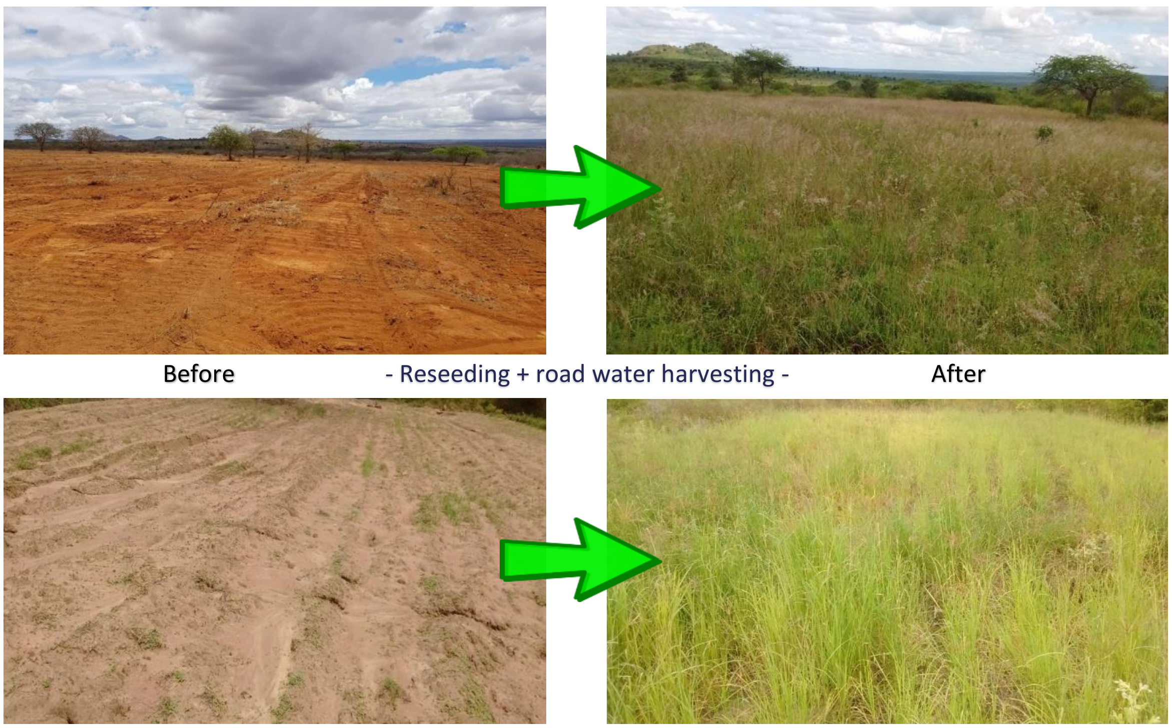
The potential of road water harvesting for improved indigenous pasture production in arid and semi-arid lands (ASALs).



By: Otieno Kevin Amollo & Luwieke Bosma

With assistance and supervision from Professor Nashon K. R. Musimba and Dr. Kevin Zowe Mganga

South Eastern Kenya University and MetaMeta Research.

ABSTRACT

The depletion of free-range pasture availability in Kenya's arid and semi-arid lands (ASALs) call for a game-changer. Pasture is no longer available in sufficient quantity and quality; therefore, it is recommended to agro-pastoralists in ASALs to consider active cultivation of pasture. Established pastures will: combat soil erosion and rehabilitate degraded lands, improve land productivity with improved water holding capacity, and to secure feed for livestock and allow for excess sales, as there is ready market for sales of hay, seeds and livestock units itself.

This report documents the potential of indigenous grass reseeding combined with road water harvesting methods for rehabilitating degraded grazing land and provide sufficient and qualitative yield of grass. Thereby specifically comparing biomass yields of the grasses grown (*Enteropogon macrostachyus*, *Cenchrus ciliaris* and *Eragrotis superba)* with soil moisture data. Whereby road water harvesting was practiced by directing water from the road into trenches that were laid out over the entire field.

The results indicate that rainwater harvesting through road surface runoffs increased soil moisture content and subsequently improved pastures biomass yields. Trenches enabled higher and prolonged soil moisture content within 5m distance from the trench, this enabled grasses within this range to develop well reaching higher biomass yields and plant moisture content. Therefore, road water harvesting is a valuable strategy to improve grass development and resulting biomass yields. It is recommended to combined in-situ with ex-situ water harvesting, soil conservation techniques and weeding management to improve overall grass establishment and development.

Key words: arid and semi-arid lands (ASAL), pasture production, reseeding, land rehabilitation, rangeland, indigenous pasture, road water harvesting, soil moisture.

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CHAPTER 1: INTRODUCTION

A majority of communities in arid and semi-arid lands (ASALs) of Kenya practice (agro)-pastoralism and are largely dependent on adequate fodder for their livestock. However, erratic rainfall regimes in ASALs have reduced existing free ranging pasture sites which would naturally occur in the area, allowing for pastoralists to let their cattle graze.

The ASALs of Kenya have undergone increasing pressure on the land use within the last 25 years. Various factors have caused a decline in forage resources which threaten the sustainability of land production systems and the livelihoods of (agro-)pastoralists. These ASALs are particularly vulnerable because the soils have poor soil structure as a result of low levels of organic matter. “The decline of productivity, the loss of biodiversity and the increasing rate of soil erosion are degradation’s evidence in these environments” (Mganga et al., 2010). Natural grazing lands and forage resources have reduced, leaving (agro-) pastoralists with unhealthy livestock especially during the dry seasons. This is a big threat for many families and livelihoods living in ASALs, as it is their main financial security.

In this study a field under typical ASAL conditions was reseeded with three indigenous grass species, notably *Eragrostis superba* (Maasai love grass)*, Cenchrus ciliaris* (African foxtail/Buffel grass) and *Enteropogon macrostachyus* (Bush rye grass). In combination the field has been laid out with trenches which store water which is harvested from the road adjacent to the field. Trenches aim to harvest water and allow it time to infiltrate into the soil layers, ensuring water is stored inside the soil to reduce evapotranspiration and make it available to the plant. This is combined with *in-situ* water harvesting through furrows/micro-catchments done by ploughing.

Grass reseeding has been used successfully as a means of restoring degraded drylands in Africa (Nyangito et al. 2009; Mganga et al. 2010; 2015; Opiyo et al. 2011). It is surmised that increased pasture production through rainwater harvesting will generate additional income (farming as a business) and improve livelihoods through sale of surplus beef, milk, hay and grass seeds.

This study tested the extent to which soil moisture content increases as a result of road water harvesting using trenches in a typical pastureland. The research was conducted under the Road water harvesting for increased pasture production (ROFIP) project. At the experiment field at the South Eastern Kenya University (SEKU), pasture has been planted using the three different grass species. Trenches are constructed to trigger improved grass growth and production. The data on soil moisture measurements will be compared with the data on biomass yields, percentage moisture content and other plant attributes. This will provide insight as to what extent trenches can impact soil moisture content, and pasture yields consequently.

This innovative approach can make an enormous contribution to land restoration and enhance livestock forage productivity, which is essential to the vast African ASALs. Especially in light of climate vagaries combining road water harvesting with reseeding of indigenous grasses has the potential cushion grasses in the stages of establishment and development. Furthermore, it also cushions farmers, as they can then deal with shocks and stresses in a resilient manner, keeping their livestock in good condition and securing household income.

CHAPTER 2: RESEARCH DESIGN

2.1 PROBLEM STATEMENT, OBJECTIVES AND RESEARCH QUESTIONS

PROBLEM STATEMENT

In Africa, livestock are critical to rural household incomes, livelihoods, nutrition and food security and resilience. Increased pressure on forage resources, climate variability and change has contributed to shrinkage of feed resource base, thus threatening livelihoods and constituting the greatest challenge to livestock production in African drylands. In order to combat this challenge, we need to explore innovations which can contribute to improved establishment and development of grasses native to African drylands.

OBJECTIVE

The main objective for this research is to determine the potential of rainwater harvesting using roads for improved pasture establishment and rehabilitation of degraded ecosystems in semi-arid Kenya.

This research therefore assesses how road water harvesting with trenches impacts soil moisture content, and how this reflects in different plant attributes, focusing on plant moisture content and biomass production. Three indigenous grasses, notably *Enteropogon macrostachyus*, *Cenchrus ciliaris* and *Eragrostis superba* are investigated.

RESEARCH QUESTIONS

Main question: Does the use of roads for rainwater harvesting facilitate a successful establishment and subsequent development of sown grasses under dryland conditions?

Sub-questions:

- How does soil moisture content impact different plant attributes of the indigenous grass species?
- How does road water harvesting with trenches impact soil moisture in the pastureland?
- How do soil moisture content and, grass moisture content and biomass production relate to each other?

2.2 METHODOLOGY

Methods focus on determining soil moisture at different locations from the trenches and to compare this with biomass data and ground coverage from comparable locations. At first the field was prepared and laid out with trenches, following this setting the data measurement points and methods are explained.

FIELD PREPARATION AND LAY-OUT

The field is located on land belonging to SEKU, in Kitui County (1°18'54.49"S - 37°45'10.83"E) (see chapter 3). Its perimeter is 0.68 Km and the total area is 2.79 ha. A road is passing on the upstream side. The average slope measured is 5%. The total length from highest to lowest point is 250 m. So, there is a difference of 0.05 X 250 = 12,5m in elevation. The plot has been ploughed with oxen-plough and reseeded with three species of indigenous grasses: *Eragrostis superba, Enteropogon macrostachyus, and Cenchrus ciliaris*. Road water harvesting structures have been constructed, diverting water from the upstream road and collecting this water in the field in trenches. The soil type in the experimental plot is >90% sand, and therefore classified as sandy soil. It is classified as Cambisol, with: pH 6.62; NH_4^+ 1.33 µg g soil; NO_3^- 0.6 µg g soil; Carbon 0.58%; Nitrogen 0.05%; C:N ratio 11.

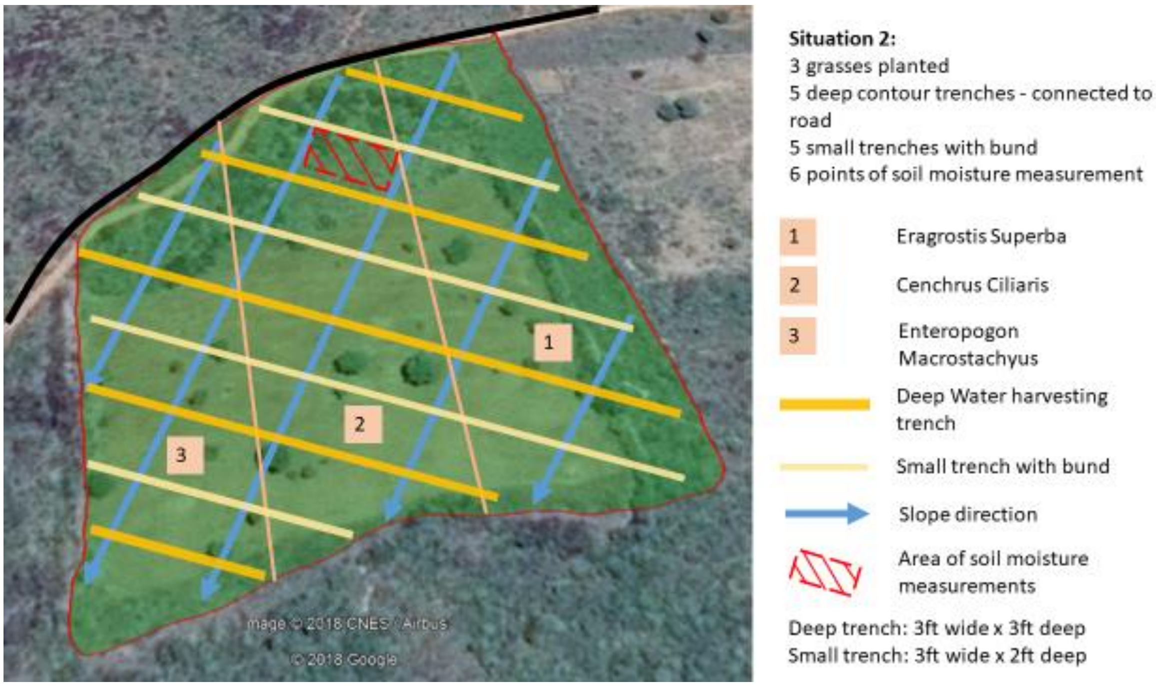

Figure 1: Field lay-out overview

Figure 2: Road water harvesting intake and collection structures

SOIL MOISTURE MEASUREMENTS

Mini-logger sensors are installed which measure soil moisture content in relative percentage. PlantCare's sensor technology is based on the micro thermic measurement of soil moisture. Specially developed felt material in moisture balance with the soil acts as the interface between the surrounding soil and the sensor. To measure the moisture level, the sensor is briefly heated and the cooling-down time, which varies depending on soil moisture, is determined. The sensor's cooling-down time thus provides a reliable statement of the soil's moisture content (PlantCare manual). Installation was done by digging a narrow hole with a soil auger, wetting the sensor itself, put the sensor inside the hole and filling it back with soil. In the proceeding time data were collected from the sensors in the field and analysed with PlantCare software.

GRASS BIOMASS DETERMINATION

Assessing pasture dry matter (DM) yield is important in budgeting feed and making management decisions such as evaluating different pasture mixtures and stocking rates, estimating forage inventory, cost benefits, and calculating net return on investment. Knowing the forage dry matter yield of given acreage is important when making decisions about forage productivity, purchasing or selling hay, fertility and feeding, grazing schemes, and stocking rates.

A direct method was used that involved hand clipping, drying, and weighing samples. The precision of this method depended largely on pasture variability and sampling efficiency. Also biomass yield was determined at different locations from trenches and the results were compared in order to elucidate on potential of road water harvesting for increased soil moisture availability and subsequently, improvement on biomass yield of indigenous pastures. The following vegetation attributes were measured:

- Total herbage yield (Biomass Production): (DM/m^2).
- Percent dry matter: measure of %DM for the collected samples.
- Moisture percentage: (wet weight - dry weight)/wet weight) x 100 %.
- Plant density: number of plants spotted and counted within a given quadrant were expressed as per $1m^2$.
- Average plant density = summation of the no. of the grass species divided by no. of samples (quadrant recorded).

SAMPLING DESIGN

In order to collect samples for estimation of biomass yield. Three transects (T1, T2 and T3) were set parallel to each other and running almost perpendicularly from one trench to another in every sub-section of the farm. Thereby crossing through the different plots with three different grasses. Biomass that was collected at distinct quadrants in each transects and the quadrants acted as the sampling points for estimation of biomass yield.

Each transect line has sampling points at distances of 0, 5 and 10m from the trench. Each transect line runs through 3 terraces, so within each terrace 3 sampling points are taken, times 3 (amount of terraces crossed) = 9 sampling points per terrace. Times 3 transects makes a total of 27 sampling points. The complete lay-out can be seen in **Error! Reference source not found.** (Though subject to changes made in the field.)

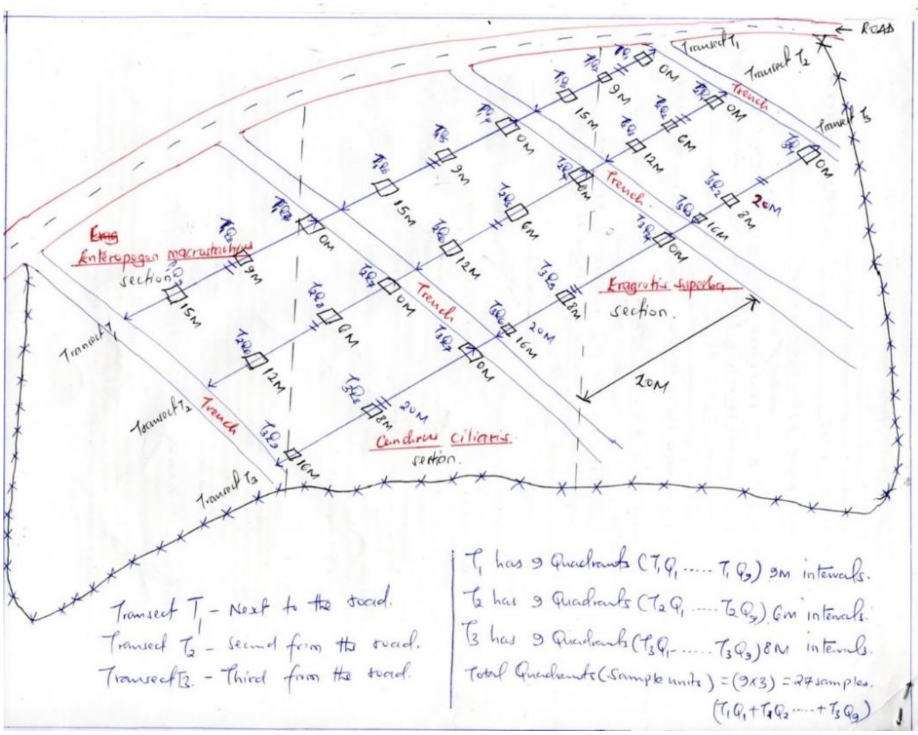

Figure 3: Sketch of the transects for measurements in the field with the different grass species and trenches laid out

9 measurements were randomly taken per grass species.

To summarize: for grass species A there are 9 sampling points, these 9 points lie on 3 transects, and on each transect it has 3 points at the 3 different distances from the trench (0, 5 and 10m). This also means that for each grass species 3 measurements are taken at each distance (0, 5 and 10m) from the trench.

CHAPTER 3: CLIMATIC AND AGRICULTURAL BACKGROUND

This chapter provides concise background on the climatic conditions of the location of the test plot. Plus additional insights on agricultural practices in the area and the type of grass species suitable for pasture production.

3.1 CLIMATIC CONDITIONS

Kitui County is classified as Arid to Semi-Arid Land (ASAL), which form up to about 80% of Kenya. ASALs in Kenya are often characterized by limited and scarce permanent water sources. The rainfall in these environments range from 450 mm in ACZ V to 900 mm in ACZ IV (transitional zone) (Biamah, 2005). Rainfall patterns in Kenya are governed by the seasonal shifts and intensity of the low pressure Inter-Tropical Convergence Zone (ITCZ). Rainfall occurrence is primarily bimodal, with rains between March and May, while the more reliable rains occur from October through to December. Mean annual temperatures range between 14-34 ºC with an average of 24 ºC. Rehabilitation of degraded lands in these rangelands is very difficult due to the high deficits in soil moisture, resulting in low germination of seeds and seedling mortality.

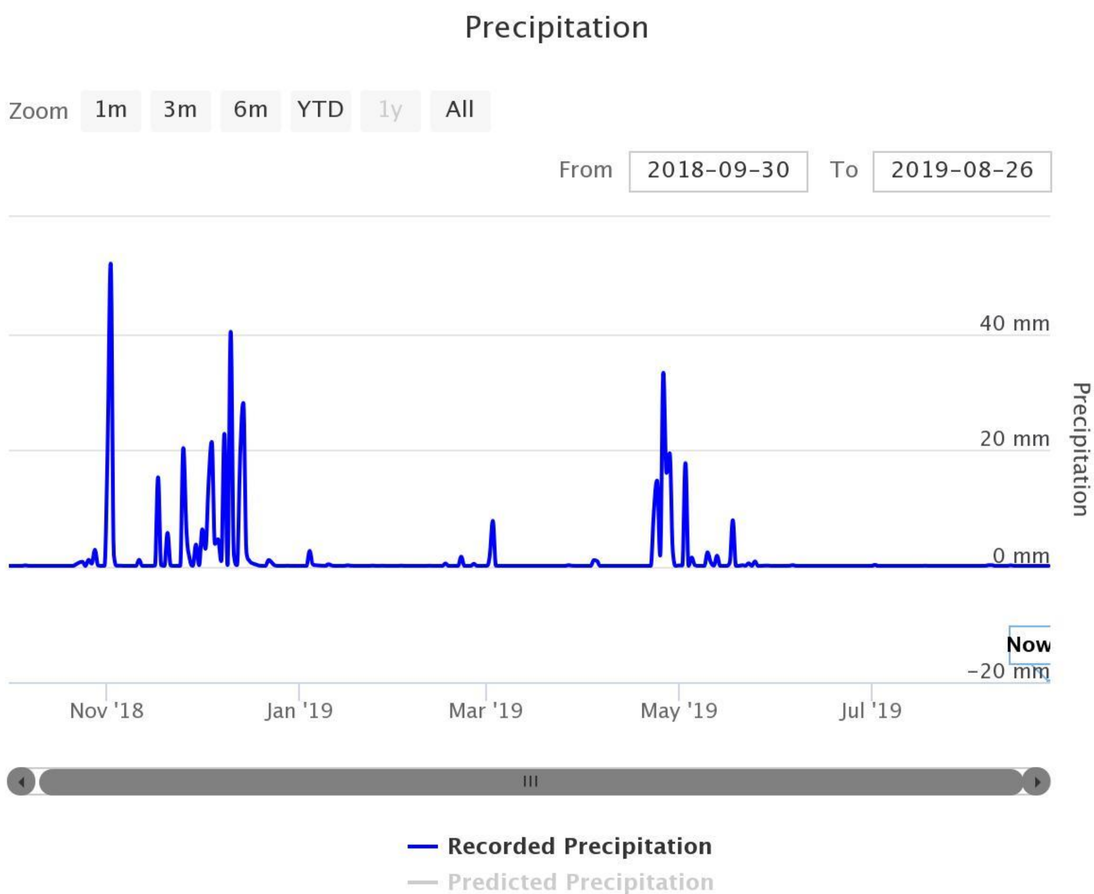

Figure 4: Precipitation in the project area

Total rainfall in October – November – December rains of 2018 amounts to 220mm in a time span of about 1,5 month. The total rainfall in March – April – May rains of 2019 amounts to 112mm in a time span of about 1 month, with one preceding rain event in March 2 months ahead of the majority of rainfall. This event in March is included in the 112mm. So the total rainfall in one year at the experimental plot is 332mm.

3.2 AGRICULTURE AND PASTURE PRODUCTION

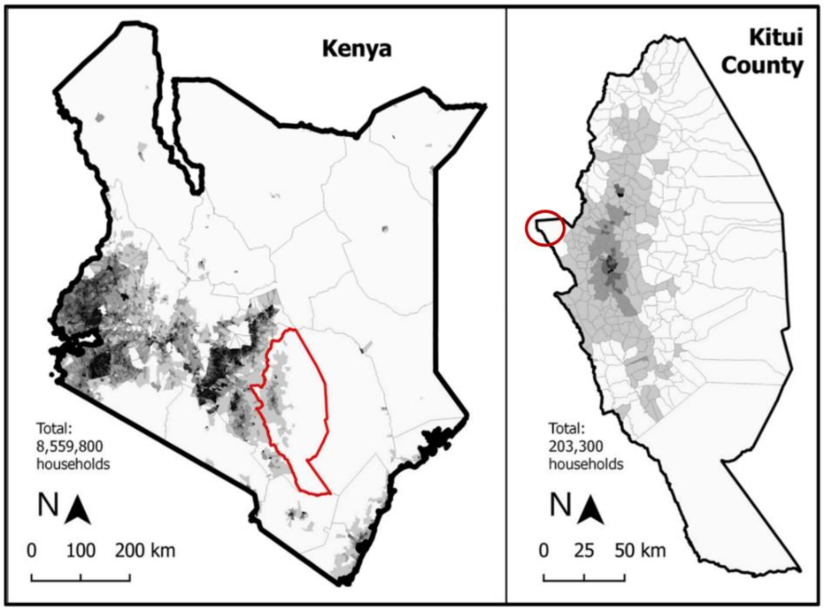

Figure 5: Location of Kitui County in Kenya, SEKU field is located in the red circle.

The location of the study area is in Kitui County, Kenya. It is part of the land which belongs to South Eastern Kenya University (SEKU).

Livestock production is a key source of livelihood among communities inhabiting dryland environments in Kenya, contributing significantly to the agricultural sector and national GDP (80% of Kenya is arid and semi-arid land (ASAL), 60% of livestock herd is found in ASALs, accounting for 12% of Kenya's GDP, 40% of agricultural GDP and employs 50% of agricultural labour force).

A main challenge is the quantity and quality of livestock feed available and market access for farmers in this sector. Indigenous pasture farming is an innovative strategy to address this 'livestock feed gap', especially during lean dry periods. Reseeded pasture minimizes overgrazing and contributes to land restoration. However, lack of rainfall and consequentially soil moisture, often hinders development of grass growth. Besides, pasture cultivation is a new practice to most agropastoral farmers in Kitui County, who normally depend on free-range pasture. However, since the availability of free-range pasture is diminishing there is an enormous potential for pasture production. Harvesting road-runoff and rainwater can aid to restore soil moisture levels, increasing pasture production levels.

In their study, Mganga et al. (2010) state that "moisture is the most important ecological factor necessary for successful rehabilitation of denuded patches in semi-arid environments of Kenya." Rehabilitation of denuded patches of land in ASALs is only possible with proper water and soil management. Reseeding first needs a limited soil disturbance, enough to allow for root penetration and still hold soil moisture, combined with the establishment of micro- and macro-catchments for water harvesting. Water harvesting techniques such as pitting, contour furrows and trenches can be implemented. These techniques greatly improve infiltration capacity and amount of water in the soil. Also, they reduce runoff, hence erosion, thus ensuring grass seeds can get water for a prolonged period of time which improves their chances of germination and establishment (Mganga et al., 2010).

3.2.1 INDIGENOUS GRASS SPECIES

Indigenous perennial grass species are critical in sustaining rangeland production. The choice of grass seeds depends on: forage value for livestock (nutrient content), drought tolerance, grazing resistance, palatability, biomass and seed production, and marketability of produce. Perennial grasses indigenous to African drylands namely; *Eragrostis superba* (Maasai love grass), *Cenchrus ciliaris* (African foxtail/Buffel grass), and *Enteropogon macrostachyus* (Bush rye grass) have been identified as important forage species in the ASALs.

Table 1: Some characteristics of the three indigenous grasses

Grass species	Description	Ecology
African foxtail / Buffel grass ***Cenchrus ciliaris***	Perennial, extremely variable. Deep, strong, fibrous rooting systems to more than 2m. Spreads well by seed, easily covers the ground.	Prefers black cotton soils. Extremely drought tolerant. Can do well with only 100 mm rainfall. Tolerant to grazing pressure.
Maasai love ***Eragrostis superba***	Perennial, quick growing, up to 1m tall. Green, often flushed purple when young. Naturally occurs in ASALs.	Prefers sand soils, but also does well on clay loams and clays. Needs a 500-800mm rainfall, drought tolerant. Tolerant to salinity and alkalinity. Less tolerant to waterlogging and shade.
Bush rye ***Enteropogon macrostachyus***	Perennial, can grow up to 120 cm tall. Feathery and pale green or purple when young. Occurs in open grasslands in ASALs.	Common grass in dry areas, wide adaptation. Drought tolerant, needs around 500 mm rainfall. Prefers loose sandy soils, loams and alluvial silts.

CHAPTER 4: COMPARISON PLANT ATTRIBUTES

This section depicts and discusses the results on the plant attributes of the different grass types. The variables include plant frequency, plant density, phenological stage, wet weight, dry matter weight and percentage moisture content. The measurements are taken in transects.

The measurements are divided per grass species and specified for the combined measurements for each

Table 2 below shows the average of the plant attributes for each grass species, being an average of 9 sampling points each (n=9). The sampling points are from different transects including different distances from the trench. The phenological stage includes an equal share of early vegetative, vegetative and reproductive stages.

Table 2: Average measure of plants attributes of the grasses

Grass species	Frequency (%)	Density (No. of plants/m^2)	Wet Weight (g/m^2)	Dry Matter Weight (g/m^2)	% Moisture content
Enteropogon macrostachyus	47	9	22	19	15
Cenchrus ciliaris	33	4	45	30	30
Eragrostis superba	42	5	78	58	23
Average	41	6	49	36	23

BIOMASS YIELD

Eragrostis superba recorded highest biomass yield with mean biomass yield of 58 g/m^2. *Cenchrus ciliaris* at 30 g/m^2 and Enteropogon macrostachyus at 18 g/m^2 were ranked 2nd and 3rd respectively. Significantly higher biomass yields of *E. superba* is mainly attributed to its higher proportion of stemmy biomass. Higher leafy biomass in *C. ciliaris* compared to *E. macrostachyus,* contributed to higher biomass in the former. Biomass sampled was predominantly at the early vegetative stage of grass development. At this stage, accumulated biomass by pastures is relatively low, with optimum yield for pastures, usually, being attained at reproductive stage, towards late maturity. However, this phenological stage of development yields the most nutritious grass forage. At late maturity, forage quality is relatively low due to high accumulations of complex carbohydrates, notably through cellulose, that are not easily digested by livestock. From Table 2 above, total biomass yield estimated for the three grass species was 36 g/m^2. This translates to approximately 360 kg Ha^{-1}. These estimates, at early vegetative stages compare well with previous studies conducted in arid and semi-arid rangelands in Kenya (Mganga, 2009; Mganga et al. 2010).

MOISTURE CONTENT

Percent moisture content of the grass forages ranged between 15-30%. *Cenchrus ciliaris* recorded highest mean percentage moisture content of 30.3 %. *Eragrostis superba* with 23.3% and *Enteropogon macrostachyus* with 14.7% were ranked second and third, respectively. These results demonstrate the higher capacity of *C. ciliaris* to take maximum advantage of available moisture for aboveground leafy biomass production. Despite its characteristic deep root system to enable it uptake water from the deep soil horizons, it also has a high proportion of its roots at the upper soil profiles to take advantage of episodic rainfall events. Less leafy biomass in *E. macrostachyus* and *E. superba* resulted to relatively low water content in the harvested biomass.

PLANT FREQUENCY AND DENSITIES

Trend in plant frequencies and plant densities of the established grasses was comparable in the established grasses. *Enteropogon macrostachyus* displayed higher plant frequencies (47%) and densities (9 plants m^{-2}) compared to *E. superba* (42% and 5 plants m^{-2}) and *C. ciliaris* (33% and 4 plants m^{-2}), which were ranked 2nd and 3rd, respectively. Higher plant frequencies and plant densities in *E. macrostachyus* is linked to its relatively higher and prolific germination, attributed mainly to its larger seed size compared to those of *E. superba* and *C. ciliaris.* These results demonstrate the greater potential of *E. macrostachyus* for rehabilitation of degraded pasturelands by providing relatively higher basal cover at the initial stages of restoration programmes. However, considering the perennial nature of these grasses beyond the establishment year, the dynamics of these attributes (frequency and densities) are bound to change.

REMARKS

The low averages recorded on these plant attributes are possibly due to low germination percentage of the indigenous grass seeds as rainfall amount has been relatively low to provide sufficient soil moisture to break the seed dormancy. For this field it was the first sowing after being transformed from bushland to pastureland, with the consequence of many weeds and shrubs interfering with the grass. This pastureland has not been fully established yet, with majority of grasses in early vegetative stage and no full occupancy. Therefore, the carrying capacity of the pastureland at this stage does not give reliable numbers. Also, the field has witnessed free roaming cattle trampling on young vegetation. For pastures with poor establishment, the recommended allowance for forage should be 40% at maximum. Normally pastures would occupy the full field, at least after 2-3 years, with good establishment you would reach an 80-100% allowance.

CHAPTER 5: IMPACT ROAD WATER HARVESTING ON SOIL MOISTURE CONTENT

Trenches in the field are laid out to harvest runoff water from the road, capture this water inside the trench and allow it to infiltrate more slowly. This water consequently will have more time to infiltrate into the soil substrata. The hypothesis is that depending on the soil conditions, the water will move vertically and laterally into the soil, increasing soil moisture content.

This chapter will discuss to which extent soil moisture content increases as a result of road water harvesting using trenches in pastureland. Soil moisture measurements are done at 40-50cm depth at different locations from the trench. This is done for two rainy seasons, covering the time between 1st of November 2018 until 1st of August 2019.

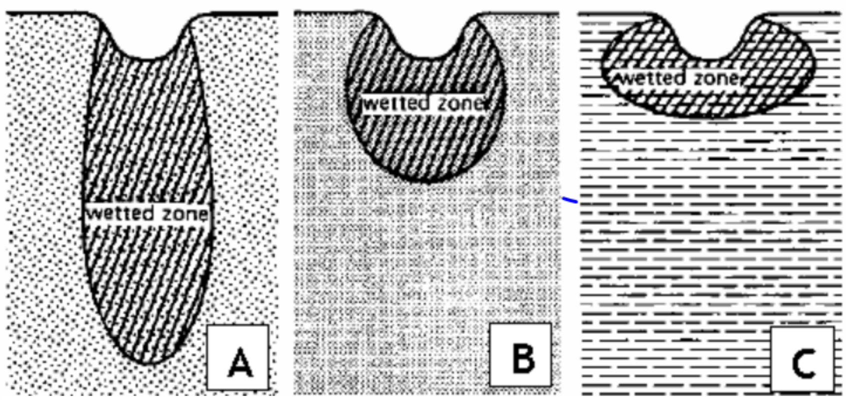

Figure 6 wetting patterns in soil, A-sand, B-loam, C-clay (source: FAO)

The field where pasture production takes place is >90% sandy. Given these sandy conditions the water quickly infiltrates vertically into the soil and little water spreads laterally, see Figure 6. It is therefore expected that the wetting pattern of the trenches will be limited to the nearby area of the trench. Considering that there is a downslope in the field, it is however expected that water will gradually 'build up' at the downside of the trench.

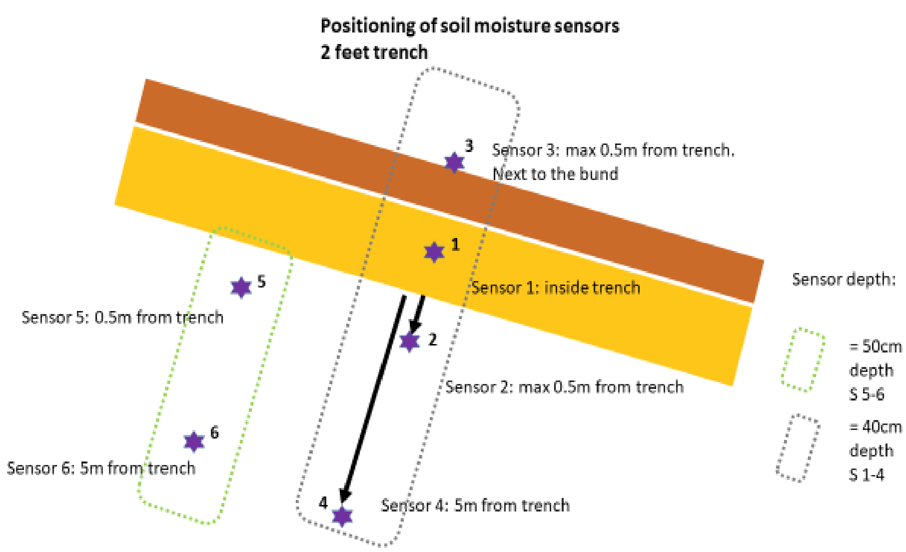

Figure 7 overview of positioning of soil moisture sensors

Figure 7 shows the placement of the sensors. The sensors 1-4 are installed at a 40cm depth, sensors 5-6 are installed at 50cm depth. Sensor 1 which is inside the trench is at a depth of 61 cm (2ft) + 40 cm = 101 cm.

5.1 OVERALL SOIL MOISTURE COMPARISON

This first paragraph will discuss the overall results of all the sensors and their data on soil moisture content. Below is the graph with the overall data on soil moisture from the six sensors installed. In the table also a legend is provided of which line colour correlates to which sensor and the specifics of each sensor. The sensors 1-4 are installed at a 40cm depth, sensors 5-6 are installed at 50cm depth. Sensor 1 which is inside the trench is at a depth of 61 cm (2ft) + 40 cm = 101 cm.

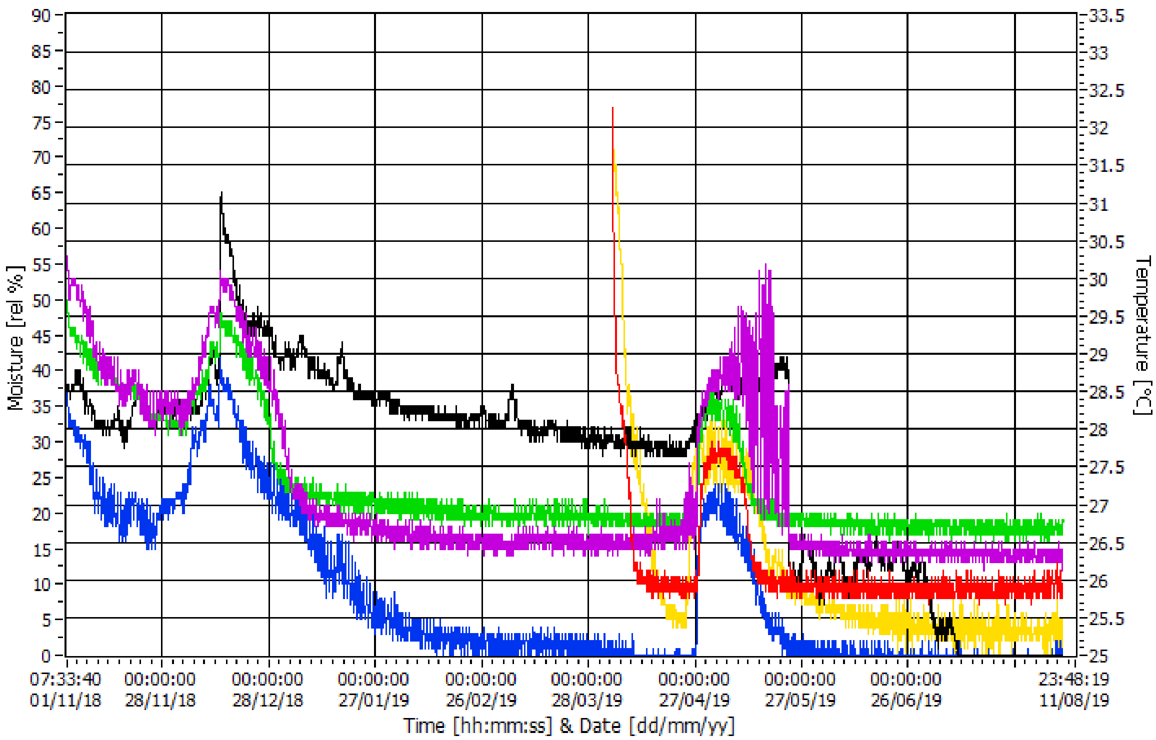

Figure 8 overview soil moisture data for all sensors

Table 3 legend for graph in figure 8

Legend		
Sensor	Colour	Distance from trench
1	(black)	0 – inside
2	(green)	0.5m
3	(purple)	5m
4	(blue)	15m
5	(yellow)	0.5m
6	(red)	5m

What you can see is that sensor 1 – black, inside the trench has the highest soil moisture and can retain a higher percentage over a long time. After the first rain season it drops gradually from 45% to 30%. You can also see the peaks in the black sensor, which are not seen in the others, especially in the months of May and June. Meaning that the trench receives extra water coming in from the road water harvested. This is additional water stored. After a longer time of drought, it is seen that the moisture content of the sensor inside the trench drops to an absolute minimum. Regarding this we must also consider the depth of this sensor which is 101cm deep (trench is 61 cm deep and sensor is 40cm deep). It appears that no moisture content is held in that soil depth after a longer period of drought.

Sensor 2, in green is just 0.5m from the trench on the downside. This shows the second highest percentage of soil moisture content. It can retain the % soil moisture content between 20-25%.

Sensor 3, in purple, is at 5m from the trench on the downside. It also retains a quite stable percentage of soil moisture content. Just a bit less compared to sensor 2 at 0.5m from the trench. In the last part the trend line shows an anomaly. However, previously it is also seen that at 5m from the trench the percentages soil moisture content at times is higher, compared to the location at 0.5m from the trench. This depends on the actual wetting patterns that are found in the soil, and the specific soil characteristics.

Sensor 4, in blue, is on the upside of the trench, just behind the soil bund. This line shows clearly a much lower percentage of soil moisture content compared to the locations on the downside of the trench. In this particular situation the terraces in between the trenches are not levelled. At this location there is an immediate response to rainfall concerning soil moisture content, which is lost very quickly. No moisture is retained for a longer time. This trend is clearly visible over a longer period of time. It means that water harvesting in the trench has no effect on the upstream part, plus the width between the trenches (20m) is too far to

Sensor 5 (yellow) and 6 (red) have been installed at the 5th of April, before the main rains of the March - April - May season. Especially the yellow line (0.5m) shows that though it has low initial moisture, it retains a higher amount of moisture for a prolonged time after a rain event. Where the red line (5m) shows higher initial moisture but this cannot be retained for a longer time after the rain event.

Table 4 comparison of soil moisture retention for different distances from a trench

Line colour		Distance from trench (m)	Depth (cm)	% rel soil moisture content – maximum amount (during rainy season)	% rel soil moisture content – stabilized (after rainy season)	Amount of soil moisture retained (%)
1	Black	0 - inside	101	67	35	52
2	Green	0.5	40	47	20	43
5	Yellow	0.5	50	29	12	41
3	Purple	5	40	53	20	38
6	Red	5	50	29	10	34
4	Blue	15	40	40	5	13

Table **4** shows three different things. The fourth column shows the maximum percentage relative soil moisture during the rainy season, the fifth column then shows the average percentage at which this relative soil moisture has stabilized for 2 months after the rains, and the last column indicates what percentage of soil moisture has been retained in 2 months' time. (For yellow and red the 2nd rainy season is taken as they were installed later).

The table is ranked upon the last column, indicating the percentage soil moisture retained from the initial maximum amount after 2 months' time. It can be seen that even after 2 months between 34-52% of soil moisture is still retained within 5 meters from the trench.

The trenches have the aim to collect more runoff water and allow it more time to infiltrate into the soil. Herewith bridging gaps of zero rainfall which occur within a rainy season, and to prolong water availability for a longer time after the rains have ceased. It was therefore expected that trenches will only hold water for a 1-2 days to infiltrate, resulting in a higher soil moisture content for about 2 weeks (depending on soil conditions). In this case it can be seen that even after 2 months a large share of the initial moisture is retained – with a significant difference for locations within 5 meters from the trench and at 15 meters away, highlighting the direct impact from the trench. Possible influences can be the vegetation cover being better able to retain soil moisture at relatively shallow soil depth.

5.2 COMPARISON SOIL MOISTURE RETENTION OVER TIME

This paragraph goes into detail on the aftermath of a rain event (April 27, 2019) and the impact of a trench on the soil moisture at different distances. Taking a 35-day period to verify the length of time it can retain moisture in the soil, comparing the retention every 5 days.

Table 5 gives an overview of the numbers on percentage relative soil moisture that were measured at the different locations, for 35 days with an interval of 5 days. It is seen that the location at 0.5m from the trench, the green sensor is keeping the highest amount of relative soil moisture after 35 days. However, when looking at the average amount of soil moisture the purple sensor at 5m is having a higher amount of soil moisture (leaving out black as it is inside the trench).

Table 5 comparison % relative soil moisture up to 35 days after a rain event

				% relative soil moisture – measurements							
Line colour		Distance trench (m)	Depth (cm)	day 5	day 10	day 15	day 20	day 25	day 30	day 35	Average
1	Black	0	101	38	38	38	38	40	14	14	31
4	Purple	5	40	39	40	40	35	26	16	15	30
2	Green	0.5	40	35	33	24	20	20	19	19	24
3	Yellow	0.5	50	28	27	25	15	10	9	9	18
5	Red	5	50	28	27	18	12	10	9	10	16
6	Blue	15	40	21	20	15	5	3	1	1	9

Figure 9 shows that soil moisture is best retained within 15 days. Most soil moisture is lost after 20 days. At a location between 0-5m from the trench, there is considerable retention of soil moisture.

At 15m distance, the blue line clearly shows a quick drop in soil moisture. Also, the amount of moisture at the beginning was lower for this location see **Error! Reference source not found.**. The green line at 0

.5m has retained the highest amount of soil moisture over 35 days of over 50%. The location at 5m with the purple sensor has been able to retain the moisture percentage gradually over a longer time.

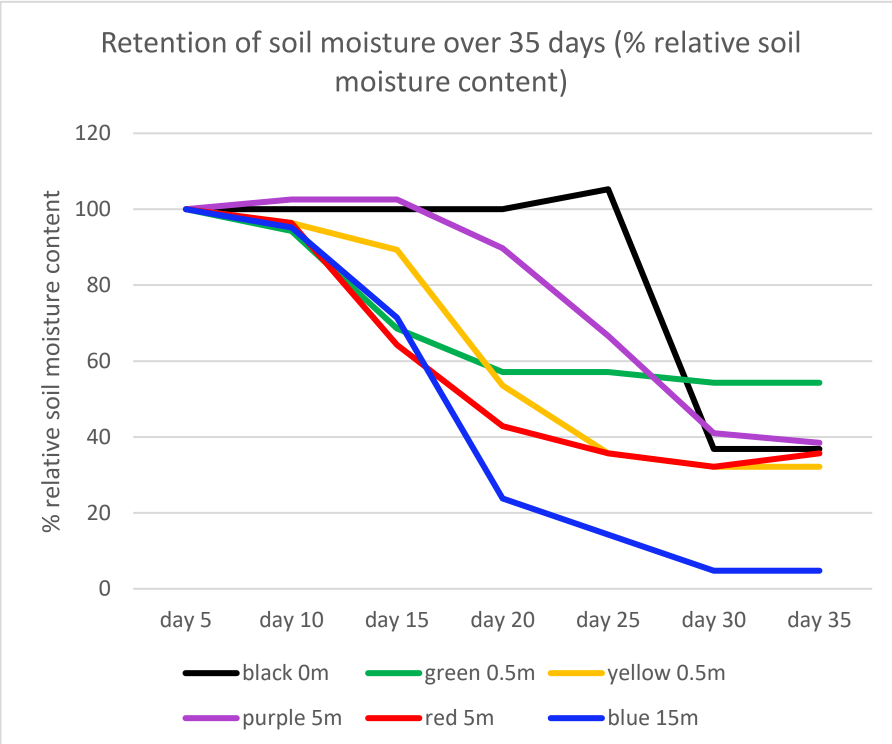

Figure 9: Retention of soil moisture over 35 days

The retention of soil moisture on is above 50% until day 15 for all locations. This would be without major influence of harvesting water in a trench. After 20 days in four locations the retention is above 50% (green, yellow, purple and black). After 25 days only three locations have retention above 50% (green, purple and black). It becomes clear that the location from the trench is a determinant for the amount of relative soil moisture and the retention capacity over time.

A location near the trench receives more water that feeds into the soil, resulting in higher initial soil moisture content after a rain event. Furthermore, it leads to a higher percentage of soil moisture content being spread out over a longer period of time. Especially when comparing the moisture percentages at 0-5m from the trench with the location at 15m, the differences both in initial soil moisture and over a 35 days period of time are stark. At 15m the initial soil moisture is low as it does not benefit from the additionally harvested water which infiltrates for a longer time. Besides, the soil moisture available at the 15m location shows a quick drop after 15 days, while in other locations the drop is more gradually. The results between the locations of 0.5m and 5m from the trench seem interchangeable, there is no stark difference between either location.

It therefore can be concluded that water harvesting from road runoff and storing this inside trenches laid out in a gradually sloping land (<5%) has a positive contribution on soil moisture within a 5m distance downstream from the trench. This positive contribution includes higher maximum amount of soil moisture content and a relatively higher amount of moisture content over an average period of 25 days.

CHAPTER 6: COMPARISON SOIL MOISTURE WITH PLANT ATTRIBUTES

The aim of this paragraph is to connect the results of soil moisture content and biomass yields at the different locations from the trench. In order to analyze if there is an impact factor, and to determine if road water harvesting has the potential to increase pasture production through an increase in soil moisture content.

6.1 COMPARISON MOISTURE CONTENT AND BIOMASS YIELDS

Below the results of moisture content and biomass yields for each grass at different distances of the trench are obtained and compared. It shows a positive relation between the moisture content and the above ground biomass yield. Table 6 shows mean comparison of percentage moisture contents (%) for biomass production at different locations from the trench for each grass species.

Table 6 mean comparison percentage moisture contents with biomass production at different distances from a trench

	Distance from trench					
Grass species	**0.5 m**		**5 m**		**10 m**	
	Moisture content %	Biomass yield = DM weight (kg)	Moisture content %	Biomass yield = DM weight (kg)	Moisture content %	Biomass yield = DM weight (kg)
Enteropogon macrostachyus	20	20	13	20	11	16
Cenchrus ciliaris	30	35	41	35	20	20
Eragrostis superba	31	90	22	35	16	50
Average	**27**	**48.3**	**25.3**	**30**	**15.7**	**28.7**

The mean biomass decreased when the location of the grass was further in distance from the trench. On average, from 48.3 g/m^2 at 0.5m, to 30 g/m^2 at 5m and lastly 28.7 g/m^2 at 10m. This is attributed by change in soil moisture content at different points away from the trench. And likewise the percentages of moisture content in the grasses is also highest at 0.5m being 27%, at 5m it is 25.3% and at 10m it is 15.7 percent. Moisture content in perennial grasses indigenous to dryland environments in Africa are predominantly a function of soil moisture availability. The observed moisture contents at different distances from the trenches (range 15-27%), are within the expected range of between 10-30% moisture content across the different seasons.

It can be seen that especially the percentages of moisture content in the grasses are higher within 5m distance from the trench. This corresponds to the findings in chapter 5 which indicated that soil moisture within 5m from the trench is both higher in number and is retained at a higher percentage for a longer period of time (up to 25 days). However, a big drop in biomass yield is seen from 0.5 to 5m, while for the moisture (both in the soil as in the plants) this happens at a distance from the trench larger than 5m.

These differences are attributed to the differences in soil moisture availability as a function of distance from the water harvesting structures (trenches).

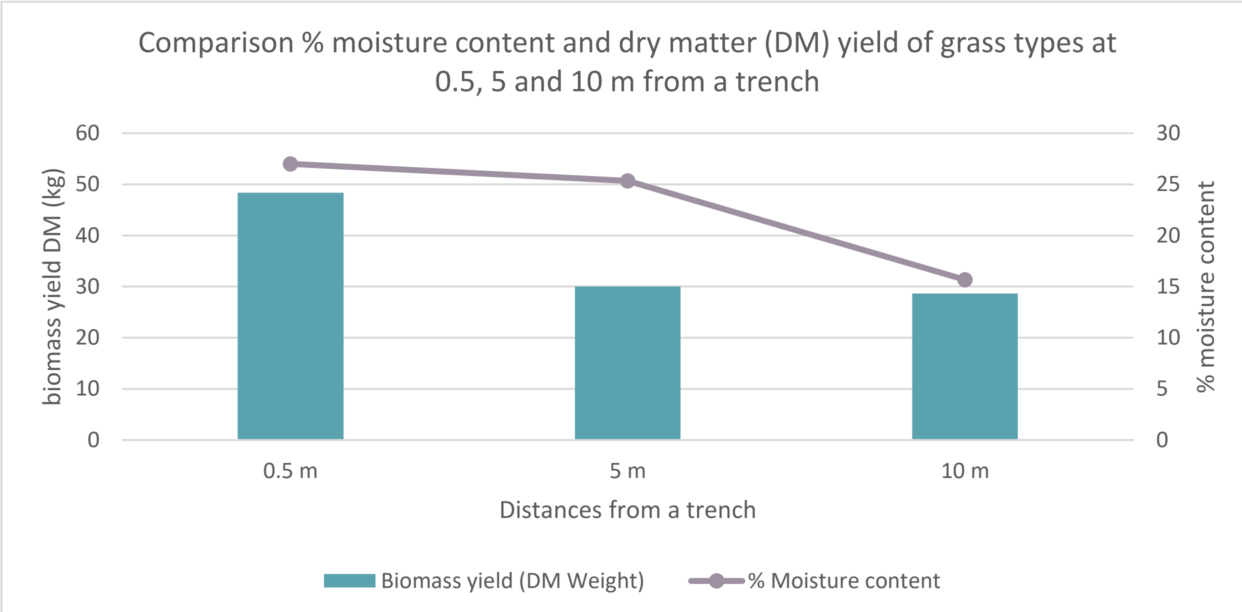

Figure 10: Comparison % soil moisture content and biomass yield (DM) of grass types at different distances from a trench

This graph shows the averaged biomass yields and % moisture content of the grass for the different distances from a trench. Spearman's correlation matrix Table 7 below, shows that both individual species and distance from the trench affected the observed biomass yields and moisture content in the harvested biomass. The % moisture content and biomass yields were positively correlated with the individual plant species. However, the distance from the trench demonstrated a negative correlation to percent moisture content in the harvested herbage and biomass yields. This clearly shows the influence of the water harvesting structures on biomass yields and % moisture content in plant biomass.

Table 7: Spearman's correlation matrix between biomass moisture content, distance and biomass yield

Variable	Species	Distance	% Moisture in biomass	Biomass
Species	1.00			
Distance	0.00	1.00		
% Moisture in biomass	0.37	-0.51	1.00	
Biomass yields	0.74	-0.36	0.45	1.00

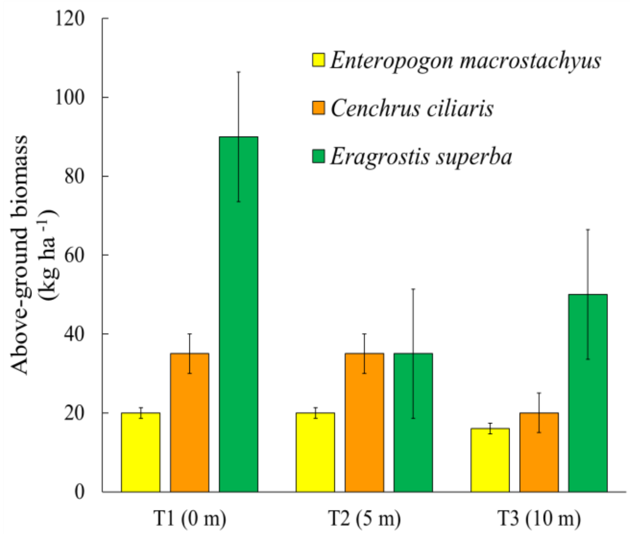

Figure 11: Graph showing above ground biomass for each grass species at each distance from a trench

Figure 11 compares the above ground biomass production of the three indigenous grasses established. There is a general trend in reduction in biomass yields in all the three grasses as a function of distance away from the water harvesting trenches i.e. T1>T2>T3. Grasses were ranked *E. superba* > *C. ciliaris* > *E. macrostachyus.* These show that enhanced and prolonged water availability in trenches promotes biomass production. Higher yields in *E. superba* is attributed to the high proportion of stem biomass. Apart from *E. superba,* the biomass yields of *C. ciliaris* and *E. macrostachyus* showed similar trends.

Simultaneous study on comparison of grass species suitability as livestock feed indicate that *Eragrostis superba* has significantly higher nutritional value, demonstrating its suitability for livestock feed. *Enteropogon macrostachyus* and *Cenchrus ciliaris* showed significantly higher values for percent plant frequency, basal cover and plant density, thus their suitability for rejuvenating denuded pastures.

CHAPTER 7: CONCLUSION

Increased pressure on forage resources, climate variability and change has contributed to shrinkage of livestock feed resource base, thus threatening livelihoods. Rainwater harvesting from roads combined with deep trenches, is a strategic approach to combat these climate vagaries and cushion grasses with enhanced and prolonged soil moisture content. Improved soil moisture conditions improve effective pasture establishment and fodder production. Additionally, 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 harvesting of water.

The functionality of the trenches lies in collecting the water in a confined area, thereby forcing it to stay and infiltrate into the subsoil. Because the amount of water is higher, a larger percentage of soil moisture can be retained over a longer time. This is especially observed within a 5m distance from the trench, due to the sandy soil conditions lateral spread over a longer distance from the trench is not achieved.

However, in this case it was witnessed that at the time of seed germination, it is pivotal to have adequate soil moisture content. Otherwise the seeds remain dormant in the soil and at the same time weeds will take over.

Another very important aspect is the type of grass species, while they are all indicated to be suitable for dryland conditions, they respond differently to low or high soil moisture conditions. *C. Ciliaris and E. macrostachyus* are most suitable for restoration of depleted pastures and denuded lands, and can do well under extremely low soil moisture conditions (<10%). *E. superba* has highest potential as livestock feed and displayed the best response to higher soil moisture content through road water harvesting exemplified by higher biomass yields. It especially shows an increase in biomass production with a soil moisture content >20%.

The conclusion is that harvesting water with roads coupled with in-situ rainwater harvesting increases soil moisture content for a prolonged time after a rain event. In this way it cushions the grasses and it reduces shocks and stresses of dry spells within a rainy season. The prolonged higher % of soil moisture content is for a duration of up to 20-25 days after a rain event. The effect is greatest within 5 meters from the trench in sandy soil conditions. It greatly aids grass species to achieve higher biomass production and plant moisture content. For a successful germination it is key to time the sowing well, as also trenches depend on rainfall and therefore can only increase and prolong soil moisture after a rainfall event.

7.1 RECOMMENDATIONS

It is important to consider the purpose of reseeding a piece of land, whether the purpose is land restoration or production of livestock feed. For livestock feed you likely need a grass species with a higher need for soil moisture content, while for land restoration there are grass species that can thrive under conditions of minimum soil moisture. Mixed sowing can be a viable option to allow for both and thereby also cushion the livestock feed grass species with the more drought resilient grasses.

Road water harvesting with trenches are best to be combined with other in-situ water harvesting (half-moons, furrows) and soil conservation techniques (ripping, no-till) to enhance water availability and improve indigenous pasture production.

Long term monitoring and evaluation of the established pastures (numerous growing seasons and cycles) is necessary to support a comprehensive assessment of the contribution of the water harvesting structures to the estimated vegetation attributes.

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ANNEX 1: ADDITIONAL DATA PLANT ATTRIBUTES FOR EACH GRASS SPECIES

Table 1: Showing Average Plant Attributes (Variables) for *Enteropogon macrostachyus*

Transect	Frequency (%)	Density (No.of plants/M^2)	Phenological Stage	Wet Weight (g/M^2)	Dry Matter Weight (g/M^2)	% Moisture content
T1	47	5	Vegetative stage	25	20	20.0
T2	73	3	Early Vegetative	23	20	13.0
T3	20	18	Seedlings	18	16	11.1
Average	46.7	8.7		22	18.7	14.7

Table 2: Showing Plant Attributes (Variables) for *Cenchrus ciliaris*

Transect	Frequency (%)	Density (No.of plants/M^2)	Phenological Stage	Wet Weight (g/M^2)	Dry Matter Weight (g/M^2)	% Moisture content
T1	20	3	Vegetative	50	35	30.0
T2	67	4	Reproductive	60	35	41.0
T3	13	5	Early Vegetative	25	20	20.0
Average	33.3	4		45	30	30.3

Table3: Showing Plant Attributes for Plot C; *Eragrostis superba*

Transect	Frequency (%)	Density (No.of plants/M^2)	Phenological Stage	Wet Weight (g/M^2)	Dry Matter Weight (g/M^2)	% Moisture content
T1	33	3	Vegetative	130	90	31

T2	40	4	Reproductive	45	35	22.2
T3	53	8	Early Vegetative	60	50	16.7
Average	42	5		78.3	58.3	23.3

ANNEX 2: EXPANDED TABLE ON SOIL MOISTURE RETENTION AFTER A RAINFALL EVENT

				Absolute % soil moisture content and % retained for 35 days with 5 day interval													
Line colour		Distance trench (m)	Depth (cm)	5d	%ret	10d	%ret	15d	%ret	20d	%ret	25 d	%ret	30d	%ret	35d	%ret
1	Black	0	101	38	100	38	100	38	100	38	100	40	105	14	37	14	37
2	Green	0.5	40	35	100	33	94	24	69	20	57	20	57	19	54	19	54
3	Yellow	5	50	28	100	27	96	25	89	15	54	10	36	9	32	9	32
4	Purple	5	40	39	100	40	103	40	103	35	90	26	67	16	41	15	38
5	Red	0.5	50	28	100	27	96	18	64	12	43	10	36	9	32	10	36
6	Blue	15	40	21	100	20	95	15	71	5	24	3	14	1	5	1	5