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Effects of manuring and grass-legume mixtures on herbaceous vegetation in semi-arid East African rangelands

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Rangelands are essential ecosystems for livestock grazing, wildlife conservation and other uses. However, East African rangelands face multifaceted challenges of land degradation exacerbated by climate change. This study examined the impact of manure and grass-legume mixtures on herbaceous plant species diversity, cover, and biomass production in the Karamoja border region between Kenya and Uganda. Using a randomised complete block design, four treatments, these being grasses (G), grasses with legumes (G+L), grasses with manure (G+M), and grasses with legumes and manure (G+L+M), were applied to the study sites, alongside natural regeneration and open grazing areas. A total of 97 herbaceous species were identified, with 66 species recorded in West Pokot and 54 in Napak. The dominant species were *Bothriochloa insculpta* in West Pokot and *Heteropogon contortus* in Napak. The reseeded grasses *Cenchrus ciliaris* and *Chloris gayana* were more frequent in the West Pokot and Napak sites, respectively, while *Macroptilium atropurpureum* was the most frequently-occurring legume across both sites. Natural regeneration and the G+L treatment exhibited the highest species diversity (12 species) while G+M treatments yielded the highest biomass, attaining 1 458 kg ha^{-1} in West Pokot and 2 299 kg ha^{-1} in Napak. The findings highlight the potential of integrating native grasses, forage legumes and manure to restore degraded rangelands and enhance forage production.

Keywords: biomass production, forage legumes, herbaceous layer, land degradation, manure

Introduction

Rangelands cover approximately 54% of the World's terrestrial surface, primarily in the arid and semi-arid zones (ILRI 2021a). Rangelands support the livelihoods of around 2 billion people, with a variety of uses and management systems (UNCCD 2024). These ecosystems provide essential services such as fodder, food, fibre, water, recreation, and habitat for wildlife (Angerer et al. 2016). In Africa, rangelands constitute up to 43% of the total land area, characterised by low and variable rainfall and high temperatures, which lead to substantial evapotranspiration (Lutta et al. 2020). Such climatic stresses accelerate vegetation loss, reduce soil moisture and heighten vulnerability to rangeland degradation (Mussa et al. 2016). Other causes of degradation include overgrazing, population pressure, bush encroachment, changes in land use systems, and a decline in traditional resource management institutions (Bolo et al. 2019).

Rangeland health plays a crucial role in sustaining biodiversity, both directly and indirectly, as native flora and fauna are intricately adapted to the evolutionary processes that have shaped these ecosystems over time. However, degraded rangelands, often resulting from unsustainable human activities, exhibit reduced biological and economic productivity. Such degradation disrupts key ecological processes, including hydrology, soil stability, and vegetation dynamics (Mussa et al. 2016), which in turn contributes to sparse herbaceous vegetation cover. The reduced cover further intensifies these challenges through high surface run-off during heavy storms leading to flooding and heightened vulnerability to soil erosion (Lutta et al. 2020).

In East Africa, rangelands cover approximately 80% and 44% of Kenya's and Uganda's total land area, respectively (Njoka et al. 2016; Byakagaba et al. 2018). Livestock production is the main economic activity in the rangelands in both countries, providing employment for 90% of the population and contributing over 95% of family income (Engida et al. 2015; Angerer et al. 2016; Njarui et al. 2016; ILRI 2021b; Walie et al. 2022). Besides this, the livestock sector supports 70 to 80% of the national herds, contributing 12% and 3.2% to Kenya's and Uganda's Gross Domestic Product (GDP), respectively (ICPALD 2013; Njoka et al. 2016; Byakagaba et al. 2018; ILRI 2021b). Sustaining livestock production in East African rangelands therefore hinges on restoring degraded rangeland ecosystems to produce adequate and high-quality pasture and fodder (Mureithi 2018). Yet the region regularly faces shortages of both quantity and quality of fodder, particularly during prolonged dry seasons, leading to major livestock losses due to starvation (Abule et al. 2007; Gelayenew et al. 2020; Walie et al. 2022). Pastoral mobility, which was once the main management strategy, is increasingly constrained by land use changes, land degradation and climate change (Bostedt et al. 2023). This highlights the urgent need for effective rangeland restoration interventions to restore degraded rangelands and enhance fodder production.

Several fodder production strategies have been promoted to address land degradation and feed scarcity in the East African rangelands (Omollo et al. 2018; ICPALD 2020; Kimaru et al. 2021). Among these, reseeding of degraded areas with perennial rangeland grasses has been widely promoted as a low-cost and effective method to restore vegetation cover, increase forage biomass and enhance species diversity (Mnene 2006; Mganga 2009; Tebeje et al. 2014; Kirwa 2019). In addition, grass-legume mixtures improve forage quality and quantity and soil fertility while the application of livestock manure enhances the recycling of plant nutrients in the soil, nutrient availability and soil moisture retention (Mut et al. 2010; Walie et al. 2022). Importantly, livestock manure is readily available in pastoral systems, making it a practical and an inexpensive organic fertilisation option. Another common approach is the use of enclosures. Enclosures have been adopted in Kenya and Ethiopia, reducing soil erosion, enhancing water infiltration and promoting natural vegetation regeneration (Makokha et al. 1999; Verdoodt et al. 2009; Nyberg et al. 2015; Mureithi et al. 2016; Kimaru et al. 2021). Despite these interventions, feed shortages and land degradation persist in many rangelands, such as in the Karamoja border region between Kenya and Uganda.

Although evidence exists showing the benefits of reseeding, grass-legume mixtures and manure application, there is limited understanding of their combined effects on both fodder production and ecological parameters in the semi-arid rangelands of East Africa. This study was therefore carried out to determine the effects of manure application, grass reseeding and grass-legume mixtures on biomass production, cover, abundance and diversity of herbaceous plant species in two different semi-arid sites in the cross-border area between Kenya and Uganda. The overall aim was to contribute knowledge to inform rangeland restoration practices in the region. It was hypothesised that the combined application of manure and grass-legume mixtures would increase herbaceous aboveground biomass production, ground cover, species abundance, and diversity, hence supporting the restoration of degraded lands in the region.

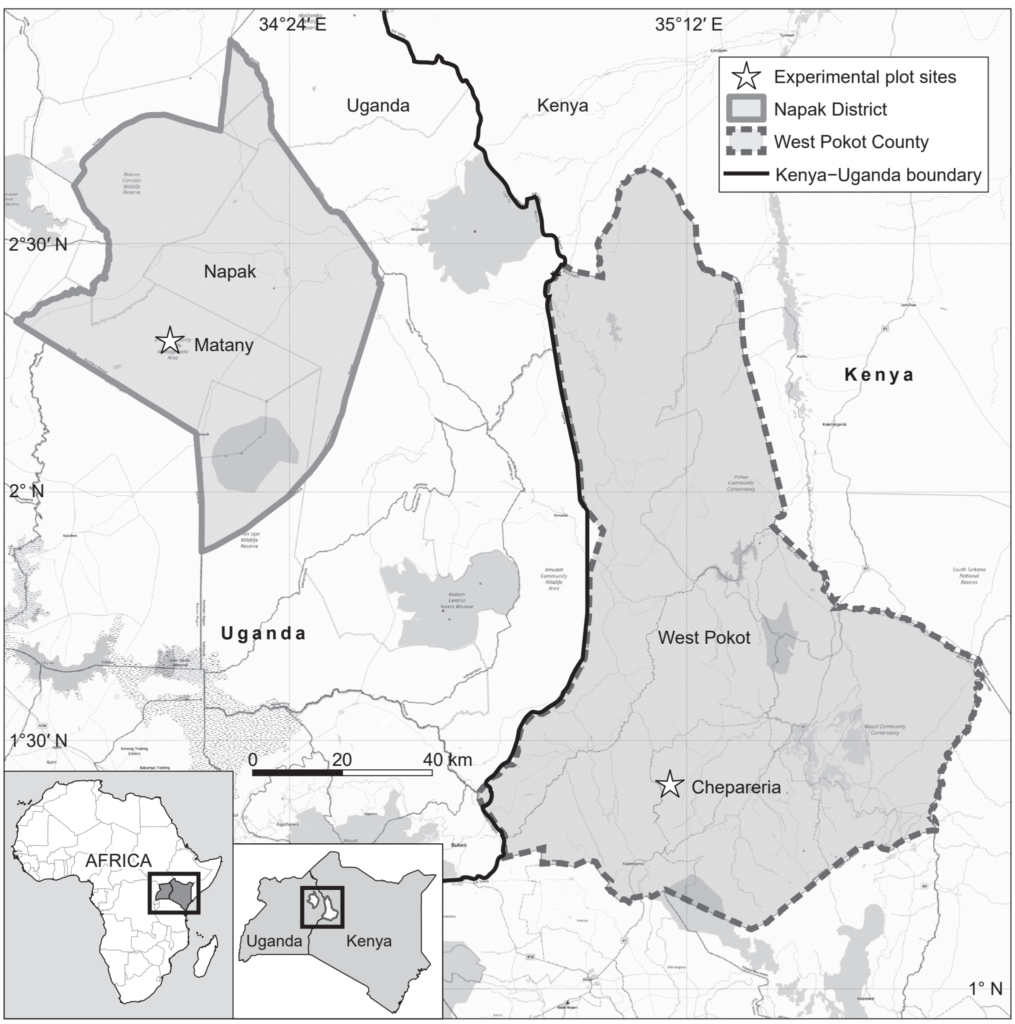

Figure 1: Map of the study sites in the Karamoja border region of Kenya and Uganda

Materials and methods

Study area

The geographical focus of the study was the cross-border region of Kenya and Uganda located within the Karamoja Cluster (IGAD 2021). This cluster comprises at least 13 pastoralist and agro-pastoralist communities that share many cultural and linguistic traits (Catley et al. 2021).

Two field experiments were conducted in two sites, one in Chepareria Ward in West Pokot County, Kenya, and the other one in Matany Sub-County in Napak District, Uganda (Figure 1). Chepareria Ward lies between latitude 1°15´ to 1°55´N and longitude 35°7´ to 35°27´E. The semi-arid area, inhabited by agro-pastoralists, experiences a highly variable and seasonal climate. It receives an average of 600 mm of rainfall which is bimodal with the long rains occurring between March and May and the short rains being experienced from August to November (NDMA 2014). The average annual temperature ranges from 24 to 38°C. The soils in the area originate from metamorphic bedrock rich in ferromagnesian minerals. The soils are predominantly rocky, moderately shallow and friable in the lowlands transitioning to deeper, well drained profiles in the upper areas (Wairore et al. 2015). They range in texture from reddish-brown clays to sandy loams and their fertility ranges from low to moderate. The study area is largely characterised by rangeland enclosures, some of which were established as early as the 1980s as a community-led approach to restore degraded lands. Some enclosures are fully closed off from livestock grazing while others are selectively opened for controlled grazing during specific seasons. The experimental site was subjected to continuous livestock grazing prior to the establishment of the treatments (Makokha et al. 1999; Karmebäck et al. 2015; Nyberg et al. 2015).

Matany Sub County in Napak District is a semi-arid area inhabited by an agropastoralist community, marked by unpredictable rainfall, high temperatures, and savanna grasslands interspersed with sparse woodlands (Mubiru 2010; Egeru et al. 2015). Napak District lies between latitudes 1°53′ N, 3°05′ N and longitudes 33°38′ E, 34°56′ E (UNDP 2014). The topography includes a low-lying plateau, rolling and broad flat plains, and elevations between 1 000 and 1 440 m a.s.l. The soils of the region are derived from Precambrian basement complex. In the plains and valleys, the soils are dominated by dark grey to dark brown calcareous clays noted by their extreme stickiness when wet and aridity shrinkage-forming large deep cracks when dry. In general, the soils are characterised by black cracking cotton clays classified as Vertisols (Nakileza et al. 1999; Egeru et al. 2019; Mureithi et al. 2024). Livestock grazing occurs on native forages across local, landscape, and regional scales, depending on season, pasture availability, and water in the grazing areas (Egeru et al. 2015). The area experiences consistently high temperatures and evapotranspiration, leading to limited surface water availability (Avery 2014). The mean maximum temperatures range from 28 to 33 °C during the dry season (UNDP 2014; Egeru et al. 2019). The hottest months are January and February when the average daily maximum temperature may reach 34 °C (UNDP 2014). Rainfall is highly variable both within and between years, with periodic droughts towards the end of the rainy season, particularly in the months of September, October, and December, characterised by sharp declines in rainfall, thereby shortening the potential vegetation growing period in the region (Mubiru 2010). The annual rainfall is in the range of 300–1 200 mm with a mean annual rainfall of 800 mm. The wet season is from April to August with marked minima in June and marked maxima in May and July (UNDP 2014). The experimental site consisted of patches of indigenous vegetation surviving after extensive livestock grazing and disturbance. The land is open-access for grazing and is frequently subjected to burning (Opige et al. 2023).

Experimental layout and design

At the West Pokot site, the experiment started on 13 May 2022. To avoid grazing, an area of approximately 2 ha was fenced with barbed wire reinforced with *Euphorbia candelabrum* splits as a living fence. To prevent and reduce the speed of surface runoff, half-moons were dug in the whole fenced treatment area due to the initial high level

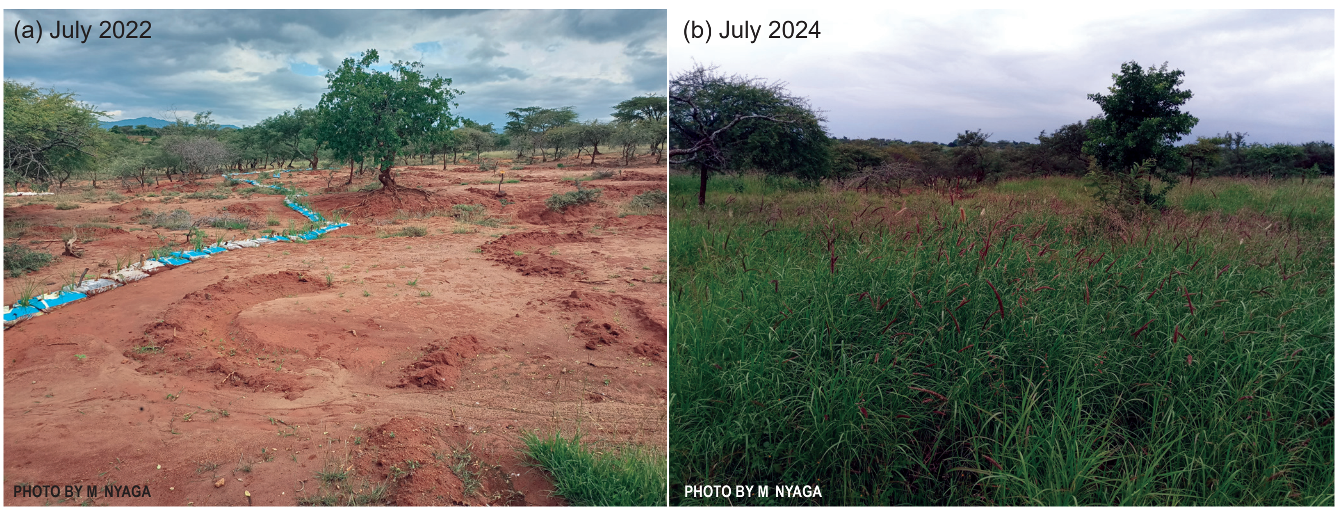

Figure 2: Experimental site at Chepareria Ward in West Pokot County in Kenya (a) before and (b) after experimentation

of degradation of the site and as one of the restoration interventions, whereas no half-moons were constructed in the control plots (Figure 2). Half-moons are semi-circular bunds approximately 2 m in diameter with their tips on the contour. The ponding area inside the half-moon retains water flowing down the slope. Four experimental blocks measuring 86 × 20 m were established across to the slope at a spacing of 5 m. Each block was subdivided into plots measuring 20m × 20m at a spacing of 2 m. The area within the blocks was ripped using digging hoes followed by broadcasting of a mixture of grass and legume seeds. The mixed grass seeds used were *Cenchrus ciliaris* L. (African foxtail), *Eragrostis superba* Peyr. (Maasai lovegrass) and *Chloris roxburghiana* (African horsetail). These are all indigenous perennial grasses that are robust, establish well from seed, and are drought, grazing and fire resistant. The forage legumes used in the mixtures were *Clitoria ternatea* L. (Butterfly pea), *Crotalaria juncea* L. (Sunn hemp), *Neonotonia wightii* (Wight & Arn.) J.A.Lackey (Glycine), and *Macroptilium atropurpureum* (DC) Urb. (Siratro).

The experimental layout was a randomised complete block design (RCBD) in which each block contained all treatments, replicated four times (4 blocks). The treatments consisted of reseeding the experimental plots with (i) mixed grasses alone (G); (ii) mixture of grasses with forage legumes (G+L); (iii) grasses alone with livestock manure added in the plot (G+M); and (iv) mixture of grasses with forage legumes and manure (G+L+M). Additionally, natural regeneration (NatReg) plots were included alongside the blocks inside the fenced area to capture the spontaneous regrowth that occurred after fencing. Natural regeneration plots were not part of the original randomised experimental design but were identified and subsequently sampled based on observed vegetation recovery. The control plots (C) were set up outside the fenced area in the adjacent open grazing area representing business-as-usual no intervention plots. All the grass and legume seeds were planted by broadcasting. Grass seeds were broadcast at rate of 15 kg ha^{-1}. The individual grass species were not assigned specific seed rates; instead, they were proportionately distributed within the mixture, with both *C. ciliaris* and *E. superba* comprising 80% in equal proportions per species, and *C. roxburghiana* making up 20% due to the limited availability of seeds. Forage legumes were broadcasted at a rate of 5 kg ha^{-1} consisting of *C. ternatea*, *C. juncea*, *N. wightii*, and *M. atropurpureum*. Livestock manure was applied separately at a rate of 3 t ha^{-1}. As a result of a short drought period that followed shortly after the germination of the first seeding, which led to the drying up of most of the seedlings, a second reseeding at the same rates was done on 16 July 2022.

At Napak site, the experiment started with bush clearing and land preparation by tractor harrowing on 15 May 2022. However, due to the delayed onset of rains, seeding was conducted later, on 28 June 2022.The area already had an existing remnant vegetation of indigenous grass species, but was degraded in having lost many of the most palatable species (Figure 3). Fencing was made using barbed wire and *Commiphora africana* (A.Rich.) Endl. posts as a living fence. Four experimental blocks were marked out at 5 m spacing, then subdivided into 20 m × 20 m plots with 2 m spacing. The same treatments used at West Pokot site were applied to this site. All legume and grass seeds were broadcasted at the same rates as in West Pokot site, except that *Chloris gayana* Kunth. was used in place of *T. roxburghiana* as these seeds were in short supply.

Data collection and analysis

Data collection on abundance, richness, diversity, biomass production, frequency and ground cover of herbaceous species was carried out during the peaks of the wet and dry seasons in the years 2022 and 2023, respectively. Abundance is the number of individuals of a particular species in a specific ecosystem or community (Magurran 2004). Species richness is the number of different species present in a community (Oba et al. 2001; Tracy et al. 2018) while frequency is the number of times a plant species is present in a given number of quadrats of a particular size or at a given number of sample points (Mueller-Dombois and Ellenberg 1974). Ground cover is any material on the ground that protects soil from the effects of erosion and run-off. It could

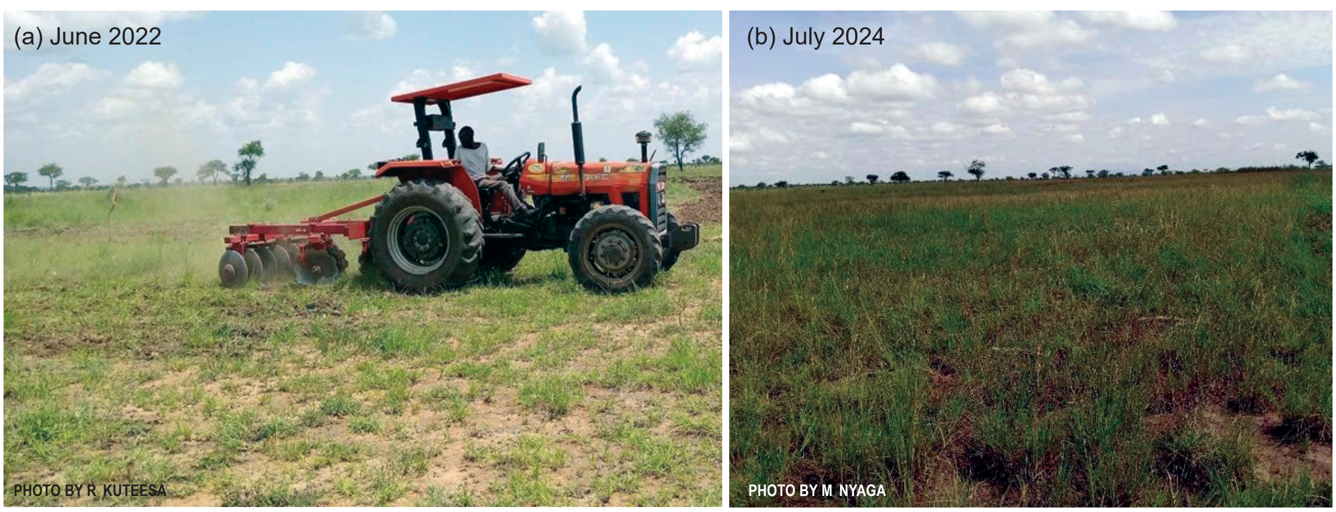

Figure 3: Experimental site at Matany sub-county in Napak District in Uganda (a) before and (b) after experimentation

be made up of plant material (living or dead), leaf litter, dung, mosses, lichens or rocks.

The wet season data collection at the West Pokot site was done from 22 to 30 September 2022, while the dry season data collection was from 27 February to 7 March 2023. At the Napak site, the wet season data collection was done from 15 to 25 November 2022 while the dry season data collection was done from 9 to 18 March 2023.

Characteristics follow of the herbaceous layers determined in the experimental sites in both seasons.

Herbaceous plant species abundance, richness, diversity and evenness

The plot was subdivided into four quarters. A quadrat measuring 0.5 m × 0.5 m was laid out randomly in each quarter. All the herbaceous plant individuals within a quadrat were identified at species level, and individual plants were counted. Abundance was expressed as number of plants per unit area.

Data on species richness was determined by counting the number of different species present in each 0.5m × 0.5 m quadrat. The collected data on the number of herbaceous species in each of the 0.5m × 0.5 m quadrats was used to calculate the Shannon–Wiener index (*H*) (equation 1) and the Pielou's evenness index (*E*) (equation 2) (Shannon 1948; Magurran 2004).

$$H' = \Sigma\left[(pi) \times \ln(pi)\right] \quad (1)$$

where: H' = Shannon diversity index; pi = proportion of individuals of one plant species in a whole plant community: $(pi = \frac{n}{N})$, where n = number of individuals of a particular plant species; and N = total number of individuals of all sampled plant species

Species evenness (*E*), which compares the similarity of the population size of each species, was computed based on Kiros et al. (2018):

$$E = \frac{H'}{Hmax} \quad (2)$$

where: H' = the Shannon diversity index; and H_{max} = ln (species richness).

Herbaceous biomass production

Aboveground biomass production was estimated within a quadrat measuring 0.5 m × 0.5 m placed randomly within each quarter, by clipping all the plant material to 2 cm stubble height to simulate grazing (Mureithi et al. 2014). The harvested material was packed in collection bags and wet weight recorded. In the laboratory, the harvested material was oven dried at 60 °C for 48 hours to determine the biomass dry weight.

Herbaceous plant species frequency

Frequency was estimated using the following equation.

$$Frequency\ (\%) = \frac{No.\ of\ plots\ in\ which\ a\ species\ occurred}{Total\ no.\ of\ plots} \times 100 \quad (3)$$

Percentage ground cover

A line transect method was used to determine cover (Evans and Love 1957; Wasonga 2009; Mureithi et al. 2014). Two diagonal transects, each measuring 28 m in length, were laid out across the plot. Any ground cover type including plant species, rock, litter, dung or bare ground hit at every 1 m was recorded. Ground cover types are the various components that cover the soil surface in a particular area (Briske 2011). Percentage ground cover by each cover type was estimated using equation 4.

$$Cover\ (\%) = \frac{No.\ of\ hits\ on\ cover\ type}{Total\ no.\ of\ hits} \times 100 \quad (4)$$

Statistical analysis

The collected data on species abundance, richness, diversity, evenness, biomass production and cover were analysed to determine if there were significant differences among the treatments and between seasons. Data analysis was conducted using R Core Team software Version 4.2.3 *Shortstop Beagle* (R Core Team 2023). Data visualisation on species frequency and richness recorded in the different treatments, seasons and sites was performed using the ggplot function from ggplot2 package (Wickham 2016).

Normality of data was tested using the Shapiro–Wilk test function (Shapiro and Wilk 1965) whereas the homogeneity of variance was tested using Levene test function (Levene 1960) from the *CAR* package (Fox and Weisberg 2019). Linear mixed effects models (LME) (Bates et al. 2015) were fitted using lmer function from the lme4 package with treatments and seasons as fixed effects and blocks as random effects. However, the models resulted in a singular fit, indicating that blocks as random effects were not contributing meaningfully to the model. Consequently, the blocks as random effects were excluded, and a simplified linear model was adopted. Separate models for each experiment, representing the different sites, were fitted using the lm function from the stats package. Pairwise comparisons were conducted using the emmeans function from the emmeans package (Lenth 2024).

Results

Abundance, richness, diversity, evenness and aboveground biomass production of herbaceous plant species

At the West Pokot site, there were significant differences ($p \leq 0.05$) in species abundance, richness, diversity and evenness among treatments and between seasons. Species abundance was significantly ($p \leq 0.05$) higher in the natural regeneration plots (173 plants m^2) compared to the open grazing area (41 plants m^2), with treatments G+L+M, G+M, G and G+L having relatively high values (89-118 plants m^2) (Table 1). In addition, species richness was higher in the natural regeneration area (12 species), while the treatments with legumes and manure showed moderate richness (8–10 species) and lowest in the open grazing area (4 species). The Shannon diversity index showed significant differences among the treatments ($p = 0.04$) but no significant differences across seasons. Significantly ($p \leq 0.05$) higher species diversity and evenness were recorded in treatment G+L+M (1.61 and 0.80, respectively) compared to the open grazing area (0.74 and 0.42, respectively) (Table 1).

For biomass production, a significant effect of season was found ($F = 273.36$, $p < 0.001$), along with a significant interaction between treatments and seasons ($F = 41.15$, $p < 0.001$). Highly significant differences ($p < 0.001$) were

Table 1: Herbaceous plants species abundance, richness, diversity, evenness and biomass production (kg ha^{-1}) in West Pokot site (Kenya) during wet and dry seasons

Parameters	Season (S)	Treatments (T)						F-value	*p*-value
		Open grazing	NatReg	G	G+L	G+M	G+L+M		
Abundance (plants m^{-2})	Wet	61.00^{c}	209.00^{a}	129.00^{b}	154.00^{b}	124.00^{b}	126.00^{b}	3.56	0.021
	Dry	20.00^{c}	137.00^{a}	83.00^{b}	8.003^{b}	72.00^{b}	52.00^{c}	4.54	0.007
	Overall	41.00^{b}	173.00^{a}	106.00^{a}	118.00^{a}	98.00^{a}	89.00^{a}	7.40	< 0.001
	Season effect							2.99	0.092
	S × T interaction effect							0.20	0.961
Species richness	Wet	6.00^{c}	16.00^{a}	7.00^{b}	13.00^{b}	11.00^{b}	11.00^{b}	2.65	0.058
	Dry	3.00	9.00	6.00	6.00	8.00	6.00	1.65	0.197
	Overall	4.00^{c}	12.00^{a}	7.00^{b}	10.00^{a}	10.00^{a}	8.00^{a}	4.35	0.003
	Season effect							5.20	0.028
	S × T interaction effect							0.38	0.860
Shannon–Weiner diversity index	Wet	0.82	1.70	1.09	1.59	1.59	1.73	1.74	0.177
	Dry	0.65	0.99	1.19	0.95	1.37	1.48	2.04	0.121
	Overall	0.74^{c}	1.34^{b}	1.14^{b}	1.27^{b}	1.48^{b}	1.61^{a}	2.62	0.040
	Season effect							4.18	0.048
	S × T interaction effect							0.66	0.659
Species evenness	Wet	0.35	0.60	0.57	0.63	0.70	0.75	1.89	0.162
	Dry	0.50	0.47	0.75	0.56	0.73	0.86	2.12	0.110
	Overall	0.42^{c}	0.54^{b}	0.66^{b}	0.59^{b}	0.72^{b}	0.80^{a}	3.34	0.014
	Season effect							0.52	0.476
	S × T interaction effect							0.65	0.661
Biomass production (kg ha^{-1})	Wet	55.00^{e}	1268.00^{b}	475.00^{d}	1045.00^{c}	2758.00^{a}	1923.00^{b}	82.73	< 0.001
	Dry	0^{e}	533.00^{a}	245.00^{c}	263.00^{b}	158.00^{d}	305.00^{c}	16.86	< 0.001
	Overall	27.50^{f}	900.00^{c}	360.00^{e}	654.00^{d}	1458.00^{a}	1114.00^{b}	48.48	< 0.001
	Season effect							273.36	< 0.001
	S × T interaction effect							41.15	< 0.001

Different superscript letters along the rows indicate significant differences among the treatments within a season at $p \leq 0.05$ based on linear models followed by pairwise comparisons using the estimated marginal means (emmeans) method. Treatment abbreviations:
G = grasses only
G+L = intercrop of grasses plus legumes
G+L+M = intercrop of grasses and legumes with manure
G+M = grasses plus manure
NatReg = Natural regeneration (protected area)
Open grazing = continuously grazed area without interventions

observed among the treatments with treatment G+M yielding the highest biomass (1 458 kg ha^{-1}) while the open grazing area had the lowest biomass production (27.5 kg ha^{-1}). During the wet season, biomass production was significantly higher ($p \leq 0.05$) in treatments G+M (2 758 kg ha^{-1}) and G+L+M (1 923 kg ha^{-1}), compared to G+L (1 045 kg ha^{-1}) and G (475 kg ha^{-1}). The open grazing area yielded the lowest biomass (55 kg ha^{-1}) (Table 1). Similarly, during the dry season, there were significant differences ($p \leq 0.05$) among the treatments, with the highest biomass production recorded in the natural regeneration area (533 kg/ha), followed by G+L+M (305 kg ha^{-1}) and G+L (263 kg ha^{-1}), while no biomass production was recorded from the open grazing area (0 kg ha^{-1}) (Table 1).

At the Napak site, species abundance varied significantly among treatments ($F = 6.88$, $p < 0.001$), though there were no significant differences between the wet and dry seasons ($F = 0.06$, $p = 0.816$). Treatment G+L+M recorded the highest species abundance (84 plants m^{2}) and the lowest (30 plants m^{2}) in treatment G. During the wet season, species abundance was significantly affected by treatments ($F = 12.09$, $p < 0.001$), with the highest species abundance being recorded in treatments G+L+M (101 plants/m^{2}) and G+L (86 plants m^{2}) while significantly lower values were observed in treatments G+M and G (32 and 29 plants m^{2}, respectively) (Table 2). However, no significant differences in abundance were detected among the treatments during the dry season.

Species richness differed significantly among treatments ($F = 6.02$, $p < 0.001$) and between seasons ($F = 40.59$, $p < 0.001$), with treatment G+L recording significantly ($p < 0.05$) higher richness (12 species) compared to the natural regeneration plots which recorded the fewest (6 species). In the dry season, significantly ($p \leq 0.05$) higher species richness was recorded in treatment G+L (9 species) followed by G+L+M (8 species), with the lowest values observed in G (4 species) and natural regeneration (4 species) (Table 2). The Shannon–Weiner diversity index and species evenness did not show significant differences across treatments in either the wet or dry seasons.

Biomass production significantly differed among the treatments ($F = 9.61$, $p < 0.001$), season ($F = 18.00$, $p < 0.001$) and there was a significant interaction between treatment and season ($F = 5.86$, $p < 0.001$). Significantly higher ($p < 0.001$) biomass production was recorded in treatment G+M (2 299 kg ha^{-1}) compared to treatment G which recorded the least biomass production (1 239 kg ha^{-1}) (Table 2). During the wet season, significantly ($p \leq 0.05$) higher biomass production was recorded in treatments G+M (1 903 kg ha^{-1}) and G+L+M (1 858 kg ha^{-1}), significantly exceeding the values in treatment G (1 033 kg ha^{-1}). Similarly, in the dry

Table 2: Herbaceous plants species abundance, richness, diversity, evenness and biomass production (kg ha^{-1}) in Napak site (Uganda) during wet and dry seasons

Parameters	Season (S)	Treatments (T)						F-value	*p*-value
		Open grazing	NatReg	G	G+L	G+M	G+L+M		
Abundance (plants m^{-2})	Wet	38.00^{b}	42.00^{b}	29.00^{b}	86.00^{a}	32.00^{b}	101.00^{a}	12.09	<0.001
	Dry	87.00	48.00	31.00	64.00	34.00	66.00	1.91	0.143
	Overall	63.00^{a}	45.00^{b}	30.00^{b}	75.00^{a}	33.00^{b}	84.00^{a}	6.88	<0.001
	Season effect							0.06	0.816
	S × T interaction effect							1.36	0.264
Species richness	Wet	9.00	9.00	9.00	15.00	11.00	12.00	2.67	0.057
	Dry	6.00^{b}	4.00^{c}	4.00^{c}	9.00^{a}	7.00^{b}	8.00^{b}	3.98	0.013
	Overall	7.00^{d}	6.00^{e}	7.00^{d}	12.00^{a}	9.00^{c}	10.00^{b}	6.02	<0.001
	Season effect							40.59	<0.001
	S × T interaction effect							0.29	0.918
Shannon–Weiner diversity index	Wet	1.66	1.49	1.77	2.03	1.91	1.89	1.38	0.279
	Dry	1.07	1.02	0.76	1.43	1.48	1.35	1.35	0.288
	Overall	1.36	1.25	1.27	1.73	1.69	1.62	2.19	0.077
	Season effect							20.88	<0.001
	S × T interaction effect							0.65	0.665
Species evenness	Wet	0.76	0.69	0.80	0.77	0.85	0.76	1.16	0.366
	Dry	0.64	0.63	0.51	0.65	0.77	0.67	0.53	0.759
	Overall	0.70	0.66	0.65	0.71	0.81	0.72	0.80	0.555
	Season effect							6.05	0.019
	S × T interaction effect							0.41	0.841
Biomass production (kg ha^{-1})	Wet	1615.00^{a}	1584.00^{b}	1033.00^{c}	1301.00^{a}	1903.00^{b}	1858.00^{a}	3.76	0.003
	Dry	875.00^{d}	1275.00^{d}	1444.00^{c}	1829.00^{b}	2695.00^{a}	1429.00^{b}	9.22	<0.001
	Overall	1245.00^{c}	1429.00^{d}	1239.00^{d}	1565.00^{b}	2299.00^{a}	1644.00^{a}	9.61	<0.001
	Season effect							18.00	<0.001
	S × T interaction effect							5.86	<0.001

Different superscript letters along the rows indicate significant differences among the treatments within a season at $p \leq 0.05$ based on linear models followed by pairwise comparisons using the estimated marginal means (emmeans) method. Treatment abbreviations:
G = grasses only
G+L = intercrop of grasses plus legumes
G+L+M = intercrop of grasses and legumes with manure
G+M = grasses plus manure
NatReg = Natural regeneration (protected area)
Open grazing = continuously grazed area without interventions

season, biomass production was significantly affected by the treatments ($F = 9.22$, $p < 0.001$), with treatment G+M recording significantly ($p \leq 0.05$) higher biomass production (2 695 kg ha^{-1}) compared to the open grazing area (875 kg ha^{-1}) and other treatments (Table 2).

Herbaceous plants species frequency

A total of 97 herbaceous plant species were recorded in both study sites during the two seasons, with West Pokot (66 species) recording more species than the Napak site (54 species). A total of 23 common plant species were recorded in the two sites during the wet and dry seasons. Among the treatments, the highest number of species was found in the treatment G+L, while the lowest was in the control (open grazing area) on both sites (Figure 4). Generally, more species were observed during the wet season than in the dry season (Figures 5 and 6).

In the West Pokot site, 62 species were recorded in the wet season and 36 in the dry season, with the natural regeneration showing the highest species count during the dry season (Figure 4). *Bothriochloa insculpta* (Hochst. ex A.Rich.) A.Camus was the most frequently observed species in West Pokot site (Figure 5). Among the reseeded grasses, *Cenchrus ciliaris* was the most frequent grass species, followed by *Eragrostis superba* (Figure 5). For forage legumes, *Macroptilium atropurpureum* was the most frequent across seasons, while *Clitoria ternatea* and *Neonotonia wightii* were the least frequent forage legumes (Figure 5).

In the Napak site, 53 species were recorded in the wet season and 29 in the dry season (Figure 6) with *Heteropogon contortus* (L.) P.Beauv. ex Roem. & Schult. being the most frequent species (Figure 6). *Chloris gayana* Kunth was the most frequent reseeded grass species, followed by *Cenchrus ciliaris,* with *Eragrostis superba* being the least frequent species. Among the forage legumes, *Macroptilium atropurpureum* was the most frequent, followed by *Clitoria ternatea* and *Crotalaria juncea*, with *Neonotonia wightii* being the least frequent (Figure 6).

Percent ground cover

At the West Pokot site, there were no significant differences in percent ground cover across treatments ($F = 0.23$, $p = 0.948$), between seasons ($F = 0.29$, $p = 0.592$), or in the interaction between treatments and seasons ($F = 0.14$, $p = 0.983$) (Table 3). However, notable differences ($p \leq 0.05$) were found within each treatment by season for different ground cover types (Table 3). The open grazing area had significantly higher bare ground cover during both the wet (80%) and dry (74%) seasons, with all other treatments showing considerably lower bare ground cover in both

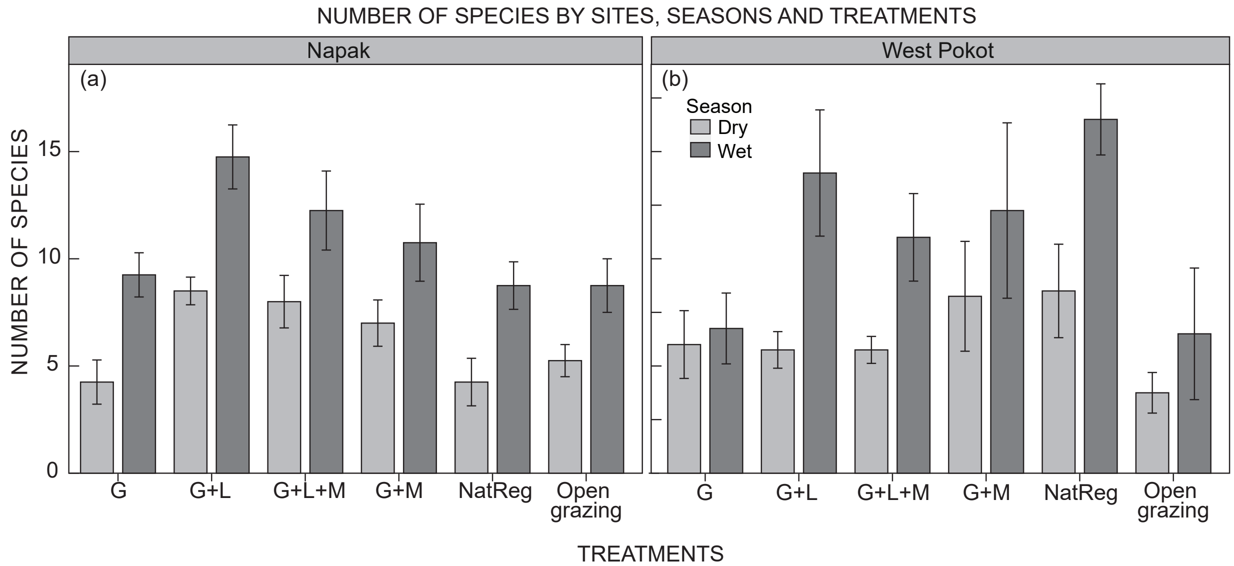

Figure 4: Herbaceous plant species richness by treatments with standard error bars in West Pokot and Napak sites. Treatment abbreviations:
G = grasses only; G+M = grasses plus manure
G+L = intercrop of grasses plus legumes; NatReg = Natural regeneration (protected area)
G+L+M = intercrop of grasses and legumes with manure; Open grazing = continuously grazed area without interventions

Table 3: Effect of season on ground cover (% mean) in West Pokot, Kenya

Cover type	Open grazing	NatReg	G	G+L	G+M	G+L+M	*F*-value	*p*-value
Wet season								
Bare ground	80.4^{aA}	15.2^{bC}	33.0^{aB}	25.0^{bB}	24.1^{bB}	17.9^{bC}	3.72	0.017
Forb	5.4^{b}	10.3^{b}	8.9^{b}	6.3^{c}	5.4^{c}	7.6^{b}	0.71	0.625
Grass	13.4^{bB}	69.2^{aA}	58.9^{aA}	54.5^{aA}	66.5^{aA}	60.3^{aA}	13.78	< 0.001
Legume				9.8^{c}		12.5^{b}	0.72	0.430
Litter	3.6^{b}	4.8^{b}	3.6^{b}	6.0^{c}	3.6^{c}	1.8^{b}	1.17	0.384
Rock		7.1^{b}	7.1^{b}		1.8^{c}	2.7^{b}	2.80	0.408
F-value	22.95	19.44	37.07	7.98	12.75	14.89		
p-value	<0.001	<0.001	<0.001	0.001	<0.001	<0.001		
Dry season								
Bare ground	73.7^{aA}	3.6^{bC}	19.2^{bB}	21.4^{bB}	17.0^{bB}	11.6^{cC}	4.00	0.017
Dung	2.4^{c}							
Forb	1.8^{c}	5.8^{b}	1.8^{c}	2.4^{d}	3.0^{c}	1.8^{d}	2.3	0.115
Grass	19.0^{bB}	81.3^{aA}	60.7^{aA}	68.8^{aA}	58.0^{aA}	61.2^{aA}	7.15	0.001
Legume				2.7^{d}		1.8^{d}	0.33	0.667
Litter	4.8^{c}	8.3^{b}	10.3^{c}	7.1^{c}	13.8^{b}	20.1^{b}	2.17	0.109
Rock	6.3^{c}	6.5^{b}	17.0^{b}	6.5^{c}	11.9^{c}	10.7^{c}	0.33	0.882
F-value	13.27	9.49	7.94	20.51	7.60	11.41		
p-value	<0.001	0.001	0.002	<0.001	0.002	<0.001		

The same lower-case superscript letters along the columns indicate significant differences in cover type while upper-case superscript letters along the rows indicate significant differences in treatments at $p \leq 0.05$ based on linear models followed by pairwise comparisons using the estimated marginal means (emmeans) method. Treatment abbreviations:
G = grasses only; G+M = grasses plus manure
G+L = intercrop of grasses plus legumes; NatReg = Natural regeneration (protected area)
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seasons. Forb cover remained low across treatments in both seasons, though natural regeneration showed the highest forb cover at 10.3% in the wet season and 5.8% in the dry season. Similarly, the natural regeneration area recorded higher grass cover, reaching 69% in the wet season and 81% in the dry season (Table 3). Legume cover was observed only in the G+L and G+L+M treatments, with higher coverage in the wet season. Litter cover was generally low in the wet season (1.8–6%) but increased in the dry season, with the lowest cover being recorded in open grazing area (4.8%) and the highest in treatment G+L+M (20%) (Table 3).

At the Napak site, no significant differences were found in ground cover among treatments ($F = 0.41$, $p = 0.842$), between seasons ($F = 0.28$, $p = 0.597$) and in the interaction

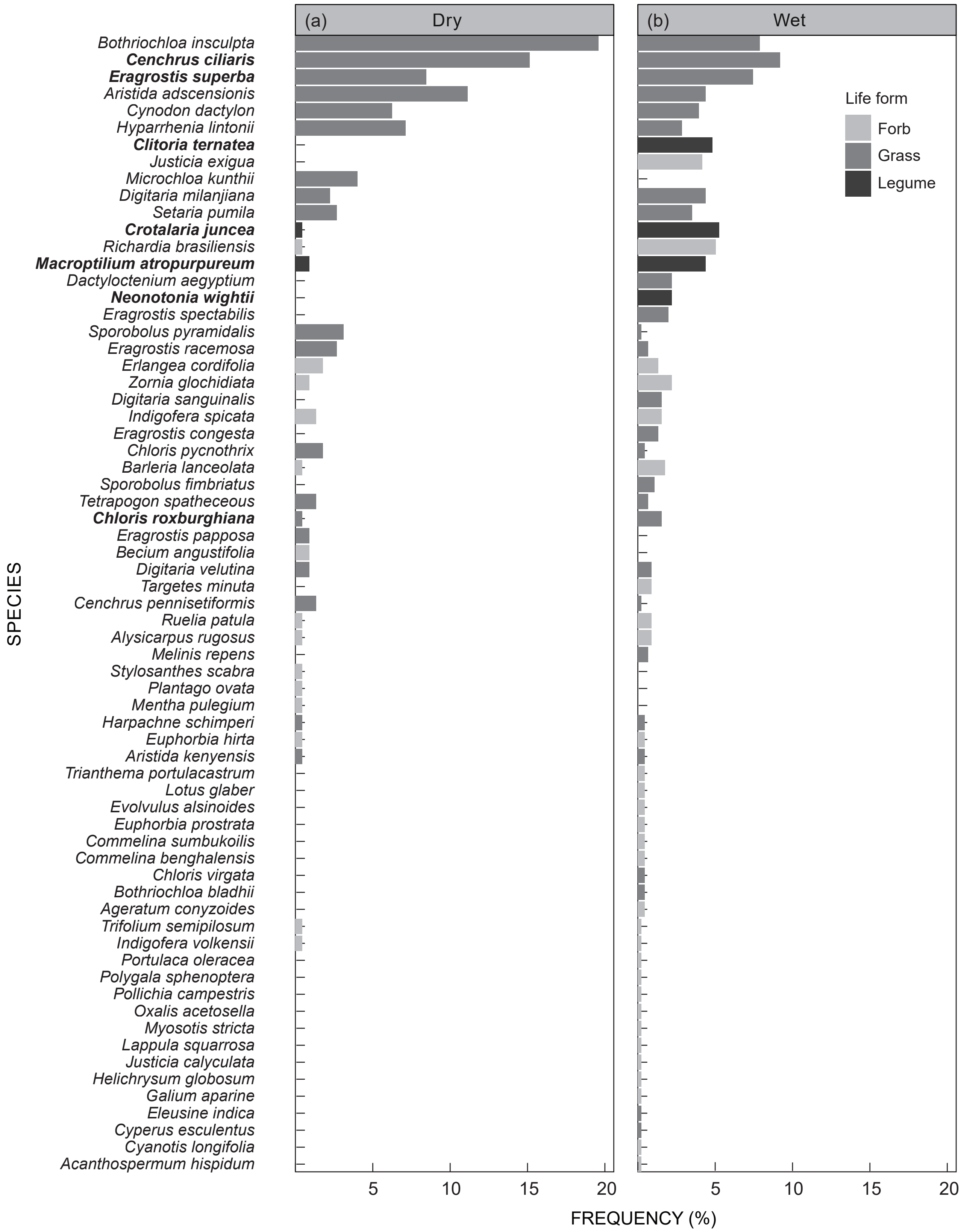

Figure 5: Frequency of herbaceous plant species identified at West Pokot study site during (a) dry; and (b) wet seasons. The reseeded species are shown in bold

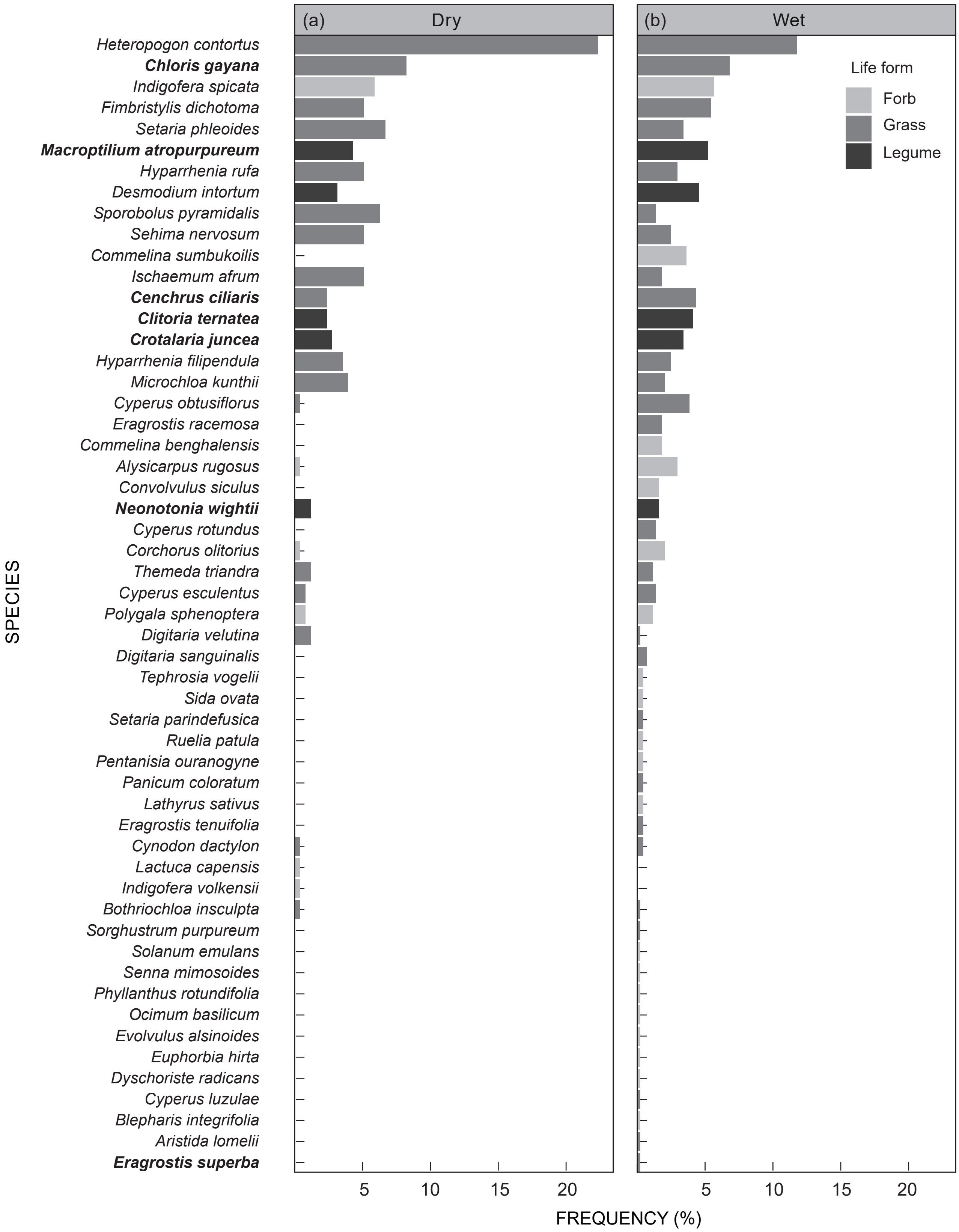

Figure 6: Frequency of herbaceous plant species identified at Napak study site during (a) dry; and (b) wet seasons. The reseeded species are shown in bold

Table 4: Effect of season on ground cover (% mean) in Napak, Uganda

Cover type	Open grazing	NatReg	G	G+L	G+M	G+L+M	F-value	*p*-value
Wet season								
Bare ground	15.6^{bB}	17.9^{bA}	18.3^{bA}	8.5d^{C}	12.1^{bB}	10.7d^{B}	3.89	0.014
Dung						1.8f		
Forb	12.5^{b}	5.8d	5.8^{c}	9.4^{c}	14.3^{b}	4.8e	2.65	0.062
Grass	58.9^{a}	60.3^{a}	58.0^{a}	51.8^{a}	55.4^{a}	48.2^{a}	1.30	0.306
Legume				20.1^{b}		24.6^{b}	1.31	0.296
Litter	12.9^{b}	12.9^{c}	15.6^{b}	9.4d	14.3^{b}	11.6^{c}	1.07	0.409
Rock	4.2^{c}	6.3^{c}	3.0^{c}	1.8e	4.0^{c}	1.8f	0.84	0.554
F-value	32.65	13.23	44.05	30.19	22.16	32.09		
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001		
Dry season								
Bare ground	25.0^{b}	14.3^{c}	17.0^{b}	9.8^{b}	7.1^{b}	7.1^{b}	0.74	0.604
Dung	3.6^{b}					1.8^{b}		
Forb	2.7^{cB}	3.0d^{B}	3.6^{cB}	2.2^{bB}	13.1^{bA}	3.6^{bB}	8.86	<0.001
Grass	54.9^{a}	50.9^{a}	41.1^{a}	55.4^{a}	42.9^{a}	54.5^{a}	0.60	0.697
Legume				1.8^{b}		4.0^{b}	2.46	0.192
Litter	16.5^{b}	31.7^{b}	37.1^{a}	33.9^{a}	41.1^{a}	33.9^{a}	2.46	0.073
Rock	2.7^{c}	1.8d	1.8d	3.6^{b}	1.8^{c}		1.61	0.274
F-value	6.81	12.10	17.03	29.78	35.12	26.75		
p-value	0.004	<0.001	<0.001	<0.001	<0.001	<0.001		

The same lower-case superscript letters along the columns indicate significant differences in cover type while upper-case superscript letters along the rows indicate significant differences in treatments at $p \leq 0.05$ based on linear models followed by pairwise comparisons using the estimated marginal means (emmeans) method. Treatment abbreviations:
G = grasses only
G+M = grasses plus manure
G+L = intercrop of grasses plus legumes
NatReg = Natural regeneration (protected area)
G+L+M = intercrop of grasses and legumes with manure
Open grazing = continuously grazed area without interventions

between treatments and seasons ($F = 0.15$, $p = 0.980$). At the same site, bare ground cover differed significantly ($p \leq 0.05$) among treatments during the wet season with treatment G and natural regeneration area recording the highest bare ground cover 18% and 17.9%, respectively (Table 4). During the dry season, forb cover was significantly influenced by treatments ($F = 8.86$, $p < 0.001$), with treatment G+M recording the highest forb cover (13%) compared to other treatments (2.2–3.6%). Additionally, all the cover types varied significantly within each treatment across seasons ($p < 0.001$) (Table 4).

Discussion

The natural regeneration recorded higher species abundance in West Pokot during the wet (209 plants m^2) and dry (137 plants m^{-2}) seasons, with treatment G+L+M recording the highest species abundance (101 plants m^2) during the wet season in Napak site. The higher number of species during the wet season may be attributed to increased water availability, which supports the germination of more annuals and the growth of seedlings (Huxman et al. 2004). During the dry season only perennial and drought-tolerant species persist (Omollo et al. 2023) reducing the overall number of species that are recorded during that season. In addition, the life cycle of many annual species is synchronised with the wet season, capitalising on the optimal conditions for growth and reproduction, resulting in a higher number of species during the wet season than during the dry season (Baskin and Baskin 1998). The results from this study corroborate with the findings of Angassa et al. 2010 and Ombega et al. 2017 who reported higher herbaceous species richness, abundance and diversity during the wet season compared to the dry season in studies conducted on rangeland sites in Ethiopia and Kenya.

Generally, there was higher species richness in all the treatments inside the fenced area when compared to the open grazing area used as the control (Fig. 4), with the highest number of species being recorded in treatment G+L (14 species) at the Napak site, and in the natural regeneration plots (17 species) at West Pokot. This corroborates with the findings of Oba et al. 2001 from northern Kenya and Angassa et al. 2010 from southern Ethiopia, who reported that areas protected from grazing exhibited greater overall herbaceous species richness (Oba et al. 2001) and grass species richness (Angassa et al. 2010) compared to open grazing areas. The observed recovery of herbaceous species in our study may be attributed to the combined effects of grazing exclusion alongside restoration interventions such as reseeding, soil disturbance and manure application, all of which can enhance germination and establishment success. In a study to evaluate potential indicators for payment of environmental services on the impact of rehabilitation of degraded rangeland sites in South Africa, Mansour et al. (2013) similarly found higher species diversity in the rehabilitated area compared to a degraded area. The lower species abundance, richness, diversity and evenness observed in the open grazing area suggest that continued grazing without any management interventions may lead to further degradation in an area, increasing the risk of soil erosion and biodiversity loss, especially in the soil seed bank.

Application of manure combined with grass reseeding (G+M and G+L+M) showed substantial increases in biomass production, particularly in West Pokot where G+M yielded over 2 700 kg ha^{-1} during the wet season. This implies that manure not only improved soil fertility but also increased moisture retention and nutrient cycling thus supporting vigorous growth (Dahlin et al. 2021). Manure is a locally readily available resource in the rangelands, especially where livestock are corralled in bomas (traditional enclosures made of thorny tree branches used by pastoralists to keep animals in overnight) (Mukoma 2015). This nutrient-rich resource can be valuable if used to improve the fertility of the rangeland soils, thereby boosting vegetation growth and biomass production (Dahlin et al. 2021). The combined treatment (G+L+M) outperformed most single interventions suggesting synergies between nutrient addition and the complementary growth strategies of grasses and legumes (Cardinale et al. 2007). Nevertheless, nutrient addition through manure application may also favour the growth of invasive species which could dominate under high nutrient conditions and outcompete the reseeded grasses (Knauf et al. 2021; Chang et al. 2025).

The natural regeneration plots inside the fenced area particularly in West Pokot produced higher levels of biomass than the open grazing area, thus demonstrating the benefits of livestock exclusion for vegetation recovery. These results corroborate the findings of Singh et al. 2011, Mansour et al. 2013 and Ombega et al. 2017, who found higher biomass production within rehabilitated areas with different soil and water conservation structures such as terraces and rainwater harvesting compared to degraded areas with no interventions. The natural regeneration at West Pokot maintained relatively high productivity even during the dry season, highlighting the resilience of indigenous perennials once grazing pressure is removed. However, in Napak, where frequent wildfires are common (Opige et al. 2023), the natural regeneration was less effective, emphasising that enclosures should be complemented by fire management for long-term success. The reduced biomass production observed at the Napak site in the open grazing area during the dry season may be partly attributed to the recurrent fires experienced in the area. The Karamojong communities in Napak burn the rangelands annually at the peak of the dry seasons as they migrate to areas with better pasture and water (Opige et al. 2023). Frequent burning hinders succession and degrades ecosystems. This poses a significant risk to biodiversity (Opige et al. 2023).

Generally, biomass production was higher inside the experimental area compared to the open grazing area, which could be attributed to protection from grazing (in the natural regeneration plots), and the improvement of soil fertility through manure application and the inclusion of legumes that enhance nitrogen availability (in the treated plots G+M and G+L+M). This suggests that the enhanced performance of treatments G+M and G+L+M may be attributed to the improved nutrient availability through the addition of manure (Dahlin et al. 2021), the complementarity nature of grasses and legumes (Cardinale et al. 2007) and grazing protection. Grazing exclusion not only helps to halt further degradation but also enhances the effectiveness of other restoration strategies such as manure application and grass-legume mixtures by minimising disturbance during plant establishment and growth (Mekuria et al. 2007; Atsbha et al. 2020). Therefore, while the exclusion of grazing likely contributed to vegetation recovery, the introduction of new species through seeding and application of manure enhanced biomass production but may have reduced species diversity by favouring the vigorous growth and dominance of the introduced grasses and legumes. The natural regeneration plots, which contained remnant patches of the natural vegetation, supported the spontaneous growth of a wider variety of species from the soil seed bank. Proper grazing management such as temporary livestock exclusion has been found to enhance aboveground biomass and diversity in severely degraded areas (Atsbha et al. 2020).

Seasonal differences influenced the treatment outcomes. Biomass production was consistently higher in the wet season, indicating the vital role of moisture for nutrient uptake and growth (Chaves et al. 2002; Robinson et al. 2013). Nevertheless, manure-amended plots maintained relatively high productivity even under dry conditions. Animal manure is a vital source of plant nutrients, affecting soil nutrient availability and the soil's physical properties by contributing to its organic matter pools (Dahlin et al. 2021). The digging of half-moons as water harvesting structures in West Pokot also improved water infiltration and water retention, contributing to higher biomass production than in Napak where such structures were absent. In bare and heavily denuded sites, starting rangeland restoration with water harvesting structures such as half-moons or ripping the hard surface crust allows more water to infiltrate into the soil, supporting plant growth even when the rains are followed quickly by a dry season (Singh et al. 2011; Ombega et al. 2017; Kelil et al. 2023). The results indicate that reseeding in enclosures improves species richness, abundance and cover; manure boosts biomass production, while enclosures facilitate natural vegetation recovery. When combined (G+L+M), these interventions provided consistent gains in both productivity and species diversity. Therefore, restoration outcomes are more effective when interventions are adapted to local conditions with the use of multiple practices rather than any single intervention alone. Additionally, the effectiveness of treatments varied across locations and seasons, with some treatments showing significantly higher effectiveness in certain conditions.

In this study, *Bothriochloa insculpta* was the most frequently observed species in West Pokot, while *Heteropogon contortus* was the most common species in Napak (Figs. 5 and 6). This could be attributed to their adaptation to the local environmental conditions and resistance to disturbance such as heavy grazing and fire. In addition, both species are indigenous perennial grass species (Heuzé et al. 2016; 2017). At the West Pokot site, although the experiment was started on bare ground, there was regeneration, indicating that the soil seed bank was not entirely depleted. The dominance of the two native species could be attributed to their competitive abilities. Differences in competition abilities may explain the maintenance of existing plant populations and the invasion of plant species in new areas. Competition occurs mostly for belowground resources such as water and mineral nutrients in areas with limited productivity typical of rangelands (Bakker and Wilson 2001). The remnant species may outcompete the reseeded species for resources such as water, minerals and sunlight, reducing the success in establishment and long-term persistence of the introduced species. Conversely, the reseeded species may alter the ecosystem structure and function once established, reducing the favourability of the habitat for native plants (Bakker and Wilson 2001).

Cenchrus ciliaris and *Chloris gayana* were the most frequently-occurring grass species among the selected grasses in West Pokot and Napak site, respectively. The grasses selected for use in the experimentation were perennial, drought-tolerant, and indigenous to the African rangelands (Mutwedu et al. 2020; Mganga et al. 2021). Perennial grasses, which live for more than a year due to their ability to regenerate from their root systems, are more reliable sources of forage across seasons compared to annuals that live for only one year, and hence need to be re-established through seeds. Perennials help maintain livestock during wet and dry seasons, increasing productivity due to their high biomass yields and high crude protein content (Omollo et al. 2023). Additionally, the grasses are warm climate (C4) species, thus species such as *Chloris gayana* achieve their maximum growth at temperatures above 30°C and decline significantly under lower temperatures (Temel et al. 2015). However, the establishment and survival of the reseeded species may be hampered by competition from the already established species, defoliation, deep shade, mineral nutrient shortage and drought (Moles and Westoby 2004).

The most dominant forage legume was *Macroptilium atropurpureum* in the two sites during both wet and dry seasons, suggesting it's competitive advantage over other species under similar conditions. These forage legumes were used in the experiments to enrich the forage quality because they are perennial and produce high amounts of dry matter and litter drop (Macharia et al. 2011). Species such as *Macroptilium atropurpureum* and *Neonotonia wightii* are deep-rooted, characterised by taproots with few lateral roots, and reaching depths of up to 80-95 cm into the soil (Macharia et al. 2010). This root system allows them to access moisture and nutrients from deeper soil horizons, enhancing their drought resilience and soil improvement potential.

Ground cover is considered to be the most reliable measure for monitoring the herbaceous layer on the ground (Everson et al. 2007; Mansour et al. 2013). Bare ground decreased among the treatments during the wet and dry seasons; for instance, the treatment involving grasses, legumes, and manure (G+L+M) improved the herbaceous cover and reduced the relative cover of the bare ground, particularly during the wet season. In West Pokot, the natural regeneration showed high grass cover and minimal bare ground in both seasons. To ensure sustainable livestock productivity in rangelands, interventions and policies should address the impacts of continuous grazing pressure on the open grazing lands. Overgrazing and livestock trampling not only reduce the aboveground biomass production but also damage grassroots, diminishing the production capacity of herbaceous plant species. This ultimately compromises the total dry matter yield essential for supporting livestock. Implementing sustainable grazing practices and community-led rangeland management practices is critical to maintaining rangeland productivity and ecosystem health.

Conclusion

The study shows the use of grass reseeding in mixtures with legumes and manure application as strategies for restoring degraded rangelands in enclosed semi-arid areas. The integration of these interventions improves plant community structure, vegetation cover and forage production. In particular, the use of manure as a locally available resource emerges as a low-cost and practical option for fertilisation when restoring degraded lands. Protection of rangelands from continuous grazing combined with restoration interventions can restore degraded lands and enhance forage production. To scale up these benefits, rangeland restoration efforts should be supported through community-led initiatives, policy frameworks promoting sustainable land use, and training on restoration techniques. Future research should focus on long-term monitoring of these interventions and their socio-economic implications to ensure widespread adoption and resilience of pastoral systems in dryland ecosystems.

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