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ORIGINAL ARTICLE

Combining Rainwater Harvesting and Grass Reseeding to Revegetate Denuded African Semi-arid Landscapes

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Abstract

In African drylands, perennial grasses preferred by grazing livestock are disappearing at an alarming rate. This has led to recurrent livestock feed shortages threatening pastoralist's livelihoods. Combining native grass reseeding and rainwater harvesting offers a viable and innovative solution to reverse this trend. However, studies to determine how biomass yields are affected by soil moisture availability attributed to in situ rainwater harvesting in African drylands are limited. We investigated how biomass yields of three grasses native to Africa, i.e., *Enteropogon macrostachyus* (Bush rye grass), *Cenchrus ciliaris* (African foxtail grass), and *Eragrostis superba* (Maasai love grass), are affected by soil moisture content in a typical semi-arid landscape. Rainwater harvesting structures included trenches, micro-catchments and furrows. Additionally, rain runoff was diverted from an adjacent road used as a catchment area. Soil moisture was measured between November 2018 and August 2019 using PlantCare Mini-Logger sensors installed at 40 and 50 cm depths and 0, 1, 5 and 15 m away from the trench. Quadrat method was used to determine biomass yields in August 2019. Peaks in soil moisture were observed after rainfall events. Soil moisture content gradually decreased after the rainy season, but was higher closer to the trench. This is attributed to the prolonged rainwater retention in the trenches. Biomass yields were in the order *Eragrostis superba* > *Cenchrus ciliaris* > *Enteropogon macrostachyus*. Biomass production was higher near the trenches for all the studied species. Sensitivity to soil moisture demonstrated by the magnitude to yield reduction during the growing season was in the order *Eragrostis superba* > *Cenchrus ciliaris* > *Enteropogon macrostachyus*. These results suggest that *Eragrostis superba* is more sensitive to drought stress than *Enteropogon macrostachyus* that is adapted to a wide range of soil moisture conditions. We demonstrated that in situ rainwater harvesting structures enhanced soil moisture availability and displayed great potential for revegetating denuded natural rangelands in semi-arid African landscapes. Thus, combining rainwater harvesting and reseeding techniques can produce measurable improvements in pastoral livelihoods and should be incorporated in dryland development policies

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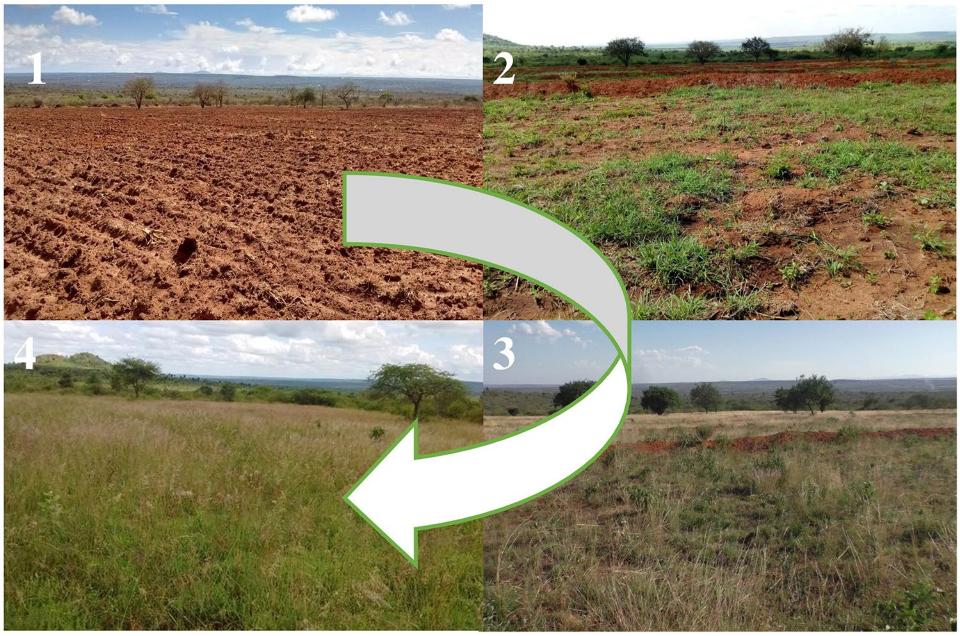
in the region. Ultimately, incorporating such innovative strategies can strengthen the effectiveness of ecological restoration in African drylands to meet the objectives of the UN Decade on Ecosystem Restoration and achieving the UN Sustainable Development Goals.

Graphical abstract



Keywords Biomass · Drylands · Grasses · Perennials · Rangeland · Runoff · Reseeding · Soil moisture · Sustainability

1 Introduction

Global drylands account for ~ 41% of the earth's surface and are host to approximately 2 billion people whose livelihoods mainly depend on the services provided by these ecosystems (Berdugo et al. 2021). More than 1 billion people from the developing world depend on dryland natural resources to sustain their livelihoods (Ryan and Elsner 2016). In Africa, dryland ecosystems are home to over 100 million pastoralists, whose livelihoods are derived mainly from subsistence livestock production characterized by mobility in search of forage and water resources (King et al. 2018). In Kenya, arid and semi-arid drylands cover approximately 90% of the country's landmass and hosts approximately 30% and 70% of the human and livestock populations, respectively (Amwata et al. 2016).

Native grass pastures provide the main source for forage for the free-ranging livestock. Dryland environments in Kenya receive very low and erratic bimodal rainfall that is highly variable. On average, annual rainfall ranges from 150 to 450 mm and 500 to 850 mm, in the arid and semi-arid lands, respectively (Huang et al. 2016). However, rainfall in the Kenyan drylands is highly variable in space, and time with some years characterized by above and below average annual rainfall. Subsequently, inter-annual rainfall in these environments can vary from 50 to 100% in arid lands and 20 to 30% in the semi-arid lands (Mumo et al. 2019). This erratic nature and low rainfall regimes and recurrent droughts have partly contributed to the gradual depletion of native perennial forage resources for livestock in these drylands. Current and projected climate trends across most of African drylands show increasing drought frequency and rainfall variability (Sheffield and Wood 2008). This worsens vegetation degradation and escalates environmental sensitivity to drought, leading to ecological and social vulnerability among pastoralists (Bardgett et al. 2021; King et al. 2018).

In addition, an increased pressure on the arid and semi-arid drylands in Kenya in the last 3 decades has contributed to severe degradation. Shrinkage of the pastoral-production livestock feed resource base has confined pastoralists to the less productive grazing lands. This has resulted in further depletion and fast disappearance of preferred native grasses forage resources threatening the sustainability of land production systems and livelihoods of pastoralist communities (Mganga et al. 2015). Drylands are particularly vulnerable, because the soils have a relatively poor soil structure because of low levels of organic matter. Decline in primary productivity, loss of biodiversity and accelerated rate of soil erosion are degradation's evidence in these environments (Mureithi et al. 2014). Natural grazing pastures and forage resources have reduced in quantity and quality, exposing the pastoral livestock to perennial feed scarcity, especially during the long lean dry seasons. Considering that livestock are critical to rural household incomes, livelihoods, nutrition and food security and resilience in African drylands, there is need to explore innovations which can contribute to improved establishment of grass pastures in their native environment.

Livestock destocking, rangeland bush management and controlled grazing patterns have been used to improve the quantity and quality of native pastures and replenish depleted rangelands (Angassa 2014). Other strategies such as tilling, ripping and seeding are rare in pastoral drylands. This is mainly because of their high capital requirements (Mureithi et al. 2016; van den Berg and Kellner 2005). A combination of in situ rainwater harvesting and revegetation through minimal soil disturbance and native grass reseeding has the potential to restore depleted grazing pastures and improve their potential for livestock production in dryland landscapes. Such innovative strategies have a great potential to strengthen the effectiveness of ecological restoration in African drylands to meet the aspirations of the UN Decade on Ecosystem Restoration and attaining the UN Sustainable Development Goals.

In situ rainwater harvesting (e.g., trenches, micro-catchments, furrows) is one of the promising practices to support sustainable development in African drylands facing climate change impacts (Vohland and Barry 2009). This is because such structures enhance water infiltration thus providing an excellent opportunity to stabilize dryland landscapes, through restoration of degraded natural grazing lands, making them more productive and resilient (Lal 2001). Additionally, marginal water sources, e.g., road and land runoffs, which are normally lost through erosion processes, can also be harvested and used more efficiently. Minimal soil disturbance through the creation of shallow micro-catchments traps rainwater and surface runoff, and thus promotes seed germination and subsequent establishment and development of the seedlings (Visser et al. 2007).

Use of native perennial grass seeds for reseeding depleted arid and semi-arid rangelands is advantageous because of their better survival and growth. They also reduce the risk of restoration failure attributed to poor adaptation to prevailing environmental conditions, restricting local gene pools 'pollution' and outbreeding depression (Mganga et al. 2021; Broadhurst et al. 2008). Moreover, perennial grasses native to African drylands are prolific seeders and efficient in seed dispersal, and thus have a great potential of replenishing depleted seed banks (Marshall et al. 2012). Therefore, in this study, we reseeded a typical semi-arid landscape with three grass species native to African drylands, i.e., *Eragrostis superba* (Maasai love grass), *Cenchrus ciliaris* (African foxtail/Buffel grass) and *Enteropogon macrostachyus* (Bush rye grass). Selection criteria of these three grasses was not only based on their evolved adaptive mechanisms for survival in African drylands, but also their multipurpose uses among pastoral communities, e.g., livestock feed, source of income (sale of seed and hay), thatching material and role in soil conservation (Mganga et al. 2015; Mureithi et al. 2016). Some general characteristics of the selected grasses are shown in Table 1. Trenches were excavated to harvest rainwater and store surface runoff diverted from a road adjacent to the site. Additionally, minimal soil disturbance was achieved by creating shallow ox-driven plough micro-catchments (around 15 cm depth) that also supplemented rainwater harvesting. These in situ rainwater harvesting structures were set up to assess their potential contribution in enhancing soil moisture content and their subsequent contribution to sustainable native pasture production.

Table 1 Morphometric characteristics of selected perennial grasses used for reseeding Kenyan dryland environments

Plant trait	Units	Selected characteristics of perennial grasses native to African drylands		
		Cenchrus ciliaris	*Enteropogon macrostachyus*	*Eragrostis superba*
Distribution	m a.s.l	0–2000	300–1600	0–2000
Leaf blade	Length, cm Width, mm	15–30 3–8	10–60 2–10	Up to 40 3–12
Stem thickness	Width, mm	1–2	1–2	2–3
Height	cm	20–150	30–100	20–120
Rooting depth	cm	Up to 240	Up to 220	Up to 220
Inflorescence type		Panicle	Spike	Panicle
Inflorescence length	cm	2–14	8–20	10–30
Optimal rainfall	mm	300–750	550–800	500–900
Crude protein	%	Up to 10	9–12	Up to 15

Thus, the broad objective for this study was to determine the potential of in situ rainwater to prolong soil moisture availability and thus enhance sustainable native pasture biomass production in a typical semi-arid landscape in Africa. Specifically, we aimed at establishing: (1) how in situ rainwater harvesting prolongs soil moisture availability and (2) how the soil moisture availability influences biomass yields of three grass forages native to African drylands.

2 Materials and Methods

2.1 Study Area

This study was conducted in semi-arid landscape in Kitui County, southeastern Kenya (Fig. 1) (GPS coordinates latitude S 1°19′1.02317″ and longitude E 37°45′26.75293″). Akamba agropastoralists are the main inhabitants in the area. The main land-use system is a mix of local livestock breeds notably small East African shorthorn zebu, Red Maasai sheep and small East African goats and drought-tolerant cereals and pulses like millet, sorghum, pigeon peas, cowpeas and mung bean (Mganga et al. 2015), and characterizes crop-livestock production. Rainfall pattern is bimodal, with the long rains (LR) in March–May and short rains (SR) in October–December. Intense LR have a rain peak in April, while the less intense SR have a rain peak in November. Total annual rainfall averages range between 300 and 800 mm and the monthly temperatures range between 14 and 34 °C, with a mean of 24 °C (Schmitt et al. 2019). Soils are generally shallow, low in organic matter and available nutrients, especially nitrogen and phosphorus. Some of the soil classes in Kitui County include Vertisols, Cambisols, Luvisols, Ferralsols, Arenosols, Gleysols and Acrisols (in the study site). Soil surface sealing and low infiltration rates expose the soils to erosion, because heavy rains come early in the growing season, when the land is bare after the dry season. On average, the soils are characterized by the following physicochemical parameters: pH (6.4), total organic C (9.7 g kg^{-1}), total N (1.2 g kg^{-1}), total available N (11.7 mg kg^{-1}), available P (73 mg kg^{-1}), K (1.1 cmol kg^{-1}), Na (0.4 cmol kg^{-1}), and CEC (10.1 cmol kg^{-1}) (Yageta et al. 2019). Common tree and shrub species include *Lannea triphylla* (Hochst. ex A. Rich.) Engl., *Commiphora africana* (A. Rich.) Endl., *Acacia mellifera* (M. Vahl) Seigler & Ebinger and *Acacia senegal* (L.) Britton. Grasses such as *C. roxburghiana*, *E. superba*, *C. ciliaris*, *E. macrostachyus* and *Rhynchelytrum repens* (Willd.) Zizka dominated the herbaceous layer.

2.2 Field Site Layout and Land Preparations

The general study site (area of 2.79 ha and a slope of 5%) layout is shown in Fig. 2a. Perimeter of the site was approximately 0.68 km and the length from highest to lowest point was 250 m. The barren land was ploughed across the slope with oxen-plough to create micro-catchments. Thereafter, the trenches were dug to collect runoff water diverted from the adjacent road. Some general soil characteristics of the

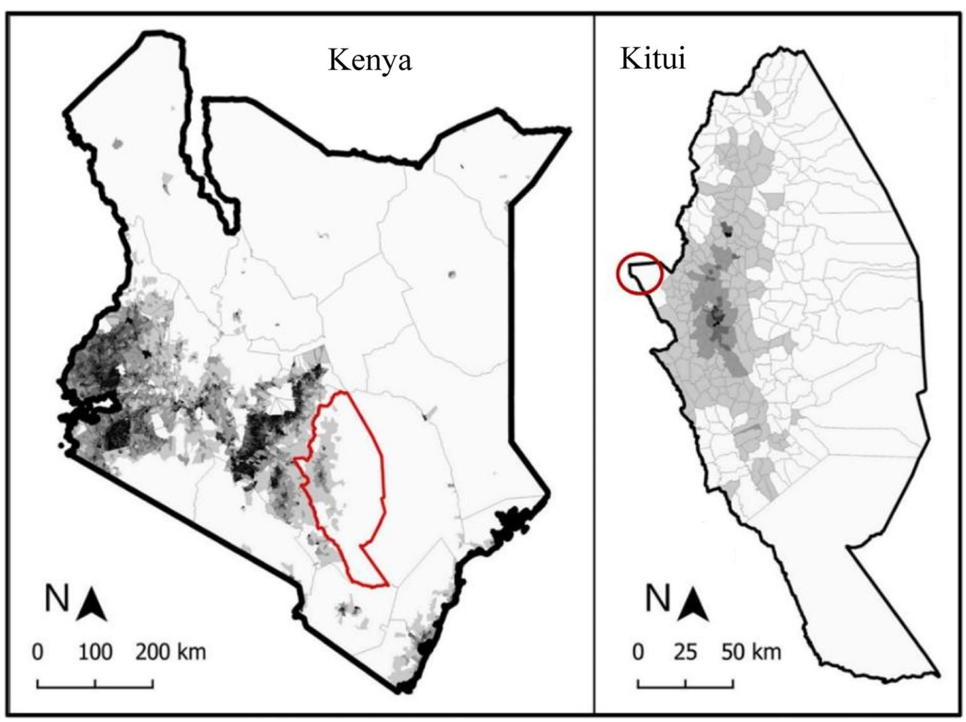


Fig. 1 Map of study location, Kitui County, southeastern Kenya

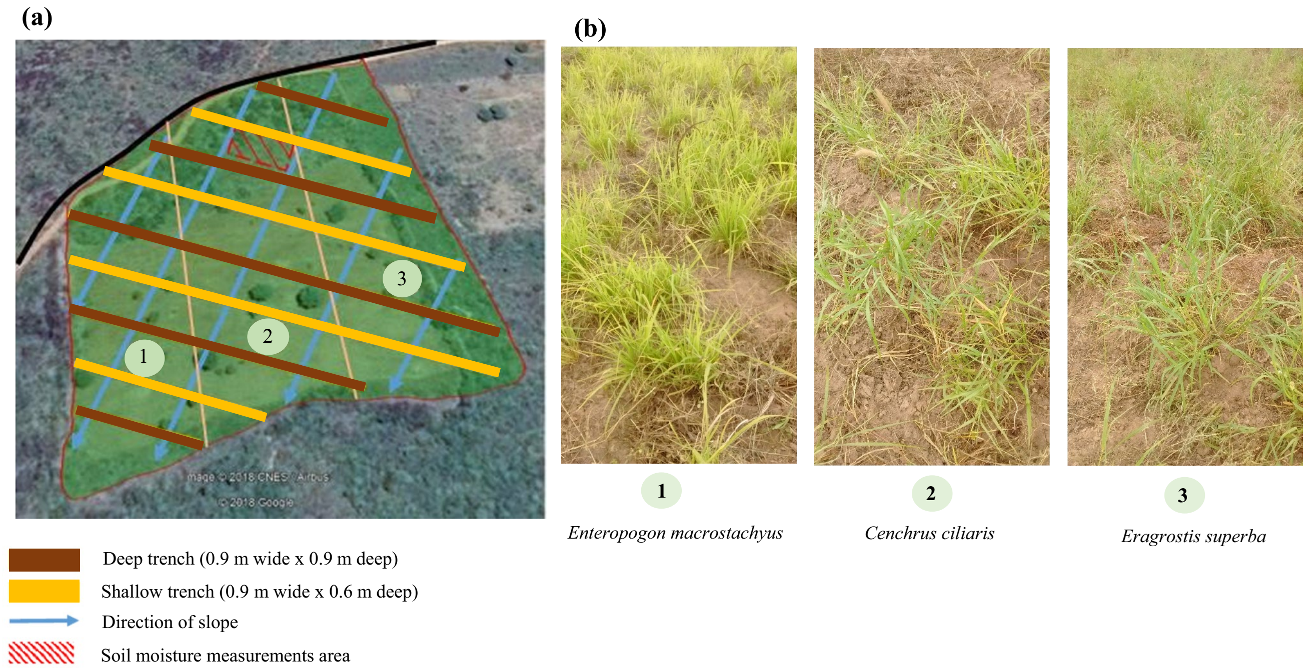


Fig. 2 **a** Layout of the experimental blocks and in situ rainwater harvesting structures and **b** photo plates of the grasses established. (Photo credit: Kevin Z. Mganga)

site were: total nitrogen 0.07%, total carbon 0.8%, C:N ratio of 11, total phosphorus 165 mg kg^{-1}, organic carbon 1.9%, humus 3.4%, clay texture—sand 7.96%, silt 19.65% and clay 72.39%.

2.3 Sowing and Plant Morphometric Characteristics' Measurements

Recommended and desired seeding rate (5 kg ha^{-1}) for grasses native to Kenyan drylands (Fig. 2b) was used for sowing the seeds, prior to the onset of the short rains (November, 2018). Here, we also adhered to the *home site advantage* principal using native seeds to conserve a readily adapted potential for reseeded populations to evolve (Visser and Reheul 2001). Biomass production was measured nine (9) months after sowing to estimate accumulated yields over two growing seasons. Plant biomass measurements were taken in three (3) parallel transects, i.e., T1, T2 and T3 representing 1, 5 and 15 m after the trenches, in each species block (Fig. 2a) to estimate the total yields in two growing seasons. Destructive sampling was used to determine aboveground biomass production. Briefly, 0.25 m^{-2} quadrats were used and clipped to a stubble height of 2 cm. Thereafter, harvested aboveground biomass was placed in paper bags and oven dried at 60 °C for 24 h to determine dry matter (DM) yield. Sensitivity (S) to drought of biomass production (Ghannoum et al. 2002) was calculated as the ratio of biomass produced under water-stress (15 m from trench) to well-watered (1 m from trench) soil moisture conditions.

2.4 Soil Moisture Measurements

Soil moisture content was determined using mini-logger sensors (PlantCare Mini-Logger) at 40–50 cm depth. Six (6) sensors were used. Briefly, sensors 1–4 were placed at a 40 cm depth, while sensors 5–6 were placed at 50 cm depth. Thus, Sensor 1, inserted 40 cm deep inside the trench (depth of 60 cm), was at 100 cm depth. Sensors 1–4 (40 cm depth) were installed in early November 2018, while sensors 5–6 (50 cm depth) in early April 2019. Data collected from the sensors installed in the field were analysed with PlantCare software. The layout of the positioning and depth of the mini-logger sensors is shown in Fig. 3a. Data were collected between November 2018 and August 2019. This was aimed at capturing the soil moisture trend during the SR (October–December) and LR (March–May) and the dry seasons in-between the two rainy season (Fig. 3b).

2.5 Statistical Data Analysis

Statistical analyses were performed using STATISTICA 10.0 (StatSoft Inc). Factorial analysis of variance (ANOVA) was used to determine whether there are any statistically significant differences in aboveground biomass yields as influenced

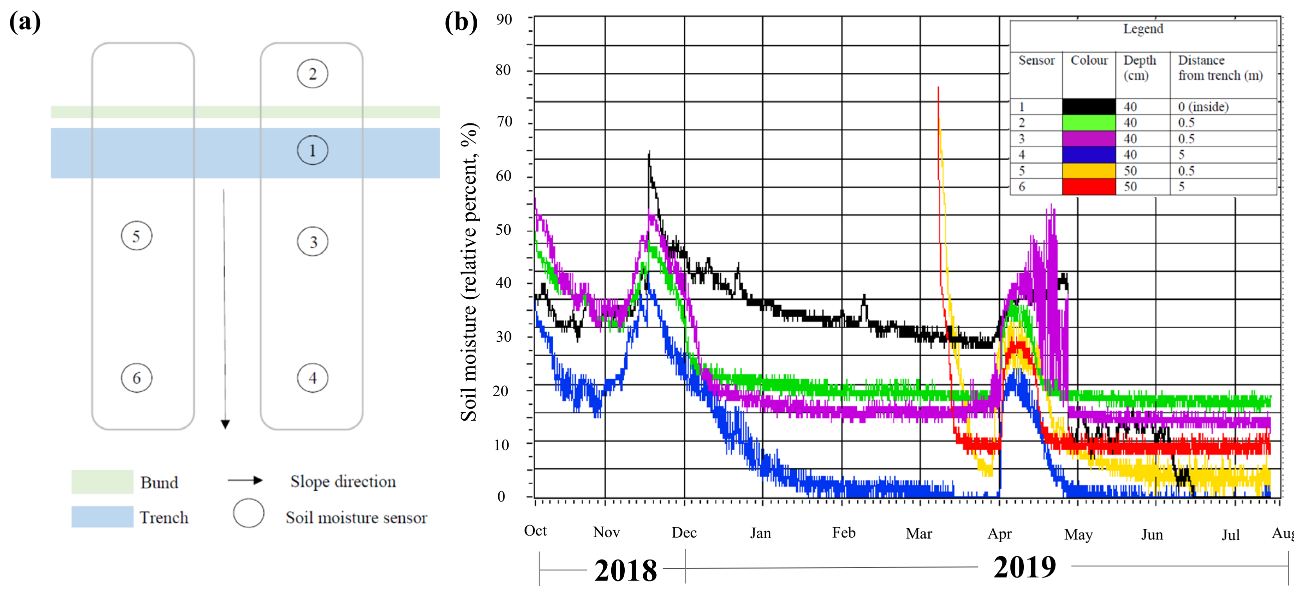


Fig. 3 **a** Positioning and depth of the mini-logger sensors and **b** soil moisture content (relative %) at different depths and distance from trench. Numbers 1–6 represent soil moisture sensors placed at different distances from the trench and soil depths

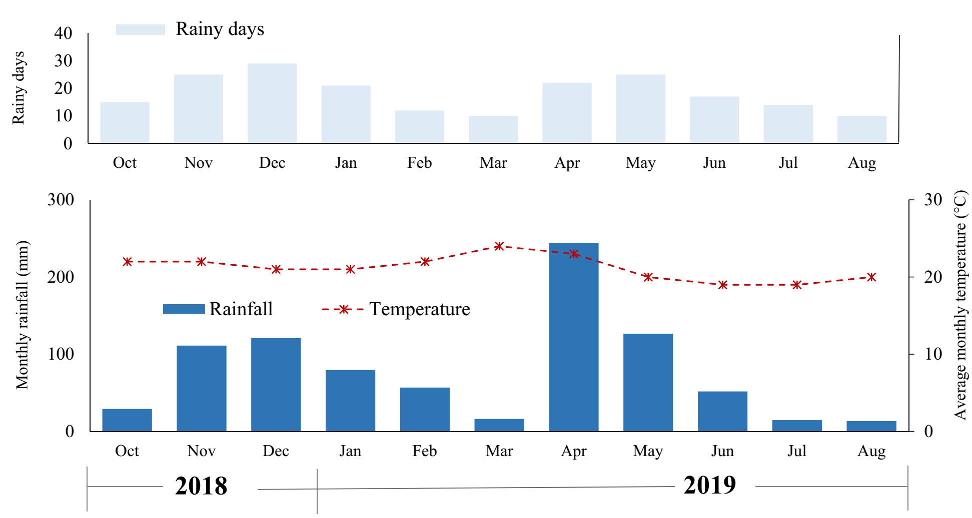
by distance from in situ rainwater harvesting structures, i.e., trenches. Tukey's HSD post hoc test was used to separate significant differences, at $\alpha = 0.05$.

3 Results

3.1 Climate Data: Rainfall and Temperature

Climate data, i.e., rainfall and temperature, were obtained from South Eastern Kenya University (SEKU) Meteorological Station, Kitui Meteorological Department and Kenya Meteorological Department. Total rainfall recorded during the study period, i.e., October 2018–August 2019, was 863 mm. Short rains of October–December, 2018 and long rains of March–May, 2019 recorded total amounts of 260 and 386 mm, respectively (Fig. 4). In total, there were 200 rainy days with 69 and 57 rainy days for the short and long rains, respectively. During the study period, April 2019 (244 mm) and August 2019 (13 mm) were the wettest and driest months. Average temperature range was between 19 and 24 °C. Maximum and minimum temperature ranges were between 22 and 28 °C and 15 and 19 °C, respectively. Highest temperature was recorded in March 2019, prior to the long rains peak in April (Fig. 4).

Fig. 4 Rainy days and monthly rainfall (mm) and average monthly temperatures (°C) during the study period. Source: South Eastern Kenya University (SEKU) Meteorological Station, Kitui Meteorological Department and Kenya Meteorological Department



3.2 Soil Moisture Data

Soil moisture data as a relative percent of soil moisture content are shown in Fig. 3b. Sensor 1 (black) placed at 100 cm depth below the trench floor displayed two peaks at the onset of the short and long rains, and had higher soil moisture over a 7-month period between November (2018) and April (2019), compared to the other sensors. During this period, soil moisture as a relative percent of soil moisture content dropped from 65 to 30%, increasing to around 42% in May 2019 because of the long rains.

Sensors 2 and 3 (green and purple, respectively), placed 0.5 m from the trench (lower and upper side of the 5% slope), at a depth of 40 cm, displayed a similar pattern and trend in soil moisture. Over a period of 7 months (i.e. November 2018 to April 2019), soil moisture, as a relative percent of soil moisture content, dropped from the range 50–55% to 15–20%, and increased to 38–55% in May, 2019, after the onset of the long rains. The soil moisture gradually dropped back to 15–20% into the dry season.

Sensor 4 (blue) at 40 cm depth, 5 m from the trench had the lowest soil moisture throughout the entire study period. It also displayed two distinct peaks in early December 2018 (40%) and late April 2019 (25%), conceding with the period after the short and long rain peaks, respectively. As the dry seasons progressed, the moisture dropped to very low levels of less than 5%.

Sensors 5 (yellow, 0.5 m from trench, 50 cm depth) and 6 (red, 5 m from trench, 50 cm depth) were installed later in early April 2019. Peak readings in early April 2019 were because of the mini-logger installation process that involves placing the sensors in water for a few minutes, before inserting them into the soil. Thereafter, the sensors measured soil moisture, represented by peaks of relative percent moisture of around 30% in late April 2019. Thereafter, the readings of sensors 5 and 6 gradually dropped and remained stable at 5 and 10%, respectively, into the dry season.

3.3 Aboveground Biomass Yields

Overall, *E. superba* had significantly higher biomass yields ($P < 0.05$) at 1, 5 and 15 m distance from the trench (Fig. 5). *Cenchrus ciliaris* and *E. macrostachyus* were ranked second and third, respectively. Biomass yields were generally higher at 1 m than 15 m distance from the trench, in three grass species. Reduction in biomass yield was 55, 50 and 28% for *E. superba, C. ciliaris* and *E. macrostachyus*, respectively. Additionally, the water-stressed (15 m from trench)/well-watered (1 m from trench) ratios of the three grasses were 0.72, 0.53 and 0.44 for *E. macrostachyus*, *C. ciliaris* and *E. superba*, respectively.

4 Discussion

4.1 Rainfall Pattern and Plant Establishment

The two rainfall peaks in October–December 2018 (short rains, SR) and April–May 2019 (long rains, LR) during the study period (Fig. 4) illustrated the bimodal rainfall pattern in southeastern Kenya (Schmitt et al. 2019; Yageta et al. 2019). Total rainfall during the SR (260 mm) and LR (386 mm) received and average monthly temperature range of between 19 and 24 °C are representative of semi-arid landscapes in Africa. Climate in semi-arid Kitui is normally hot most of the year with monthly average temperatures ranging between 14 and 34 °C and average annual rainfall ranges between 250 and 1050 mm (Yageta et al. 2019). In the arid and semi-arid Kenyan drylands, the October–December SR is the important and main season for crop production (Mumo et al. 2019; Eriksen and Lind 2009).

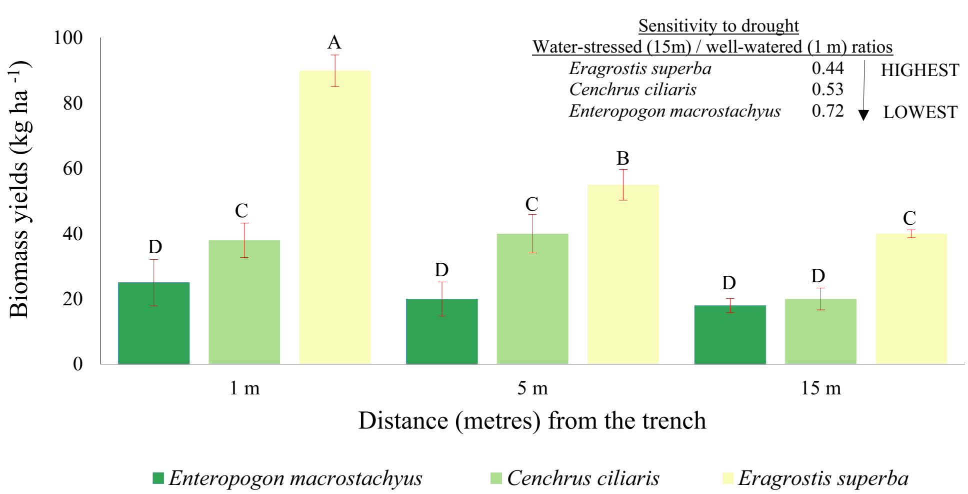


Fig. 5 Biomass yields (kg ha^{-1}) and sensitivity to drought of the three grass species. Error bars represent standard error of means (±SE). Bars with different letters indicate statistically significant differences at $\alpha = 0.05$, $n = 27$

The rainfall pattern and reliability informed the timing of seed sowing, i.e., before the onset of the SR in 2018 (dry planting). Sowing of grass seeds native to African drylands prior to the SR improves the chances of the emerging seedlings to survive and establish. This is because the emerging grass seedlings will: (1) take advantage of more reliable SR for fast growth, (2) endure a much shorter dry spell (January–February), and (3) utilize the March–May LR subsequent establishment. Dry planting, a traditional agronomic practice in dryland environments, aims at limiting the period seedlings are exposed to water-deficit conditions. The goal is to ensure that once the seeds are planted, soil moisture conditions are sufficient to trigger germination and subsequent establishment. This strategy contributed to the successful establishment and survival of the selected grass species. Other studies (e.g., Shackelford et al. 2021; Mganga et al. 2015) have also demonstrated that timing is strongly associated with successful seedling establishment in dryland environments. Poor physical properties are exacerbated by low organic matter contribute to low water-holding capacity of dryland soils, limiting its water storage capacity (Lal 2001). Thus, manipulating the soil by creating in situ rainwater harvesting structures has great potential to help overcome dry spells in drylands by reducing surface runoff, enhancing infiltration and prolong water availability for plant growth (Vohland and Barry 2009).

4.2 Rainwater Harvesting and Soil Moisture

There was a sharp increase (peak) in soil water content after each rainfall event, followed by a gradual decrease (valleys) over a period of 5 months, an indication of the soil drying (Fig. 3b). However, soil moisture was least depleted inside the trench (sensor 1, Fig. 3b). These results suggest that in situ rainwater harvesting structures, e.g., trenches, have a great potential to prolong water availability. In situ rainwater structures are thus beneficial for pasture establishment in African drylands, because enhanced water availability promotes faster growth and higher biomass production that can be harvested several times during the growing season. Higher soil moisture content in the excavated trenches is attributed to a greater water retention and reduction in runoff velocity. Trenches act as speed breakers to the runoff, thus increasing percolation of harvested water down the soil profile. Furthermore, loss of soil moisture through evaporation may be less in depressions than flat lands; thus, layers remain at relatively higher moisture content in trenches (Lenka et al. 2012). Soil bunds combined with *Vetiveria zizanioides* grass in short trenches in a grassland enhanced soil moisture up to 55% in the Upper Blue Nile Basin of Ethiopia (Sultan et al. 2018). Thus, it would be beneficial to establish deep-rooted grass species on both sides of soil bunds to stabilize the soil and reduce sediment deposition in the trenches. Furthermore, the established grasses will also reduce surface runoff along the slope, reducing water velocity and halting particles to flow along with the water. Ultimately, the grasses benefit from enhanced soil moisture availability for subsequent growth and development and simultaneously contribute to water retention. Similar to trenches, comparable in situ rainwater harvesting structures, i.e., dug tied ridges, improved soil water availability in the Tigray drylands, northern Ethiopia (Derib et al. 2009). Soil moisture was least depleted under tied ridges during the growing season commencing 4 weeks after sowing pulses including faba bean (*Vicia faba* L.), lentil (*Lens culinaris* Medic.), and field pea (*Pisum sativum* L.) in high-altitude semi-arid environment, northern Ethiopia (Tesfahunegn and Wortmann 2008).

Trenches exhibit high water-holding capacity and adequate drainage to absorb harvested water with minimal risk of waterlogging. Collected water infiltrates into the root zone and is available to the plants through lateral drainage (Denison and Wotshela 2012). General reduction in soil moisture content with distance away from the newly built trenches/bunds (sensors 2, 3 and 4, Fig. 3b) suggests that water is stored for a longer time at a shorter distance from the trench. Our results demonstrated that soil moisture retained (52%) inside the trench was 9% and 14% higher than at 0.5 and 5 m, respectively. Likewise, at a comparable slope to our study area, i.e., 5%, average soil moisture content (17.9%) recorded at 0.5 m distance from the trench/bund was 5, 14 and 20% higher than at 1, 2 and 10 m distance from the bund/trench, respectively, in the rain-fed uplands of the Kokriguda watershed, India (Dass et al. 2011). At the same distance from the trench/bund, soil moisture was higher at 40 cm (sensors 2 and 4) than 50 cm (sensors 5 and 6) soil depths, during the rainfall peaks and into the dry season (Fig. 3b). This is probably because of the slow rate of water infiltration to the lower soil horizons, due to poor soil physical properties that lead to hardening and crusting and the clay-textured soils (sand 7.96%, silt 19.65% and clay 72.39%) in the study site. Clay soils are dominated by micropores, and thus have high water and nutrient holding capacity making them less prone to leaching (Tahir and Marschner 2018).

Our results demonstrate that in situ rainwater harvesting structures, e.g., trenches, have a great capacity to collect rainfall and runoff. This allows the collected water to infiltrate into the soil slowly over a longer period, thus enhancing green water. Subsequently, this has a great potential to bridge the gaps of zero rainfall that occur within a rainy season, and to prolong soil moisture availability for a longer time after the rains have ceased. In situ rainwater harvesting is a strategic approach to combat climate vagaries, especially in water-deficit African dryland environments, where land-based production systems, including native pasture production, are largely rain-fed.

4.3 Aboveground Biomass Production

Aboveground biomass yields has been used as an index of successful ecological restoration and indicator of improved productivity of grazing landscapes (Erkossa et al. 2020; Vundla et al. 2020). Our results demonstrate that *E. superba* was more successful in terms of providing ecosystem services (i.e., biomass production) than *C. ciliaris* and *E. macrostachyus*. High biomass production by *E. superba* (Fig. 5) suggests that it is more suitable for improving productivity, forage availability and increasing the carrying capacity of similar semi-arid landscapes. Higher biomass yields displayed by *E. superba* can be attributed to its inherent superior morphoecological characteristics compared to *E. macrostachyus* and *C. ciliaris*. *Eragrostis superba* exhibits taller stems, longer tillers, large stem diameters, high broad leafy biomass and leaf-to-stem ratios (Mganga et al. 2021; Ravhuhali et al. 2019; Koech et al. 2016). These traits enabled *E. superba* to maintain higher vegetative productivity.

Taller species such as *E. superba* are suitable for sustainable livestock production, because they are more and easily accessible to free-ranging wild and domestic herbivores. This reduces grazing pressure and lowers the potential for land degradation. Livestock prefer grazing on the taller plant species than shorter ones in an open pasture composed of multi-layered forage plants (Santos et al. 2013). Interestingly, pastoral communities in Kenya have also observed a higher preference for *E. superba* compared with *C. ciliaris* and *E. macrostachyus* among free-ranging grazing livestock in the arid and semi-arid landscapes. This strongly suggests its better stockpiled forage quality (Paredes et al. 2018). Higher biomass yields of *E. superba* have made it a species of choice among pastoralists (e.g., Pokot and Il Chamus pastoral communities in Kenya) for fattening and improving their body condition score of livestock (Mureithi et al. 2016; Wasonga et al. 2003). Additionally, it is the most preferred species for restoring and rehabilitating denuded pastures. Choice of grass species to combat desertification and ecological restoration among (agro)pastoral communities in east African drylands is largely influenced by their forage value for livestock production (Mganga et al. 2015).

Eragrostis superba maintained a higher vegetative productivity. However, it displayed a significantly higher drop in biomass production with distance away from the trench and lowest water-stressed/well-watered biomass production ratio compared to *E. macrostachyus* and *C. ciliaris*. This drop in yield is directly linked to changes in soil moisture conditions as influenced by the in situ rainwater harvesting structures, notably, trenches. Perennial grasses native to African drylands have shown a decline in biomass production under water-deficit conditions (Koech et al. 2016; Ghannoum et al. 2002). This clearly shows that in dryland regions of the world, plant growth is strongly limited by scarce and variable soil moisture content (Paredes et al. 2018). Greater decline in biomass production displayed by *E. superba* compared to *E. macrostachyus* and *C. ciliaris* suggests its higher sensitivity to water-deficit conditions. This is because *E. superba* is found mainly in the relative wetter areas of typical semi-arid grasslands in Africa (Bosch 1989). *E. macrostachyus* exhibited a higher water-stressed/well-watered biomass production ratio and a marginal drop in biomass production under water-deficit conditions. This demonstrates that *E. macrostachyus* is less sensitive to changes in soil moisture content compared to *C. ciliaris* and *E. superba.* Relatively steady biomass production with changes in soil moisture displayed by *E. macrostachyus* makes it an important species to consider when selecting genotypes for yield and yield stability in African drylands. This is because African dryland soils are truncated and the available soil moisture declines towards the end of the rainy season (Visser et al. 2008).

5 Conclusions

Rainwater harvesting has been widely used in diverse social–ecological contexts proving to be a valuable approach to sustainable agricultural production. Diverting runoff from roads into in situ rainwater harvesting structures, e.g., trenches, demonstrated a high potential in enhancing soil moisture availability in a rain-fed native pasture production system in a typical African dryland landscape. Roads provide an additional catchment from which an alternative source of water is harvested. This leads to peaks in the water collection inside the trenches and adds to the in situ rainwater harvesting. Prolonged soil moisture availability increased biomass production of the established grasses, demonstrating the potential to buffer the yield gaps between the rainy seasons, and extends moisture availability at the onset of the dry seasons. There was a decrease in biomass yields with a decline in soil moisture availability as influenced by distance away from the trench. These results show that grass biomass production in African drylands is greatly constrained by soil moisture availability. However, the magnitude of this reduction in yields varied between grass species, signalling differences in sensitivity to water-deficit conditions. Thus, diverting runoff from roads coupled with in situ rainwater harvesting and reseeding using multiple species with contrasting sensitivity to water-stress conditions could be an innovative and strategic approach to increase water productivity, stabilize biomass yields and enhance sustainable native pasture production in African dryland landscapes. Thus, these innovative strategies have a great potential to strengthen the effectiveness of ecological restoration in African drylands to meet the aspirations of the UN Decade on Ecosystem Restoration and attaining the UN Sustainable Development Goals.

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Data Availability All data generated or analysed during this study are included in this published article and are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare no conflicts of interest.

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