and relief. For instance, fluvisols were obtained from near a river bank mostly influenced by siltation and river forces, while gleysols were obtained from a flat area that is commonly grazed. On the other hand, ferralsols were obtained from an area which had been cultivated continuously with annual crops for over 10 years. This difference in land use contributes to variations in soil properties (Mganga et al., 2011).

There was variability in nutrients among the 3 soils. The total organic carbon, nitrogen, potassium and calcium contents were higher for fluvisols and gleysols compared to ferralsols. However, ferralsols contained a higher amount of micronutrients (manganese, copper, iron and zinc) than the other soil types. The ferralsols were collected from an area under long-term annual crop production. Frequent growing of annual crops has been reported to result in a decline in topsoil organic carbon over long periods (Shang et al., 2024). Other than the magnesium content, the sodium concentration was also highest for gleysols compared to the other soil types. The low levels of total organic content in ferralsols and gleysols suggest that the soils had low amounts of organic matter (Mganga et al., 2011). Organic matter in soils influences most of the other soil properties including nitrogen, water-holding capacity, bulk density, and phosphorus among others. Fluvisols had the highest phosphorus content as a result of high pH and organic matter probably a result of retention in sediments (Boers et al., 1998). With a high clay content and lower particle density, gleysols are likely to retain water for longer periods unlike ferralsols and fluvisols (IUSS Working Group WRB, 2015), and hence influence crop performance.

Effects of soil type and watering regime on phenotypic traits of the grass ecotypes

In semi-arid environments, the responses of plants to different types of stimuli are mainly expressed in morphological traits. Soil type and watering visibly influenced the selected morphological parameters in the grass ecotypes. Different soils have different nutrient contents and hence their availability for plant growth. On the other hand, watering, in terms of precipitation or irrigation determines the amount of water available for plant use. Variability in any of these factors and their interactive effects will therefore have a bearing on plant morphological growth and development.

In this study, the effects of soil type on morphological traits were more pronounced in fluvisols which produced plants with higher vigor i.e. taller, bigger leaves and more tillers. This can be explained by the probable influence of soil nutrients in the soils (King et al., 2020). Compared to the other soil types, this soil had higher levels of essential nutrients including organic matter, Ca and P, which are all essential for plant growth. Fluvisols are normally young soils, rich in nutrients due to fluvial deposits (IUSS Working Group WRB, 2015). Enhanced watering, therefore, probably resulted in a higher availability of these nutrients (Eneji et al., 2008) favouring plant growth. Furthermore, the ecotypic differences among the grass ecotypes examined explain the phenotypic differences under the different treatments. The differences in morphology among range grasses in semi-arid environments, these features can be exploited for various purposes. For instance, taller grasses, with larger leaves and tillering capacity like the *P. maximum* ecotypes can be viable alternatives for fodder production due to the positive correlation of these characteristics to biomass yields (Lee et al., 2017). Shorter grasses on the other hand, with profuse tillering such as *C. ciliaris* KLF can also be used for soil conservation purposes due to their capacity to cover larger ground surfaces (Kirwa, 2019).

Effects of soil type and watering regime on shoot and root biomass

The differences in shoot and root biomass in the studied ecotypes were generally brought about by ecotypic differences, nutrients, soil structure and moisture conditions. Shoot biomass yields were highest under fluvisols. These soils generally contain superior nutrient loads, resulting from the nutrient-rich high organic matter. Fluvisols are generally young soils with an abundant concentration of organic matter and nutrients (Rodrigo-Comino et al., 2021), that provide an ideal environment for plant growth. Lower shoot biomass was produced in gleysols and ferralsols due to low fertility compared to the fluvisols. Furthermore, physical characteristics of the soils such as texture may have also influenced shoot biomass production among grass ecotypes. For instance, in gleysols, soil structure probably altered the rooting structure resulting in reduced root surface areas exposed to nutrient acquisition that could promote shoot growth. This may limit root penetration (Magha et al., 2021), leading to low growth rates and subsequent shoot reduction.

The increase in shoot biomass under enhanced watering is an indicator of nutrient uptake under sufficient watering since water is likely to enhance the availability of nutrients for plant uptake as well as other processes. Njarui et al. (2015), in an investigation of indigenous *P. maximum* ecotypes, reported a correlation between rainfall amount and above-ground dry matter production in semi-arid Eastern Kenya, where an increase in rainfall resulted in increased dry matter production and vice versa. This explains the enhanced performance under enhanced watering. Under depressed watering, the plants' capacity to uptake water from the soil is likely limited hence lower shoot biomass. Dry conditions in the soil alter cell metabolism in plants and decrease stomatal conductance, influencing water uptake by roots, and temporarily or permanently affecting crop growth (Mangena, 2017).

In the study, there was a reduction in root biomass in gleysols compared to the other soils. Under watering, these soils are frequently waterlogged for long periods due to poor drainage and hence poor for most plant growth conditions (Magha et al., 2021). Such responses of reduction in root growth and poor performance in gleysols have been reported by Kolodzjiedek, (2019) while examining the effects of soil type on growth of an invasive weed species. However, all the soils had adequate amounts of phosphorus which is a key nutrient in plant growth and development (Muindi, 2019).

Ferralsols and fluvisols normally have a higher sand content as shown in the soil analysis results hence increased porosity. They tend to dry quicker as a result of faster drainage. Roots of plants found in such soils tend to grow deeper in search of water (Fromm, 2019), resulting in increased root growth and, hence root biomass. A higher confinement of roots was observed at the bottom of the pots containing the plants, probably restricted by pot size, an observation also made by Mnene, (2006). Vigorous rooting in fluvisols soils could also indicate a faster plant growth rate of the ecotypes due to the adequacy of nutrients and with a subsequent increase in root biomass.

There was a reduction in root biomass under depressed watering in the grass ecotypes across the different soils. These results are consistent with those obtained by Cheruiyot et al. (2018) in Bracharia grass genotypes under simulated drought conditions in western Kenya. They are also in concurrence with studies in semi-arid Kenya on the same Bracharia grasses by Gichangi et al., (2017) found comparable outcomes. In their study, root biomass yields from different introduced Bracharia ecotypes varied at two sites with differing soil types and rainfall amounts. Limited water supply to plants suppresses root growth and is detrimental to crop development leading to retarded growth as a result of limited uptake of water and nutrients (Irving, 2015).

In general, soil type and watering showed distinctive effects on shoot and root biomass among the grass ecotypes. This signifies the fundamental role of rainfall or moisture availability in dictating the productivity of grasses in semi-arid environments (Izaurralde et al., 2011) as well as nutrients. The diverse responses of the grass ecotypes to different soil types and watering strengthen the notion that the grass ecotypes of the two species studied are well-adapted and can grow in a variety of soils and precipitation gradients. This probably explains their invasive nature in many environments elsewhere (Marshall et al., 2012; Soti & Thomass, 2022). On the other hand, this plasticity could be an advantage and allow the ecotypes to be promoted in semi-arid environments with diverse environmental conditions. The probable effects of moisture limitations were evident and apparent in this case, overriding the effects of even soil type.

Comparing the responses of the grass ecotypes to the different treatments, it’s evident that differences in shoot biomass yields were in some cases not significantly different. This highlights the wide tolerance limits of the ecotypes to varied growing conditions (Belovitch et al., 2023). For instance, under depressed watering, shoot biomass production in *C. ciliaris* ecotypes was still comparable to normal watering conditions demonstrating their adaptability to water limitations. Higher root biomass values were notable under *C. ciliaris* ecotypes compared to *P. maximum* ecotypes with differences observed among the grass ecotypes under the different treatments. The grass species used in this study have extensive root systems (Marshall et al., 2012; Soti and Thomas, 2021). This is attributable to individual plant inherent characteristics in morphology and growth, also highlighting the differences among these grasses in semi-arid environments of Kenya (Kirwa, 2019; Njarui et al., 2015). This intra and interspecies variation is common in grasses.

Effects of soil type and watering on Root-shoot ratio of the grass ecotypes

Root: shoot ratios reflect the allocation of photosynthates as a result of different environmental conditions including waterlogging, nutrients, soil compaction, temperature, salinity, and other biotic and abiotic stresses (Mokany et al., 2006; Qi et al., 2019). Generally, across the grass ecotypes, a higher root-shoot ratio was obtained in fluvisols than in gleysols and ferralsols. This is likely also due to the availability of sufficient growth-favouring conditions such as soil nutrients. Soil texture could also play a role in the growth of roots and shoots (Poeplau & Kätterer, 2017), consequently affecting root: shoot ratios. The high percentage of clay particles in the gleysols probably limited plant growth hence the low values obtained unlike in the other soils which had larger particles. Due to the high clay content, gleysols are prone to waterlogging and prolonged saturation. This likely depletes soil oxygen and causes root tissue death (Poorter, et al., 2012). Additionally, clayey soils such as gleysols often offer poor root penetration for crops. Under conditions of limited soil moisture, these soils compact making root penetration and growth difficult (Magha et al., 2021).

The high root: shoot ratios realized under both enhanced and normal watering regimes in the different soils, compared to depressed watering, highlight the importance of precipitation in plant growth. In the plant environment, water has a significant effect on biomass partitioning (Qi et al., 2019), by influencing other critical physiological processes including nutrient uptake, transpiration, and photosynthesis among many others. The ecotypes used in this study had already adapted to the normal growing conditions of the study region thus normal watering would allow them to perform optimally. Differences in the R: S ratio among the ecotypes under similar watering regimes can be ascribed to phenotypic and genetic differences among the grass ecotypes (Kirwa, 2019). Observed high R: S ratios especially under enhanced and normal watering can be explained by the individualistic behavior of the grass ecotypes investing more in above and below-ground components to compete for resources such as light and soil moisture under these watering regimes. The significant interaction ($p < 0.001$) of soil type and water regime effects on R: S ratio is indicative of how both factors interactively modulate biomass partitioning between shoots and roots in grasses. In natural environments, R: S ratios are likely to vary based on species, biomes, time, locations and precipitation gradients. The mean values obtained are also closely related to those reported by Mokany et al. (2006) and Qi et al. (2019) in their review of root: shoot ratios of tropical savannah grasses. Further investigations should take into account the direct influence of nutrients on growth in grass ecotype growth traits.

Implications for the management of semi-arid ecosystems

With continued degradation and decreasing productivity of semi-arid lands, rangeland restoration initiatives using indigenous range grasses continue to be explored. Continued sedentarization and livestock feed challenges have also seen many farmers and livestock keepers involved in fodder cultivation using locally adapted indigenous grass species including *Cenchrus ciliaris* and *Panicum maximum*. It is necessary to accelerate these initiatives to reverse the degradation and improve access to adequate feed for livestock. The development of appropriate range forage varieties adapted to local conditions through breeding and selection from local accessions can go a long way in fast-tracking these initiatives.

Increased above-ground and below-ground biomass production results in increased protection of the ground surface as well as soil stabilization and higher carbon inputs into the soil. Well-developed root systems in herbaceous species are also advantageous in that they help them resist some biotic stressors such as grazing, as well as an increased capacity to self-propagate (Read and Stokes, 2006). As a result, they are tolerant to grazing disturbance. Grasses with higher root biomass tend to promote soil aggregation through direct organic matter inputs into the soil and root exudates thus stimulating mineralization (Gichangi et al., 2016). Even though ecotypic variability has not been considered previously, this study opens a front on the exploitation of the potential and this variability to develop new varieties based on special attributes. These attributes include the spreading rhizomatous growth habit, drought tolerance and persistence.

In semi-arid regions, enhanced watering has been shown to improve grass productivity in terms of biomass production (Koech et al, 2015), similar to what this study has established. Thus, for increased productivity, fodder enterprises should adopt strategies that optimize water availability for increased biomass production. With limited water in arid and semi-arid regions, approaches such as rainwater harvesting and, the use of micro-catchments, terraces and other soil water conservation structures could be key to enhancing the productivity of native pastures (Mnene, 2006; Mganga et al., 2022). Under a changing climate, it is anticipated that increased precipitation may benefit C4 plants such as *P. maximum* and *C. ciliaris* in terms of biomass yields (Li et al., 2014), hence improving the quantity of feed available. The adoption of irrigated fodder production can also bridge feed deficit gaps in arid and semi-arid lands. Already, this is practiced along seasonal and perennial rivers in many parts of arid and semi-arid Kenya but with a leeway for improvement. With droughts and overgrazing reducing natural pastures in common grazing lands, there is a need to increase fodder cultivation under irrigation rather than relying on rain-fed conditions which may be inadequate to sustain production.

Grasses such as *C. ciliaris* and *P. maximum* have previously demonstrated potential for contributing to carbon sequestration in semi-arid environments. For instance, *P. maximum* with higher AGB yields could potentially contribute to a key role in carbon dioxide capture from the atmosphere. This is due to their large leaves and higher AGB production, a notion reinforced by model simulations by He et al. (2021) for perennial *Miscanthus grasses*, a biomass crop. In our case, *C. ciliaris* could prove pivotal for carbon inputs into the soil due to its high root biomass production if cultivated on a large scale and well-managed (Marshall et al., 2012). In this era of climate change, such grass species are appropriate and should be widely promoted. Already, it has been demonstrated that incorporating pastures such as *P. maximum* in silvopastoral systems has considerably enhanced the carbon sequestration potential of these environments (Montagnini et al., 2013).

CONCLUSIONS AND RECOMMENDATIONS

Overall, this study found that soil types and watering strongly modulate phenotypic traits and biomass partitioning patterns for ecotypes of *C. ciliaris* and *P. maximum* grasses. This has been demonstrated in plant morphological traits such as height, tillering, leaf area and biomass yields that were significantly affected under the different treatments with enhanced watering having a positive effect on such parameters. The studied species showed wide plasticity and capacity to grow in different soil types under varied watering regimes signifying their adaptation. Further field evaluation of the grass ecotypes could provide clear and critical insights into the potential of these species and their ecotypes for fodder production and restoration of degraded environments.

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