

**SOIL WATER AND NUTRIENT MANAGEMENT FOR IMPROVING
SORGHUM PERFORMANCE IN DRYLAND AREAS OF TANZANIA**

ATHUMAN JUMA MAHINDA

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Laboratory of Soil Science

Division of Environmental Science and Technology

Graduate School of Agriculture

KYOTO UNIVERSITY

19th August 2019

Declaration

I, Athuman Juma Mahinda, do hereby declare to the Senate of the Kyoto University that, this thesis is the result of my original works and has never been submitted for the award of a Ph. D degree in any other University.

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Signature Date

Prof. Shinya FUNAKAWA

Division of Environmental Science and Technology, Graduate School of Agriculture,
Kyoto University.

Dedication

To the Almighty God, for His favour in awarding to me a free everlasting divine permit to be opened the door before I knock, to be given before I ask, to be seen before my presence and be protected before I got victimised.

To my mentors and confidant Prof. Method Kilasara for the recognition of my academic potential and invest his very quality time, faith and efforts in helping me to develop my academic career, and make sure I become an independent researcher the world would desire to see and rely on.

To my parents, sisters and brothers who gave me courage and reasons to keep moving whenever I had academic fatigues entangled with professional and social life pressure.

May the Almighty God bless you abundantly more in return.

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Abstract

Nutrients deficiency, high rate of evapotranspiration, insufficient and erratic rainfalls are the critical challenges for crop production in dryland areas of Sub-Saharan Africa, including Tanzania, whose 61% of the arable land is prone to drought condition. In enhancing climate change resilience and productivity capacity of the land for sorghum production under the challenging weather and climate variability, two field trials were conducted in the dryland area of central Tanzania to for two consecutive cropping seasons of 2015/2016 (above-average rainfall season (966.9 mm)) and 2016/2017 (below-average rainfall season (343.2 mm)). The aim of the first experiment was to (i) evaluate the potential contribution of the selected in situ rain water harvesting technique (IRWHT), namely ripping (RP) and tie-ridges (TR), in capturing and storing rainwater at the effective root zone of the sorghum, and subsequent availability of the stored water to support sorghum growth, biomass and grain yield, and (ii) to assessing the influence of organic (FYM) and inorganic (N) fertilizers integrated with TR, RP and flat-cultivated land (FCL) in dictating soil moisture availability during the expected extended drought period, due to their different influences in crop growth and crop water uptake. The second experiment was examining the effect of the temporal intercropping patterns of sorghum-groundnut on agronomic soil moisture availability and its associated risk in crop failure during the extended dry spell. To achieve the first experiments, both IRWHT and FCL were integrated with 8 Mg FYM ha⁻¹, 70 kg N ha⁻¹, and a combination of 35 kg N ha⁻¹ and 4 Mg FYM ha⁻¹ (N+FYM). The twelve treatments, with the IRWHT as the main factors, were replicated three times in a split plot design. Amongst the treatments, TR stored a significant water volume of 577 and 458 m³ ha⁻¹, which effectively mitigated droughts during the critical period of soil moisture stress by 95% and 37% compared to the rest of the treatments in the above-average rainfall season and below-average rainfall

season, respectively; however, it only registered the highest grain yield (2.0 Mg ha^{-1}) and biomass (3.5 Mg ha^{-1}) in the below-average rainfall season. The highest overall grain yield (5.7 Mg ha^{-1}) and biomass (12.1 Mg ha^{-1}) were harvested in RP with N+FYM in the above-average rainfall season, which had a mitigation potential of 59%, while the lowest grain yield (0.5 Mg ha^{-1}) and biomass (1.2 Mg ha^{-1}), were registered in the FCL_Control in the below-average rainfall season. The results revealed a counteracting effect on soil moisture increment versus sorghum water uptake in IRWHT. Irrespective of the source, fertilizers application decreased the mitigation potential of the IRWHT at the effective root zone of the sorghum, although this reduced sorghum plant height increase rate, it increased final biomass and grain yield. The results revealed that sorghum growth performance, grain yield, and final biomass depend on the synergistic influence of in situ rainwater harvesting technique applied, rainfall amount, soil moisture level and integrated fertilizer source. In the above-average rainfall season, fertilizers mask the influence of the IRWHT, the opposite is true in the below-average rainfall season. Although RP with N+FYM resulted in the highest overall grain yield in the above-average rainfall season, the study recommends practicing tie-ridges with N+FYM as this had balanced drought mitigation during the critical period of soil moisture stress and resulted in the highest grain yield in the below-average rainfall season, which is typical rainfall characteristics in the marginal dryland areas of Tanzania. In the second experiment, five treatments, namely, sole sorghum cropping (Control), temporal intercropping of sorghum-groundnut on the same day (0SG_DAS), intercropping groundnut at the 15th day (15G_DAS), 30th day (30G_DAS), and at 45th day (45G_DAS) after sowing the sorghum were replicated three times in a complete randomized block design. The second experiment revealed that early intercropping of sorghum-groundnut increases the rate of soil moisture depletion at the effective root zone of the sorghum. This depletion in soil moisture increases the risk

of crop failure during the extended dry spell, when the crop water demand is higher, but the soil moisture is limited due to insufficient rainfall and higher rate of evaporation. Across the two seasons, the highest and lowest risk in crop failure due to moisture stress were recorded in 0SG_DAS and sole cropping, respectively. The risk in crop failure in 0SG_DAS was 70.3% in the above-average rainfall season. However, it increased to 97% in the below-average rainfall season. Although the sole sorghum cropping had the least (94%) comparable risk in crop failure, it still had a low influence in enhancing crop productivity under the low and unreliable rainfalls in the prone dryland areas of Tanzania. In order to enhance crop productivity, it is recommended to grow groundnut and sorghum separately to avoid increasing risk of crops failure. Since the risk in crop failure is still higher even in sole sorghum cropping, practicing IRWHT, could help mitigating the risk of crop failure during the extended drought period in the dryland areas.

Keywords: Climate change; water scarcity; nutrients deficiency; nutrients sources; sorghum production; critical period of soil moisture stress; expected extended drought period risk; temporal intercropping pattern; risk in crop failure.

CHAPTER ONE

INTRODUCTION

1.1 Background information

Soil water and nutrients are the foremost limiting factors that determine agricultural productivity (Brouwer et al., 1993; Eswaran et al., 1997; Mati 2007; Thornton and John, 2003; Mahinda, 2014). They play key roles in crop production, and their management is important if potential crops yields have to be sustainably realised. In Sub-Saharan Africa, where the majority are employed in the agricultural sector (URT, 2001; Bates et al., FAO, 2011; Hounkonnou et al., 2012; Makino, 2013), water and nutrients availability dictate the level of food security and social-economic welfare (Mnenwa and Maliti, 2010; Livingstone et al., 2011; Chauvin et al., 2012; FAO, 2015; Mahinda et al., 2016). Holding other factors constant, water scarcity and low soil nutrients status for crop production in Sub-Saharan Africa are the key bottlenecks that have to be critically addressed to solve the myth of hunger and poverty, which have been co-existing for centuries (Thornton and John, 2003; Barron, 2005; Barron and Okwach, 2005; Willy, 2007; Wolter, 2008; FAO, 2009; Livingstone et al., 2011; Chauvin et al., 2012; Thornton et al., 2014; Mahinda et al., 2018b).

Although the magnitude of water scarcity and nutrients availability in Sub-Saharan Africa varies across agro-ecological zones and farming systems (Liniger et al., 2011; Thornton et al., 2011; Pretty et al., 2011; Yihun et al., 2013), its effect is more severe in arid and semi-arid areas (Hatibu and Mahoo, 1999; Faz Cano et al., 2002; Shemdoo et al., 2009; Shemdoo, 2010, 2011; Chauvin et al., 2012; Mahinda et al., 2017). The problem is even exacerbated by the negative impacts of climate change (Sivakumar et al., 2005; MAFAP, 2013; IPCC, 2014). Since agricultural activities in this region rely on rain-fed

condition, any further adverse effect on climate change would intensify the negative consequences on crop production and livelihood of the majority in arid and semi-arid areas (ASALs) (Kilasara et al., 2015; Mahinda et al., 2018a; Pages et al., 2010).

In Tanzania, the extent of ASALs in 1980's was 50% of the land mass as surveyed by De Pauw (1984). A few years later, Pratt and Gwynne (1997), as cited by Serwatt and Mollel (2007) in the FAO report of the United Republic of Tanzania revealed an increased percentage of ASALs, whereby arid and semi-arid areas were covering the land mass by the same proportional, each by 30%. This means that by 1990's ASALs were already dominating the total land mass of the country by 60%. The area of ASALs might have further increased beyond 60% due to regular occurrences of extreme weather events caused by climate change and variability, increased population pressure and a high rate of environmental degradation.

The regions, which are characterised by ASALs features in Tanzania include Dodoma, Singida, Shinyanga, Tabora, Mara, Simiyu, Geita, parts of Iringa, Mwanza, Morogoro and Same district in Kilimanjaro. Of all these ASALs regions, Dodoma, which is located in central part of Tanzania, is a good representative of ASALs in the country. Like other ASALs of Sub-Saharan Africa, the area is characterized by low rainfall with high rate of intra and inter-annual variations (Hatibu and Mahoo, 1999; Mary and Majule, 2009; Chauvin et al., 2012; Kilasara et al., 2015; Mahinda et al., 2018a). The annual rainfall received (300-600 mm) is poorly distributed to meet crop water requirement of the major crops grown mainly: sorghum (*Sorghum bicolor*), millet (*Pennisetum glaucum*), sunflower (*Helianthus annuus*), maize (*Zea mays*), simsim (*Sesame indicum*), ground-nut (*Arachis hypogaea*), Bambara-nuts (*Vigna subterranean*) and grapes (*Vitis vinifera*). The annual water balance is usually negative as evapotranspiration rate exceeds precipitation for more than 7 months (Hatibu and Mahoo, 1999; Nicholas, 2010; Yihun et al., 2013;

FEWSNET, 2014; Mahinda, 2014). The amount of water, which is lost through evaporation is 70~85% (Kilasara et al., 2015), therefore, less than 15~30% is used for plant growth.

Based on the soil moisture regime, original parent materials and the transformation nature of the soil in ASALs, majority of soils in Dodoma have poor soil structure with low water retention capacity (De Pauw, 1984; Cooke et al., 1993; Braun et al., 2010; MAFC, 2013; Mahinda, 2014) and inherently low plants nutrients notably, nitrogen (N) and phosphorus (P) (Kang and Fox, 1981; Buresh et al., 1997; Bationo and Mokunywe, 1991a; Sivakumar, 1993; Msanya et al., 1994; 2002). Furthermore, intensive land cultivation without fallowing has resulted to declining of soil organic matter and depletion of the major and minor crop nutrients (Murwira et al., 1995; 2003; Kang and Fox, 1981; Kimaro et al., 2008; Nelson and Stathers, 2009). In improving soil fertility and maintaining productivity capacity of the land, industrial fertilizers and farmyard manure have shown the potential for increasing sorghum grain yield. However, soil moisture deficit dictated by inconsistent and low rainfall amount limits the dissolution of the applied fertilizers and subsequent availability of nutrients for the crop uptake. Field experience shows that the use of industrial fertilizers under limited soil moisture conditions intensify crop failure. This is because, the higher concentration of partially dissolved fertilizer at the rhizosphere causes burning effect to the roots of crops, particularly when the inorganic fertilizers are applied. As the results, farmers have not been using fertilizers to avoid a risk of crop failure, due to limited soil moisture.

The combination of soil moisture stress and nutrients deficiency has resulted into low yield potential and less farm returns of the major crops grown including sorghum, which is the main staple food in ASALs, and an emerging cash crop in Tanzania and the World in general (Odhiambo, 2011; Makindara et al., 2013; Heard, 2014; Mahinda et al., 2016;

NSP, 2017; Cogburn, 2017). Currently, sorghum is demanded as a substitute to wheat and barley in brewing industry for making clear based alcohol such as Eagle, Eagle-dark, Senator kreg, Senator plus, Red bridge, Bards beer, New grist, Revival sorghum whiskey, James F.C Hyde Songo whiskey, Harvest rum whisky, S.S sorghum whiskey as well as non-alcoholic drinks such as Malta. It is also needed in baking industry for making bread, cakes, pancakes, popped-sorghum, buns, chocolate, biscuit, muffin, pizza and pasta. Moreover, it is the crop of choice for brewing traditional African beers. Although the crop is highly demanded as the staple food and industrial raw material (TBL, 2011, 2017; Konfo et al., 2015; Mahinda, 2016, 2017; Kilasara et al., 2015; Mahinda et al 2017), its supply to meet the demand is limited (Babisho, 2016; Rono et al., 2016; Njuguna, 2018; Mahinda et al., 2018b). The acreage for sorghum production has increased by 3.6% (FAO 2013; Mahinda, 2014), but the grain yield has declined by 7% (NBS, 2019) The main reasons attributed to the declined sorghum yield production per unit area is low rainfall amount, high rate of evapotranspiration, inter and intra-annual rainfall variability, surface runoff and inherently poor soil fertility status in the dryland areas; where the crop is majorly cultivate (Mahinda et al, 2018b).

In improving sorghum yield production in Tanzania, while sustainably maintaining productivity of the land in ASALs, an integrated approach, which addresses soil water and fertility management is required. Such an approach should consider the availability of local nutrient sources, efficient utilization of the rainwater, and rational agronomic balance of water and nutrients through intercropping patterns, which are practically possible for poor resource farmers of ASALs. Already different initiatives have been carried out to enhancing sorghum yield production in ASALs of Tanzania. Breeding program for instance, has led to release of drought-tolerant varieties, including Macia variety (SDS 3220) used in this study, however, their yield potential under water-stressed

areas, with recurring droughts and extended dry spells, have never been realized (Mahinda, 2014, 2017, 2018a, 2018b, 2018c). Drip irrigation with an effective watering regime has proven the potentiality of achieving sorghum grain yield as high as 13.1 Mg ha⁻¹ (Mahinda et al., 2014, 2016), notwithstanding, the initial cost of drip irrigation investment and lack of technical backstopping are the hitherto caveat to many smallholder farmers. The intercropping of sorghum with leguminous crop have been advocated as a way of diversification to enhance sorghum production resilience as well as enhancing soil fertility and conserve soil moisture, but field experience shows that the expected benefits of intercropping are hardly to meet in less rainfall receiving areas like the ones in ASAL. Furthermore, different soil and water conservation approaches have been intensively employed (Temple, 1972; Kauzeni et al., 1987; Christainsson et al., 1993; Ellis-Jones and Tengberg, 2000; Senkondo et al., 1998; Boyd et al., 2000; Hatibu et al., 1997, 2002; Tenge and Hella, 2005; Kabanza and Rwehumbiza, 2007; Wakindiki et al., 2007; Thierfelder and Wall, 2009; Chokowo et al., 2014; Kilasara et al., 2015; TerAvest et al., 2015; Mbungu and Kashaigili, 2017; Hishe et al., 2017). Most of these studies have focused on areas prone to soil erosion, in areas where the focus has been on improving crop production, less attention has been paid to detailed examination of the potential contribution of ripping and tie-ridges in storing the captured rainwater at the effective root zone of the sorghum, and its subsequent availability to further support sorghum crop growth during the expected extended dry spell periods, which usually occurs in February or March, when sorghum water requirement is high based on its phenological stages, but the rainfall stops, creating hydric deficit. There is also limited knowledge on how different fertilizer sources, integrated with ripping and tie-ridges, would further dictate soil moisture availability during the critical period of moisture stress due to their different influences in promoting crop growth and water uptake. This research, therefore, was

capitalizing in finding the best bet interaction of the selected IRWHTs with fertilizer sources on sorghum performance in ASALs. It also explored in detail the contribution of different temporal intercropping patterns of sorghum-groundnuts on soil moisture availability for sorghum performance in ASALs of Tanzania, and its associated risk for crop failure due to soil moisture stress during the extended drought period.

1.2 Objectives

The general objective of the study was to find out the effectiveness of different IRWHT, intercropping patterns, agronomic soil water, and nutrient management on enhancing land productivity and climate change resilience for sorghum production in dryland areas of Tanzania.

In order to achieve the overall objectives above, two experiments were carried out in the dryland area of Tanzania to test selected treatments, which were responsible for (i) evaluation of the potential contribution of ripping and tie-ridges in storing the captured rainwater at the effective root zone of the sorghum, (ii) evaluation of the influence of integrated IRWHT with organic and inorganic fertilizers on soil moisture dynamics at the effective root zone of the sorghum, (iii) determination of the interactive effects of IRWHT, organic and inorganic fertilizers on mitigation of the critical period of soil moisture stress at the effective root zone of the sorghum, (iv) determination of the interactive effects of IRWHT, organic and inorganic fertilizers on sorghum growth performance, water use efficiency, biomass and grain yield and (v) determination of the effect of sorghum-groundnut temporal intercropping patterns on soil water availability for sorghum production in the semi-arid environment of Tanzania.

1.3 Hypotheses

The first hypothesis assumed that different IRWHT have different contribution to soil moisture regimes at the effective root zone of the sorghum. This hypothesis was formulated based on the specific objective, which was experimented to evaluate the potential contribution of ripping and tie-ridges in storing the captured rainwater at the effective root zone of the sorghum. The differences in IRWHT were assumed not to be equal in terms of soil moisture levels because of their observed differences in capability in capturing and retaining rainwater during rainfall events. It was therefore assumed that the differences in volume and time at which water was retained in the ripping would have resulted in more stored soil moisture at the effective root zone than in the tie-ridge treatment at any particular point in time.

The second hypothesis idealized that integration of organic and/or inorganic fertilizers were likely to influence different soil moisture dynamics at the effective root zone of the sorghum. This hypothesis was a possible explanation for the experiment tested to evaluate the influence of integrated IRWHT with organic and inorganic fertilizers on soil moisture dynamics at the effective root zone of the sorghum. The differences in soil moisture regime due to different application of the fertilizer source were due to the fact that different fertilizer sources, in this case organic and inorganic fertilizers, have different rate at which nutrients are released. Given the same initial amount of water stored within a particular IRWHT, and the relationship between soil nutrients, crop growth and crop water requirement; it was assumed that inorganic fertilizer would likely to result in a high rate of water depletion at the effective root zone as compared to organic fertilizer. This is simply because nutrients in inorganic fertilizer are readily available for the crop as opposed to organic fertilizer.

The third hypothesis assumed that application of FYM across the IRWHT would results in a higher mitigation potential during the critical period of soil moisture stress at the effective root zone of the sorghum. The aforementioned hypothesis was formulated to address the specific objective in which the collected data were intended to determine the interactive effects of IRWHT, organic and inorganic fertilizers on mitigation of the critical period of soil moisture stress at the effective root zone of the sorghum. The idealized hypothesis was based on the fact that different fertilizer source has different rate at which readily available nutrients are released in time to meet the crop nutrients demand. It was therefore proposed that the fertilizer source, which would result in a vigorously initial crop growth would have a less mitigation potential compared to fertilizer source which contributed to a less initial plant growth.

The fourth hypothesis assumed that sorghum performance would respond differently to different IRWHT and fertilizer sources and is likely to be high in TR_N+FYM across all the season and growth stages. This hypothesis was addressing the specific objective from the experiment with data collected for determination of the interactive effects of IRWHT, organic and inorganic fertilizers on sorghum growth performance, water use efficiency, biomass and grain yield. The proposed idea derived its concept from the facts on the general understanding of the relationship between nutrients, soil water, crop growth, as well as the amount of readily available nutrients from the fertilizer source. Because of the preconceived idea on the nature of nutrients released of organic (N) and inorganic (FYM) fertilizers, it was generalized that treatments with N+FYM would result in a higher crop growth performance than the rest, and that tie ridge would result in a higher sorghum performance compared to ripping and flat cultivated land across the two seasons. Considering both fertilizer and IRWHT, it was assumed that regardless of any

differences across the seasons, TR_ N+FYM would results in a higher sorghum final biomass, water use efficiency and grain yield.

The fifth hypothesis assumed that different temporal intercropping patterns have different effects on soil moisture availability for sorghum performance. The formulated hypothesis was important to initiate a further investigation on determining the effect of temporal intercropping patterns of sorghum and groundnut on temporal soil water availability for sorghum production in the semi-arid environment of Tanzania. The proposed idea was based on the general understanding of the concepts of the crop water requirement and therefore its implication on the crop performance. It was generalized that given the same volume of soil water at the effective root zone of the sorghum, the time at which groundnut is introduced in the sorghum field affects the rate of the soil water depletion and therefore water level at the effective root zone of the sorghum. The resulted different water level would subsequently result in different rates of crops performance.

CHAPTER TWO

LITERATURE REVIEW

2.1 Water scarcity for crop production under rainfed agriculture in dryland areas of Sub Saharan Africa

Water scarcity is a major concern cutting across different sectors. It is the central component that without it neither agricultural activities nor the overall life on the earth could have existed (Baron 2004; Baron and Okwach, 2005; Whitehead et al., 2009; Livingstone et al., 2011; MAFC, 2013; Mahinda, 2014). Although the magnitude of water scarcity varies across different regions and sectors, it has been observed to have more negative effects on the agricultural sector in Sub-Saharan Africa than in the rest of the world (Tatlock, 2006; Freitas, 2013; Kilasara et al., 2015; Mahinda et al., 2016). This is partly because, the major economic driver in this region is agricultural activities that depend on natural rainfall, which is insufficient and unreliable (Elasha et al., 2006; Schlenker and Lobell, 2010; White head et al., 2009; Müller et al., 2011; Mueller et al., 2012; Kangalawe and Lymo, 2013; Mahinda et al., 2018b). The problem is even exacerbated by the negative impacts of climate change and variability, which have led to increasing inconsistency in rainfall pattern, duration, amount and intensity with respect to the grown crops demands (Houghton et al., 2001; Li et al., 2009; Trenberth, 2011; Berner and Berner, 2012; IPCC-AR5 WG1, 2013; IPCC-AR5 WG2 A, 2014, IPCC-AR5 WG3, 2014; Team et al., 2014). As a result, there have been recurring crops failure even for sorghum, which for many years is believed to be the drought-tolerant crop (Mahinda, 2014; 2016). This has resulted in stagnant living standards and malnutrition due to insufficient food production and poor living standard of the majority in the region (Ngingi,

2003; Ngigi et al., 2003; Adugna, 2007; Paavola, 2008; Ahmed et al., 2009; Mbeyale et al., 2014).

In finding solution to make Sub-Saharan Africa self-sufficient for food production, different researchers have shown that most crops can be sustained through irrigation, as it plays a vital role in ensuring crop production throughout a year (Purcell, 1997; Rosegrant and Perez, 1997; Sally and Albernethy, 2002; 2011; Kadigi et al., 2004; Karlberg and de Vries, 2004; Frenken, 2005; Tesfaye et al., 2008; Liz et al., 2005; Sally and Albernethy, 2011; Kadigi et al., 2012, Friedlander et al., 2013; Mahinda, 2014, 2016; Wanvoeke et al., 2016; Mahinda et al., 2017, 2018a). However, many farmers in the region are not financially capable to meet the initial cost of drip irrigation system, including a borehole drilling. There is also insufficient technical backstopping due to few competent and experienced experts in the areas of drip irrigation to address the associated complications due to salinity problems and drip lines blockage. The evidence shows that, in many cases, it is difficult for farmers to attain even a break even on the investment in drip irrigation when the production is only intended for food production (Fox and Rockström, 2000; Kay, 2001; Lankford, 2008; Abdrabbo and Abou, 2009).

The ecological and economic friendly solution for the farmers is to utilize effective ways that would directly capture and encourage rainwater to concentrates, infiltrates and get stored in the soil for crop utilization in the later stages of the crop growth when the water requirement to meet bio-physiochemical demand of the crop is high, but the soil moisture is limited due to erratic and insufficient rainfall (Mahinda et al., 2018b). If water supply does not meet crop water requirements, water stress adversely affects crop growth, and ultimately final crop yield, particularly when the soil moisture is not available at the critical growth stage (FAO, 2002; Seleshi et al., 2009; Payero et al., 2008; MAFC, 2013, Kilasara et al., 2015; Mahinda et al., 2018c). Therefore, it is anticipated that, the increase

in grain yield as a result of additional unit of the stored water at the root zone, influenced by different in situ rainwater harvesting technique and temporal intercropping patterns would provide basis for assessing agronomic advantages for enhancing climate change and drought resilience for crop production in dryland areas. To successfully attain the targeted goal, this should be done effectively through quantifying crop development and its economic yield against water uses relationship.

2.2 Sorghum production and crop water requirement

Holding other factors constant, sorghum needs the right amount of water to grow well and produce grain yield at its genetic potential (Mahinda, 2016; Mahinda et al., 2018a). Under rainfed agriculture, sorghum depends on both rainwater and the stored soil moisture to meet bio-physiochemical demands. The amount of soil moisture storage greatly influences sorghum seed emergence, growth development, yield production and seed quality (Vanderlip and Reeve, 1972; Knox et al., 2012; Mahinda, 2014; Mahinda et al., 2017).

Sorghum requires appreciable soil moisture during early growth stage, head initiation, flag leaf formation, booting and flowering formation (Tolk and Howell, 2003). Sorghum water demand increases with the increasing rate up to booting stage, then decreases sharply thereafter (Seleshi et al., 2009; Mahinda et al., 2018a). Based on the soil type, weather conditions, and variety, the estimated water requirement for optimal growth and yield production of sorghum is between 450 to 650 mm (FAO, 2002; Tolk and Howell, 2003; Mahinda, 2014).

The crop coefficient of the sorghum, related to reference evapotranspiration and water requirement, differ with phenological stages (FAO, 2013; Mahinda, 2014). Sorghum crop coefficient at initial stage is 0.35, at crop development (K_{cd}) is 0.75, at

mid-season (Kcm) is 1.1 and at late season stage is 0.65 (Mahinda et al., 2018a). Generally, sorghum takes 120 days to mature, it takes 20, 30, 40 and 30 days for initial growth, crop development, mid-season and late season stages, respectively; however, the maturity period might vary depending on the variety and weather condition (Seleshi et al., 2009; FAO, 2013; Mahinda, 2014). For Macia sorghum variety (SDS 3220), an average daily water use is approximately 1 to 2.5 mm day⁻¹ during the first 30 days, up to approximately the 7th-leaf stage (Knox et al., 2012; Mahinda 2014). The water requirement then increases to around 7 to 10 mm day⁻¹ until the booting stage is attained (Seleshi et al., 2009; Assefa et al., 2010; FAO 2013; Mahinda, 2014). Maximum daily water requirement is from the booting stage to after flowering. The daily water requirement then decreases gradually during grain filling as the crop begins to senescence (Krieg, 1983; McWilliams, 2003; Stichler and Fipp, 2003; Assefa et al., 2010, Mahinda, 2018a).

2.3 Sorghum water use efficiency

Agronomically, the quantity of water used by the plant to accumulate one gram of dry matter is termed as water use efficiency (WUE), in this context it can also be referred to as water productivity. WUE is usually expressed as a ratio of the water used to carbon gained. Bacon (2004) define WUE as the ratio of CO₂ assimilation into the photosynthetic biochemistry to water lost by transpiration process through stomata. It can also be defined as the crop biomass produced per volume of water used (Fan et al., 2005; Conley et al., 2001; Mahinda, 2014). Technically, WUE reveals how efficiently water is being transpired by a crop in converting sunlight energy into chemical energy and its derivatives (Fan et al., 2005; Payero et al., 2008; Mahinda et al., 2018a) It is, therefore, a useful tool for yield targeting as it provides benchmarks for farm performance, which

helps in comparing different management options (Fairweather et al., 2004, Mati; 2007; Adzemi and Ibrahim, 2014; Mahinda et al., 2018a). Comparing WUE in different soil moisture conservation, temporal intercropping patterns, and fertilizer management options helps to understand the effectiveness of each option and identify areas for potential improvement.

Being a C₄ plant, sorghum is efficient in utilizing water compared to C₃ cereals plants such as rice and wheat (Mahinda, 2014). In the group of C₄ plants, sorghum has proved to utilize water more efficiently compared to other C₄ crops such as maize, lablab, and sugarcane (Mahinda, 2014). The physiological ability to transpiring little amount of water to produce a substantial amount of biomass, has given sorghum an added advantage to be grown in ASALs regions, where other crops would completely fail (Reddy et al., 2008; Mahinda et al., 2018a). High water productivity in sorghum has made it to be grown in more than 80 % in dryland areas of the world; which occupies approximately 41% of the total global land area, and support about 2.5 billion people (Corbett, 1996; UNDP/UNSO, 1997; Lizia, 2014; CGIAR, 2019). Being the drought-tolerant crop, sorghum is often preferred by producers in cases of expected water stress due to low rainfall (Mahinda et al, 2017). This is because, sorghum grain tolerates and avoid drought stress more than many other cereal crops (Africa Review, 2016). However, the drought tolerance of sorghum comes at the expense of the grain yield (Adzemi and Ibrahim, 2014; Mahinda, 2014; Mahinda et al., 2018a; 2018b).

2.4 Factors affecting sorghum water use efficiency

2.4.1 Soils

For the same given amount of water, soil types dictate the level of water availability to the crop (Brady and Weil, 2008; FAO, 2013). Under rainfed condition, where

precipitation is not sufficient, loam soil is preferred for the grain sorghum production as it has high plant-available water holding capacity compared to clayey soil (ARC-grain, 2008; Assefa et al., 2010). In soils with high bulk density, root growth might be restricted, and water use is negatively affected (Urio et al., 1979; Juma, 1999; Brady and Weil, 2008; Mahinda, 2014). Generally, soil dryness due to a high rate of evaporation, particularly in dryland areas, poses constraints on the crop growth and functioning of the roots; most of these constraints are poorly understood due to heterogeneity nature of the rooting environment, delicate nature of the relationship between roots and soil's structure and the difficulties in investigating roots growth and functioning without disrupting this relationship (Sharp and Davies, 1985; Blackman and Davies, 1985; Bacon, 2004; Costa et al., 2007). But, in general, an increased rooting depth across few centimetres of the soil, might increase water uptake by root systems, even when few roots are involved (Bacon, 2004).

It is a common phenomenon that, water use efficiency and the ability of the sorghum roots to extract soil water become constrained when soil moisture level substantially declines. As soil water potentials fall, particularly in soil with low mechanical impedance, roots are usually supplied with carbohydrate to enabling them to grow, which in turn allow the plant to explore deeper water reserves (Sharp et al., 1988; Bengough, et al., 2011). However, in most soils, the decrease in water potentials are commonly associated with increased mechanical impedance, which makes roots swell behind root apex to develop a turgor pressure as a mechanism for penetrating the soil (Atwell and Newsome, 1990; Spollen et al., 2000; Bacon, 2004; Sharp et al., 2004).

Generally, when soil water availability for sorghum growth drops below a certain level, the decrease in root turgor pressure and water potential stimulate the synthesis of several plant growth regulators including abscisic acid (Wu et al., 1994; Wright, 1977;

Bacon, 2004). The production and translocation of abscisic acid from the roots act as a suitable messenger to ensure the demand for water from the plant is closely controlled by water supply from the roots (Sharp et al., 1994; Bacon, 2004); but if soil water is still not available, the final crop yield and biomass, and hence water productivity are highly affected (Mahinda et al., 2018a).

2.4.2 Land manipulation techniques

Different land management practices play a significant role in influencing the rate at which water is converted to biomass. Through altering the heat balance at the soil surface and the exchange rate of heat between the soil and the atmosphere (Hatfield et al., 2001), as well as the rate at which water infiltrates into the soil; land manipulation techniques are known to influence soil moisture storage and a degree of surface evaporation compared to conventional tillage (Mahinda et al., 2018b).

Land manipulation techniques like ripping, ridging, tie-ridges, chololo pits and matengo pits, helps to break surface sealing and subsurface hardpans and encouraged water to concentrate, percolate, infiltrate and finally stored in the soil. By encouraging rainwater infiltration, these tillage techniques store soil moisture, which helps to mitigate the adverse drought effects in the later growth stages when the rainfalls stop, but the crop water requirement is high (Mahinda et al., 2018b). Apart from enhancing drought resilience for crop production, the appreciable soil moisture from land manipulation techniques, helps in dissolving and leaching soluble salts out of the rhizosphere (Kumar et al., 2014; Mishra et al., 2018), therefore, enhances plant water uptake and crop water productivity (Mahinda et al., 2018b).

2.4.3 Mulch

Covering the soil with inorganic mulches as well as adding crop residues, farmyard manure, and other organic materials decrease the incoming heat energy capable of evaporating water by preventing the rate of heat exchange between the soil and atmosphere, and trap vaporized water (Assefa et al., 2010). The retained soil moisture due to the presence of soil covers encourages decomposition and degradation of organic matter, which in turn provides complex functions that increase the soil water and nutrient holding capacity by acting like water sucking sponge and nutrients magnet, respectively (Brady and Weil, 2008; Mishra et al., 2018).

Permanent crop cover as a part of soil management, contributes to soil organic matters, which bind soil particles together and thus improve soil structure, and provides appreciable proportion of micropores, mesopores, and macropores (Brad and Weil, 2002). The balance of these pores is important in regulating percolation and infiltration of the water as well as improve aeration of the soil for the overall crop performance (Mishra et al., 2018). The improved soil structure also reduces bulk density, therefore, allows easy root penetration for the absorption of water and nutrients (Mishra et al., 2018). Crop cover like groundnut, lablab and other leguminous crops in intercropping, are believed to reduce the evaporation loss. However, field observation showed that when the leguminous crops are subjected to intercropping in the less rainfall receiving areas, they are likely to compete with the primary crop, therefore, compromise the yield of both primary and secondary crops. Nevertheless, cover crops are known for their ability in reducing the terminal velocity of the raindrops and ensures smooth infiltration and of the rainwater (Jama et al., 1998; Mishra et al., 2018).

2.4.4 Environmental factors

Rainfall, temperature, solar radiation, relative humidity and wind speed are abiotic factors, which significantly influence sorghum water use efficiency due to their effect on crop growth and development (Allen et al., 1998; FAO, 2002). Sorghum water requirement is higher in the climate with high evapotranspiration demand and lower under mild climatic conditions, defined by a moderate temperature range between 20 - 25°C, low wind speed of less than a meter per second, solar radiation, and a humid environment (Tolk et al., 1997; Tolk and Howell, 2003; Mahinda, 2014). Keeping other factors constant, if sorghum plant is well matched to its ideal environment, based on the crop water requirement at each phenological stage, the highest yield potential is achieved, and high-water use efficiency is realized (Mahinda et al., 2016; 2018a)

Like in other annual crops, when the rainfall is unreliable and insufficient enough to meet crop water demand, particularly during the critical growth stages, sorghum crop growth and therefore final biomass is reduced irrespective of the water availability in the earlier or late growth stages (Mahinda et al., 2018b). This leads to a reduction in water productivity because more than half of the biomass accumulation in sorghum occurs during the grain filling (Roozeboom and Prasad, 2016; Mahinda et al., 2018a).

2.4.5 Cropping window and crop density

In dryland areas, the time for sorghum planting within the cropping window influences crop growth, final biomass and water productivity (Mahinda et al., 2019, unpublished). While early planting might result in the high-water productivity by taking advantage of the first rainfall, it is becoming increasingly challenging to predict the exact planting date under the rainfed agriculture due to the shift of rainfall's onset (Mahinda et al., 2018b). Field experience shows that, the early established crop at the beginning of the season are

likely to face drought stress and sometimes failure during the expected extended drought period. In years with sufficient rainfall, and reduced extended droughts, the effect of planting date might greatly affect sorghum water productivity (Mahinda et al., 2019, unpublished). In general, planting time and crop density affect sorghum water productivity by altering canopy development and final crop biomass (Baumhardt et al., 2007; Mahinda, 2014).

Optimizing planting time and planting density on the basis of soil moisture level, rainfall pattern, distribution and amount minimizes the constraints for plant water stress, which could be raised by high crop water requirement at the critical growth stages (Krieg, 1983; Ahmad et al., 2004; Mahinda, 2014; Mahinda et al., 2018b). Sorghum plant density and time of planting in the season influences crop development, changes in leaf size and final grain yield (Mahinda et al., unpublished). Changes in leaf size alter carbon dioxide and water fluxes in and out of the leaf due to modification of the leaf boundary layer and leaf thickness; this alteration significantly affects water use efficiency (Bacon, 1999; 2004; Costa et al., 2007). Generally, thin leaves exhibit lower water use efficiencies than thick leaves (Stanhill, 1986).

Plant population that leads to a rapid leaf development in sorghum contributes to an effective water productivity (Bacon, 1999). Rapid establishment and high leaf area result in a good canopy, which prevents water loss at the soil surface, therefore, the stored water in the soil can be utilized by the plant when it is needed (Blum and Arkins, 1984; Blum, 1996; Asseng et al., 2003; Van Ittersum et al., 2003; Mahinda et al., 2018b). However, to ensure the potential crop biomass, appreciable water supply at the beginning of stages should complement with the water supply in the advanced sorghum's growth stages. Notwithstanding, this would depend on the rainfall characteristics, such as intensity,

distribution, pattern, and soil water conservation employed. (Bhagsari and Brown, 1986 cited by Bacon, 2000; Mahinda et al., 2018b).

2.4.6 Pests and diseases

Pest and diseases affect sorghum water use efficiency by interfering with plant bio-physiochemical process and general plant growth (Rabbinge and Rijsdijk, 1982; Ogecha, 1995). Therefore, they affect the way plants utilize water, and the rate at which water is converted into biomass during the photosynthesis process (Mahinda, 2014). Plant pests like fall armyworm (*Spodoptera frugiperda*) and common armyworm (*Spodoptera exampta*), substantially chew and remove essential parts of the sorghum plants including leaves and stem. Other pests like Spider mites (*Oligonychus indicus*), Ching bug (*Blissus leucopterus*), Sorghum midge (*Stenodiplosis sorghicola*), Brown stink bug (*Euschistus spp*), ice stink bug (*Oebalus pugnax*), Earhead bug (*Calocoris angustatus*), Green sting bug (*Nazera viridula*), Leaf-footed bud (*Leprogloosus phylopus*), Corn aphids (*Rhopalosiphum maidis*), Rutherglen bug (*Nysius vinitor*), Shoot bug (*Peregrinus maidis*) suck sorghum plants sap from either leaves, stem or panicle at milking stage; in doing so, they impair sap balance in plants as well as act as vectors for plant pathogens (Meyer and Whitlow, 1992; Katayama et al., 2014). Both plant sap depletion and diseases arose as a result of sucking activities, interfere with the normal functioning of the plant and affect crop biomass and efficient water productivity.

Moreover, Sorghum stem borers (*Busseola fusca*, *Chillo partellus*, *Sesamia calamistis*, *Sesemia inferens*), African ball-worm (*Helicoverpa armigera*); Semi-loopers (*Eublemma silicula*) directly feed on sorghum plants and make tunnels on stems and holes on leaves, while Cutworms (*Agrotis spp*) and Black-field-earwig (*Nala lividipes*) feed on the roots of the sorghum plants; all of these affect water and nutrients

transportation from the roots to the upper parts of the plants, and prevent the translocation and allocation of photosynthates to different parts of the plants. Under severe infestation, plants which are affected by tunnelling are highly susceptible to stem lodging and death of the entire plant. Insect like Shoot-fly (*Atherigona soccata Rondani*) feed on the base of the growing part of the plant, resulting in the dead heart of the newly formed leaves, this stimulates tiller formation and deviation of the nutrients from the main stem. Also, Leaf roller (*Marasmia trapezalis*) reduces the surface area of leaves exposed to the sun, therefore, limits the potential ability of the leaves to effectively trap and convert sunlight energy into carbohydrate through the process of photosynthesis. Other insect pests such as Sorghum webworm (*Nola sorghiella*), Sorghum head caterpillar (*Cryptoblabes adoceta*) feed on the developed grains at soft dough and hard dough stages, thereby reduce the total biomass of the sorghum, and affect the final grain yield quality.

Diseases, which affect sorghum plant, hence, the general water productivity along with their causative agents include smut (Covered kernel) caused by *Sporisorium sorghi*, zonate leaf spot caused by *Gloeocercospora sorghi*, charcoal rot caused by *Macrophomina phaseolina*, grain mould caused by *Fusarium spp*, down mildew caused by *Peronosclerospora sorghi*, anthracnose caused by *Colletotrichum graminicola*, gray leaf spot caused by *Cercospora sorghi*, rough spot caused by *Ascochyta sorghi*, loose smut caused by *Sporisorium cruentum*, rust caused by *Puccinia purpurea*, leaf blight caused by *Exerohilum turcicum* (Syn: *Helminthosporium turcicum*) and ergot caused by *Sphacelia sorghi* (Frederiksen, 1980; Jaetzold and Schmidt, 1983; Isakeit, 2008; Ochieng et al., 2011, White et al., 2012). Agronomic practices that involve timely pest and control reduces the degree of pest infestation and disease infection, thereby enhance water use efficiency. (Krausz et al., 1995; Ochieng et al., 2011; Muui et al., 2013; Blanton et al., 2011; Mahinda, 2014; Lance, 2019).

2.4.7 Sorghum variety and cultivars

The difference in the ability at which water is extracted from the soil is not only limited to crop species. Within the crop species, different varieties and cultivars have different ability in extracting and utilizing water (Mahinda, 2018a). While some sorghum varieties and cultivars are drought tolerant and utilize water more efficiently, other varieties are highly susceptible (Lewis et al., 1974; Machado and Paulsen, 2001; MAFC, 2013). An overall transpiration flux in the sorghum plant is determined by the variety or cultivar hydraulic architecture characteristics (Bacon, 2004). Any change in these characteristics due natural adjustment or breeding techniques leads to an alteration in the response in the functioning of the stomata and change in the transpiration rate (Sinclair et al., 2005). This influences water use efficiency when crop development has to be considered throughout the growing season (Richards et al., 2002; Bacon, 2004).

Drought-tolerant varieties and cultivars have deep and expansive root systems that ensure maximum water use efficiency in terms of water extraction from the soil, particularly when available soil water is limited (Mahinda, 2014). An ability of the variety to develop deep and adventitious roots when soil moisture condition is increasingly limited for crop growth, enhances sorghum's capacity to extract available soil water at the adjacent soil layers. As sorghum available soil water declines and become limited the ratio of roots to shoots is altered. According to Sharp and Davies (1979), root can still increase in length and biomass in a limited soil moisture condition.

2.4.8. Irrigation regimes and season

The amount and time at which sorghum plant is supplied with water is very important in influencing sorghum growth development, final biomass and water use efficiency

(Mahinda, 2014; Jabereldar et al., 2017; Mahinda et al., 2018a). When sorghum is supplied with water early in the morning, the rate at which water is transformed to biomass is slightly higher than irrigating late in the evening (Mahinda, 2014). But the differences are more than doubled when sorghum is irrigated both early in the morning and late in the evening (Mahinda et al., 2017).

Comparing water supply for sorghum growth in the off-season and that supplemented during rainy season in dryland areas, Mahinda et al. (2018a) revealed that sorghum final biomass and water productivity is higher in the rainy season than in the offseason. A high biomass and water productivity during the formers season, were due to the favourable weather condition and reduced effects of advection (Mahinda, 2014). It should be noted, regardless of the highest recorded biomass in the rainy season, the highest grain yield is likely to be in offseason provided that sorghum is irrigated both early in the morning and late in the evening. Such trend is not expected to occur when sorghum is only irrigated once either early in the morning or late in the evening. This could be due to the fact that during the offseason period, a single irrigation cannot counteracting the effects of advection on the crop growth and development, therefore hinders the plant to take advantage of the fully exposed solar radiation in the overall process of photosynthesis, and allocation of carbon to the economic part of the plant (Mahinda et al., 2018b).

As the time intervals for irrigation increase and sorghum plant is water-stressed, the rate at which water is converted to biomass decreases (Mahinda, 2014). However, the magnitude of the decrease in water use efficiency depends on phenological stage when the sorghum plant was stressed. While studying the effects of deficit irrigation scheduling on water use efficiency across different sorghum genotypes, Jebereldar et al. (2017) showed that when sorghum is water-stressed for three weeks at the eighth leaf stage; panicle length, panicle weight, number of grains per panicle, hundreds seed weight, grain

yield and water use efficiency are significantly reduced compared to when sorghum is water-stressed at three-leaf stage.

It should be interesting to note that given a similar irrigation regime, the rate at which water is converted to biomass varies across ecological zones. Although it could be nearly impossible to attain the highest water use efficiency in dryland areas by irrigating sorghum with 50% of crop water requirement, Garofalo and Rinaldi (2013) indicated that it might be possible to attain such value in the Mediterranean environment. However, they were not able to show the consistency in their results across the three years of their experimentation. Looking across different crops, there are different conclusions on the influence on irrigation amount and water use efficiency. Tolk and Howell (2003) reported that the increase in irrigation water could reduce water use efficiency, but Farrè and Faci (2006) disapproved the likely phenomena of Tolk and Howell (2003); notwithstanding, their findings were still in line with the work of Amaducci et al. (2000) who showed the failure of fibre sorghum to take advantage of the well-watered environment. It also agreed with the work of Zegada-Lizarazu et al. (2012), who showed insignificant relationships between irrigation amount and water use efficiency. Their findings however were subjected under condition which compromised parameters for water use efficiency (Garofalo and Rinaldi, 2013). Nonetheless, Mahinda (2014) and Mahinda et al. (2017, 2018a) clearly observed the increase in water use efficiency with irrigation frequencies, which maintained appreciable soil moisture content at the rhizosphere.

2.5 Sorghum water stress

Understanding the relationship between sorghum's phenological stages and their corresponding crop water requirement, as well as crop stage that are susceptible to drought stress, is important in enhancing sorghum performance in dryland areas. This is

because sorghum water requirement is not equally the same throughout the growing season. The sensitivity of sorghum to water deficit varies depending on growth stage. According to Mastrori et al. (1995), FAO (2002), Seleshi et al. (2009) and Mahinda et al. (2018a), sorghum is more sensitive to water deficit during seedling emergence, head initiation, booting, flowering and grain filling stage. The sensitivity of sorghum to water stress along with their implication at different phenology stages are described below.

2.5.1 Sorghum moisture stress during seedling emergence and vegetative growth

Holding soil temperature and oxygen constant, moisture is important for seed germination in sorghum, just as in any other crops (Arau et al., 2001; Mahinda, 2014). But in general, sorghum's embryo seed is dormant and highly tolerant to water stress, however, the susceptibility to moisture stress increases after seed germination and emergence (Blum, 1996). Studies by Jafar et al. (2004) and Bayu et al. (2005) showed that water stress at seedling stage reduces growth of the coleoptile, mesocotyl and radicle, which causes tremendous effects on germination of seed and seedling emergence from the soil. Since sorghum stand establishment depends on seed germination and emergence, drought stress, therefore, causes a loss in sorghum crop even before plant establishment (Arau et al., 2001; Assefa et al., 2010; Mahinda, 2014).

The increase in time intervals for water supply after germination, increases sorghum plant water stress, which affect the rate at which water is converted to biomass. The degree of decrease in water use efficiency varies within the vegetative stage. Jebereldar et al. (2017) showed that when sorghum is water-stressed for three weeks at the eighth leaf stage, panicle length, panicle weight, number of grains per panicle, hundreds seed weight, grain yield and water use efficiency are significantly reduced compared to when sorghum is water-stressed at three-leaf stage. In principle, stress reduces the rate of cell expansion,

hence cell size, which affects growth rate, stem expansion, leaf area and appearance due to changes in chlorophyll intensity, and thereby affect photosynthesis and grain yield (Stout et al., 1978a; Younis et al., 2000; Mahinda, 2014; Jabereldar et al., 2017; Mahinda et al., 2018b).

2.5.2 Sorghum water stress on reproductive stage

According to Doorenbos and Kassam (1979) and Saleshi et al. (2009), the sensitivity of sorghum to drought stress at the vegetative stage is much lesser compared to reproductive stage. Kramer (1983) revealed that a drought stress of around ten days from booting stage and after anthesis severely affect grain yield. Also, a work of Saini (1997) showed that water stress during reproductive stages stops the development of pollen and ovules, prevents fertilization, and induces premature abortion of fertilized ovules.

As sorghum grain yield is a function of the number of harvested seeds per panicle and individual seed weight (McWilliams, 2003; Mahinda, 2014), all of which can be affected by the severity of water stress during reproductive stages (Assefa et al., 2010; Jabereldar et al., 2017). Sorghum final dry matter decreases due to water stresses at the early boot stage as the result in decrease of both seed number and seed size. At heading or later stages biomass reduction is due to reduction in seed size only (Eck and Musick, 1979; Mahinda et al., 2018a).

2.5.3 Sorghum water stress on sorghum grain yield

Sorghum have ability to osmoregulate and tolerates soil moisture stress within a short period of time (Mahinda, 2014; Jabereldar et al., 2017; Mahinda et al., 2018a), but the final yield is greatly affected when the soil moisture stress is extended (Stout and Simpson, 1978b; Adzemi and Ibrahim, 2014; Jabereldar et al., 2017; Mahinda et al.,

2018b). The works of Lewis et al. (1974), Stout et al. (1978a) and English (1990) have shown that a drop of soil water potential by -12 to -13 bars from the late vegetative to boot stages reduces grain sorghum yield by 17%, and the same drop from the boot to bloom and milk stage through soft dough stages causes 34% and 10% yield reduction, respectively. Eck and Musick (1979), Gad El-Rabi et al. (1988), Machado and Paulsen (2001) have indicated that mild water stress on a well water supplied sorghum plant within 13 to 15 days starting from the early booting, heading, and early grain filling stages does not affect grain yield. Yield is reduced by 12% for a stress from 27 to 28 days, and stress period of 35 and 42 days, at the beginning of the booting stage reduce grain yield by 43% and 54%, respectively. Furthermore, Inuyama et al. (1976) observed that, during the vegetative stage, water stress for 16 days and 28 days reduces grain yield by 16% and 36%, respectively.

A long-term study by Stone and Schlengel (2006) showed that an increase of every millimetre of water above 100 millimetres resulted in an additional of 16.6 kg of grain sorghum. But generally, the relationship between grain yield and water is more complex, because sorghum plant is more sensitive to water deficit at certain phenological stages compared to other (Arau et al., 2001; Mahinda, 2014; Jabereldar et al., 2017; Mahinda et al., 2018a). The performance of sorghum grain yield is more dependent on well-distributed available soil water over the growing season depending on the sorghum's variety water requirement at each phenological stage rather than the sum amount of water available through the growing season (Howell and Hiler, 1975; Kaigama et al., 1977; Farah, 1983; Assefa et al., 2010, Mahinda et al., 2016; Jabereldar et al., 2017; Mahinda et al., 2018a).

2.5.4 Effect of drought water stress on sorghum bio-physiochemical characteristics

The biochemical and physiological responses of sorghum are highly influenced by soil moisture level (Salih et al., 1999; Mahinda, 2014). According to Cechin (1998), water stress causes stomata closure, therefore, lowers stomatal conductance and reduces transpiration rates. Water stress also leads to a decrease in leaf areas, which also has implications in the number of stomata (Perry et al., 1983; Terbea et al., 1995). In turn, this reduces the rate of photosynthesis, because stomata closure and decrease in stomata numbers stop and reduce CO₂ assimilation by the plant leaves, consecutively (Farooq et al., 2009). In mild water stress, there is a reduction in photochemical efficiency of photosystem II activities of phosphoenolpyruvate carboxylase and ribulose-1,5-bisphosphate carboxylase/oxygenase, commonly known as Rubisco (Vinita et al., 1998). Shangguan et al. (1999) indicated that a reduction in phosphoenolpyruvate carboxylase activity has an effect on sorghum plant, as it reduces Rubisco regeneration and functionality and lowers the net photosynthesis due to inhibition of function activity of photosystem II (Farooq et al., 2009; Mahinda, 2014).

Under low soil moisture stress, the closure of the stomata results in a build-up of the internal oxygen concentration, which results in photorespiration instead of photosynthesis (Zelitch, 1973). Therefore, the photosynthesis process that occurs only in chloroplast, is converted to photorespiration, which involves mitochondria and peroxisome as separate cellular organelles in addition to chloroplast (Betti et al., 2016). Within the chloroplast, glycolic acid is formed as the product of the first stage of photorespiration. The formed compound is transported to the peroxisome, where oxygen is consumed for the second time, when the glycolic acid is subjected to a series of reactions. This results in the conversion of oxygen to hydrogen peroxide, which is a toxic compound and has a harmful effect on the plant cells (Osmond and Harris, 1971; Zelitch, 1973).

To reduce the harmful effect of hydrogen peroxide produced, peroxisome catalases and destroys most of the hydrogen peroxide by using its back up enzymes (Irvine, 1970; Cousins et al., 2001). But the rate at which hydrogen peroxide is destroyed, depends on the rate of oxygen consumption (Betti et al., 2016). In the subsequent steps of the glycolic acid pathway, glycine is produced. Glycine enters the mitochondrion and loses a carbon atom in the form of carbon dioxide; it is this carbon dioxide that is released during the photorespiration process, and its loss decreases the net amount of carbon taken up by the plant, therefore, compromise the net photosynthesis (Cousins et al., 2001). In the mitochondria and peroxisome, further reactions of the glycolic acid pathway continue, with the formed compound being returned to the chloroplast, where the process starts again (Irvine, 1970). By interfering with photosynthesis in this way, photorespiration significantly limits the growth rate of sorghum and decrease crop productivity (Cousins et al., 2001; Betti et al., 2016).

2.6 Influence of soil water and nutrients availability for crop production in dryland areas

Climate change has altered hydrological cycle and nutrients cycling, which impacted soil moisture level and nutrients availability for crop production under rainfed agriculture. The problem is even severe in dryland areas where rainfall amount and distribution are not reliable (Mahinda et al., 2018a). Since agricultural activities in these regions rely on rainfed agriculture, any further shift in rainfall pattern, amount and distribution would have direct effects on the soil moisture availability to meet crop water requirements (Mahinda et al., 2018b). The secondary effect of limited soil moisture availability is that applied nutrients would be partially dissolved and therefore limited to meet crop nutrients requirements. The partial fertilizer dissolution has burning effect of the crops, particularly

when inorganic fertilizers are applied. The ultimate result is low crop yield production and poor living standard, as it has been observed in the dryland areas (Thurlow and Wobster 2003; Ahmend et al., 2009; Mahinda et al., 2016). Although soil moisture level plays a major role in soil nutrient availability and rate of crop response to applied fertilizers, improvement of soil nutrients availability enhances crop water use efficiency, which results in high yield production per unit of water transpired (Rockstrom and Falkenmark, 2000; ICRISAT et al., 2007; Mahinda et al., 2018a).

In dryland areas, the challenge of low soil moisture and nutrients for crops production, due low rainfall amount and distribution is aggravated by the low soil water retention capacity, because soil is poor in structure (Cooke et al., 1993; Braun et al., 2010; MAFC, 2013). Also, the soils are inherently low in plants nutrients notably, nitrogen (N), and phosphorus (P) (Kang and Fox, 1981; Buresh et al., 1997; Bationo and Mokunye, 199; Sivakumar, 1993). Moreover, continuous cultivation without fallow has led to substantial decline of soil organic matter and depletion of crop nutrients particularly potassium (K), magnesium (Mg) and zinc (Zn). (Murwira et al., 1995 Kang and Fox, 1981; Mahinda, 2014). Of all the crop nutrients, N is the mostly affected nutrient due to its nature of mobility in the surrounding environment. It is highly succumbed by microorganism as the source of protein to build up their bodies, and its availability to the crop is significantly dictated by the soil moisture condition, pH and temperature. Depending on the soil moisture level, the movement and availability of N at the rhizosphere are largely affected by leaching, surface runoff, volatilization, denitrification and mineralization. While nitrogen loss by volatilization is influenced by low soil moisture condition, loss due to leaching, denitrification and surface runoff occur under high soil moisture level as described below.

2.6.1 Nitrogen sensitivity in dry condition and its loss by volatilization

Commonly, Nitrogen losses through ammonia volatilization is influenced by low moisture condition in both soil and atmosphere, soon after N fertilizer application under high soil pH (Crane, 1972; Cole, 1995; Carirer and Barnier, 1971). When urea fertilizer is applied, the N loss by volatilization is even higher due to its hydrolysis that increases soil pH. However, with ammonium nitrate, the rate of N loss is insignificant as it does not elevate soil pH. Studies show that the amount of urea N loss under warm and dry weather condition varies from 5% to more than 50% of the dose applied (Overrein, 1969; Watkins et al., 1972; Cole, 1995). A dry surface at the time of fertilization may only initially slow down the rate of urea hydrolysis (Derome, 1979). Rainfall, which comes shortly after fertilizer application, before urea is hydrolysed to less mobile NH_4^+ , reduces losses of NH_3 by leaching urea deep into the soil. The depth at which urea leaches and the capacity of the soil to retain NH_3 depend on the soil moisture condition (Crane, 1972). As soil moisture evaporates, it might provide a pathway diffusion for aqueous NH_3 to escape. The rate at which NH_3 volatilization occurs in this way depends on the state of relative humidity, temperature and wind speed (Crane, 1972; Cole, 1995).

Several studies have shown the importance of rainfall in NH_3 volatilization (Cole and Gassel, 1965; Overrein, 1969; Carrier and Barnier, 1971; Crane, 1972; Watkins et al., 1972; Marshall et al., 1980; Cole, 1995). When a simulated rainfall was increased from a light regime at a 9th day to a heavy regime immediately after application of 224 kg N ha^{-1} , Crane (1972) found a decreased loss of NH_3 by 90.5% from $11.6 \text{ kg N ha}^{-1}$ to 1.1 kg N ha^{-1} . Seven years later, Crane (1979) found a drastic reduction of NH_3 volatilization from 18% to 9% when 12 mm of water was irrigated four days after 220 kg N ha^{-1} application from urea fertilizer. After application of 224 kg N ha^{-1} of urea without irrigation, Carrier and Barnier (1971) found a loss of about 30% of the urea-N. This is a huge loss compared

to 22% loss when irrigation of 50.8 mm or 3.2 mm could have been done for three days or one day, respectively, after fertilization. An application of 25 mm of water one day after application of urea, reduces NH_3 volatilization by 8%. However, this might increase when soil temperature is high, as it hastens the rate of hydrolysis. Therefore, the amount as well as timing for irrigation, are important for the reduction of NH_3 volatilization, particularly in the hot months when hydrolysis is likely to be completed between 3 to 5 days (Carrier and Barnier, 1971).

2.6.2 Nitrogen sensitivity in wet condition and its loss by denitrification, leaching, and surface runoff

In water-saturated condition, a significant loss of N is resulted from the reduction of nitrate to N gas by denitrifying bacteria (Broadbent and Clark, 1965). The process takes place even if the oxygen level depleted exists for just a few days (Will et al., 1983; Limaux et al., 1999; Ju et al., 2009; Zhao et al., 2009). The loss is usually minor under low pH condition; however, it has been observed to be higher by more than 70% when the hydrogen ion concentration is reduced to a slightly acidic of 6 or neutral pH of 7 (Bahmani et al., 2009; Nommic and Thorin, 1972).

Although N-loss is not considered to be seriously affected after urea application, urea by itself is readily leachable by mass flow in a sandy soil (Cole and Gassel 1965; Bahmani et al., 2009; Mthandike et al., 2013). When nitrate source of fertilizer is applied, substantial N loss is significantly recorded (Overrein, 1969; Mthandi et al., 2013). Following heavy rainfall, much of N fertilizer is carried together with the soil and deposited offsite into the lowland areas and water bodies. The presence of eutrophication in the water bodies, vegetation growth and higher measured levels of N from the lowland areas, is the evidence of loss of N by the surface runoff. Management practices, which

reduces surface runoff, such as tie ridges and ripping might reduce N loss by surface runoff, however, in a well-drained soil, it might encourage N leaching. This means, excessive soil moisture condition that creates an anaerobic condition is of critical challenges for N management.

2.7 Recent trend in sorghum production, demand and the impact of climate change in dryland areas of Sub-Saharan Africa

Sorghum has gained popularity in recent years; however, it has been cultivated for many years in the warmer tropical and subtropical regions of Africa and Asia, dating back to ancient times (Murdy et al., 1994; Zohary and Hopf, 2000; CSP; Mahinda, 2014). The negative impacts of climate change and occurrences of extreme weather events have favoured sorghum to be the main alternative food and cash crop (Mahinda et al., 2018b). This is due to its genetic tolerance to harsh environmental conditions (Assefa et al., 2010; Borrell et al., 2014).

A decline in wheat and barley production due to increasing temperature, attributed to climate change and variability (Ortiz et al., 2008; Ludwig et al., 2009; Braun et al., 2010; Janjua et al., 2010; Lobell et al., 2012; Kumar et al., 2014; Asseng et al., 2015; Liu et al., 2016; Harvey, 2016; Mahinda et al., 2016) has increasing sorghum market in local and international markets (Rohrbach and Kiriwaggulu, 2007; Mahinda et al., 2018b).

Sorghum, which had been serving as the main staple food in ASALs of Tanzania has become the potential cash crop in Africa and the world in general (Angioloni and Collar, 2013; Odhiambo, 2011; Makindara et al., 2013; Heard, 2014; Mahinda, 2014; TBL, 2016; 2017; NSP, 2017; Cogburn, 2017). A large quantity of sorghum is greatly demanded in brewing industries for making alcoholic and non-alcoholic drinks such as Malta. Sorghum is also needed in bakery industries for making commercial bread, pop sorghum, cakes and

biscuits (Rai et al., 2008; ARMC, 2011 McWilliams, 2003; Angioloni and Collar, 2013; Mahinda et al., 2018a). Furthermore, it is the grain of choice for brewing traditional African beers, wax, starch, edible oils and free gluten feed (Confo et al., 2014; Mahinda, 2014).

At the global scale, sorghum production trends show the yield increment from 40 million megagrams (Mg) during the early 1960s to 66 million Mg in early 1980s, and by the 1990s, it had fallen to about 58 million Mg due to rainfall variability; however, it rose to 64 million Mg by 1996, and was 73 million Mg in 2005, before it went down to 55.6 million Mg in 2010 as a result of the low amount of rainfall attributed by climate change variability (Mahinda, 2014; FAOSTAT, 2018). In 2015, the yield mounted by 15.8% to 66.0 million Mg, then decreased to 63.7 and 57.6 million Mg in 2016 and 2017, respectively (FAOSTAT, 2018). The global increment of the area under sorghum cultivation has shown a general slight decline of about 0.2% per year, and yield of 0.5 per year, before 2000 (FAOSTAT, 2018). The expansion of sorghum acreage in Africa increased by 3.6% a year, however, yields declined by 1.0% a year (FAO, 2013; MAFC, 2013; Mahinda, 2014). Trends indicate that area of sorghum production under rainfed increased from 45 million hectares in the 1970s to 51 million hectares in the 1980s. Later, there was a fluctuation in areas under cultivation by 4 to 10 million hectares and it declined to 25 million hectares by 2009 (FAOSTAT, 2018). In 2016 the area under sorghum production was 31 million hectares, nonetheless, it decreases to 27 million hectares in 2017 (FAOSTAT, 2018). This means, based on the current area (782,717 ha) under sorghum production in Tanzania (FAO, 2018), the country has a contribution share of only 3.0% in Africa. Although there is a great potential for increment in sorghum production due to the negative impacts of climate change (Heard 2014; Asseng et al., 2015; Liu et al., 2016; Mahinda et al., 2018b), Tanzania has dropped one position in rank,

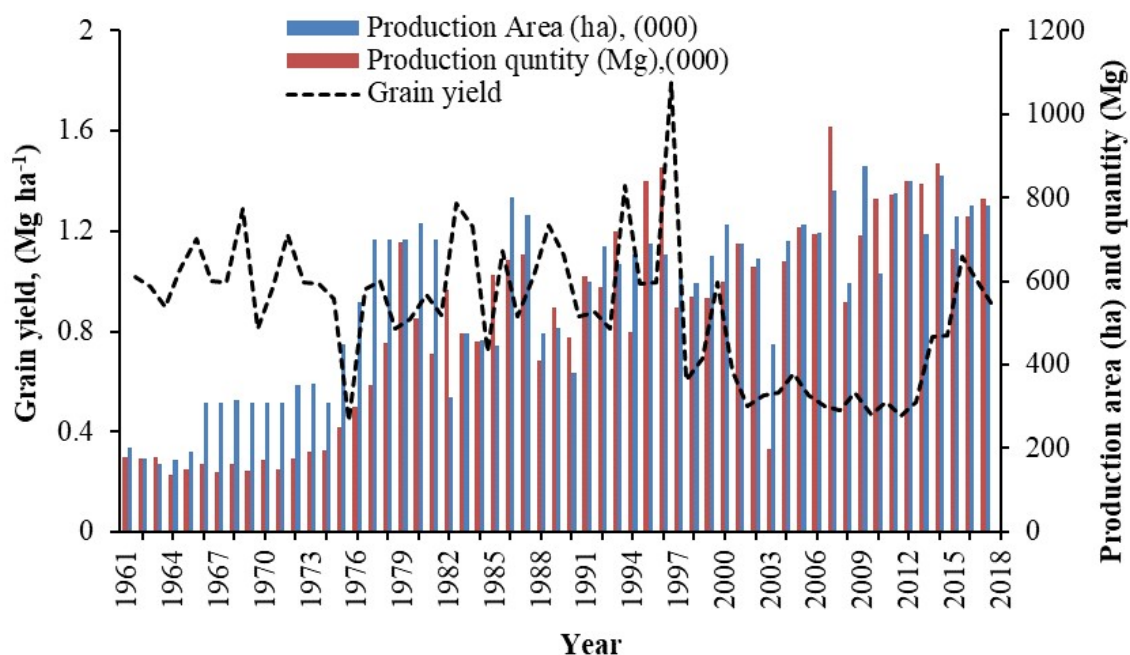


Figure 2.1: Average sorghum production (Mg), area under sorghum production (ha) and sorghum productivity (Mg ha^{-1}) in Tanzania from 1961 to 2017; this figure was plotted with the aid of data from FAOSTAT (2018) and FACTFISH (2019).

world-widely in term of sorghum yield production for its contribution share of 1.2%, and now it ranks number 17 (FAO, 2018; FACTFISH, 2019). In 1960, the production level of sorghum was 180,000 Mg, and then dropped down to 171,900 Mg in 1970 before it steadily increased up to 838,717 in 2012. The recent production quantity according to FAO (2018) shows that the average production quantity in 2017 was 796,570 Mg. The average yield production in megagram (Mg), acreage under sorghum production (ha), and sorghum productivity in Mg ha^{-1} since independence in 1961 is depicted in Fig 2.1.

CHAPTER THREE

SITE DESCRIPTION

3.1 General description of the study site

Two experimental trials were concurrently conducted in the peri-urban area of Dodoma municipality at Tanzania Agricultural Research Institute (TARI) – Makutupora Centre (05°58'S and 35°46'E, 1086 m above sea level). The first experiment was looking on the influence of in situ rain water harvesting techniques and fertilizers sources on sorghum performance, while the second experiment was observing the effect of temporal intercropping pattern of sorghum and groundnut on sorghum performance. The two experimental trials were carried out, consecutively, for the two cropping seasons of 2015/2016 and 2016/2017.

The area in the study site is classified as a semi-arid (TMA, 2016), characterized by a mono-modal rainfall pattern, with recurring droughts and extended dry spells (Mahinda et al., 2018b). The research institute was strategically selected by the government of Tanzania to cater for dryland's crop research activities because of its representative nature of the arid and semi-arid environments in the country and sub-Saharan Africa in general. Like in many other arid and semi-arid areas, the rainfall in the study site commences in December/January and ends in April, followed by a long dry season of seven or eight months from May to November or December, respectively. The annual rainfalls range from 300 to 600 mm, with a mean of 450 mm, marked with high intra and inter annual fluctuation in amount and distribution (Mahinda et al., 2016). The long-term average rate of annual potential evapotranspiration is 2346 mm. Based on the aridity index (AI) formulated by the UNEP (1992a; 1992b; 1997), the area is within the range of $0.05 < AI < 0.2$. Therefore, the area is classified as arid instead of semi-arid.

The monthly air temperatures vary between 15 °C and 35.1 °C, with higher daily ranges of temperatures within a day than across the days. The soil temperature regime is hyperthermic, and the soil moisture regime oscillates between ustic and aridic depending on the rainfall amount, distribution and pattern in a year under consideration. The area has soil originated from alluvium derived from granitic rock, but well developed into a profile. The physiographic position of the area is piedmont with flat surrounding landform with a slope of about 1-2%.

Due to the influence of El Niño, in some years the total amount of rainfall can be as higher as 966.9 mm year⁻¹ as it was revealed in the 2015/2016 cropping season. Regardless of the rainfall amount, the rainfall distribution pattern within the season is not guaranteed to meet the crop water requirement. Moreover, the inconsistency in the onset of the rainfall and the rainfalls shifting pattern is highly variable. The rainfall concentrates within few days across the cropping season, leaving meteorological and agronomic droughts, which affect the crop performance adversely.

Although the rainfall gaps might occur and cause drought stress to the crops in any of the phonological stages, the longest rainfall gap occurs in February or March when sorghum is at the critical growth stage with the high crop water requirement. In most cases, this meteorological/ agricultural drought withstands for more than four weeks, causing significant effects on the growth performance of the crop, therefore affect final crop yield of the most crops grown, notably, maize (*Zea mays*), sunflower (*Helianthus annuus*), sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum galauicum*), finger millet (*Eleusine coracana*), groundnuts (*Arachis hypogaea*), bambara-nut (*Vign subterranea*) grapes (*Vitis vinifera*), cassava (*Manihot esculenta*) and sweet potatoes (*Ipomoea batatas*).

3.2 Farming history in the study site

In the previous year, prior to the start of experimentation in 2015/2016 cropping season, various crops were grown in the study site continuously. In 2014/2015, sunflower was grown, while in 2013/2014 sorghum was grown. In 2012/2013 and 2011/2012 cropping seasons, finger millet and intercrop of maize and groundnut were planted in the study site. Many years back, the experimental site was mainly used for grapevine farming.

Some of the fertilizers, which were applied in the study site before the start of the experiment trails were urea ($\text{CO}(\text{NH}_2)_2$), super phosphates ($\text{Ca}(\text{H}_2\text{PO}_4)_2$), muriate of potash (K_2O) and farmyard manure (FYM). FYM was largely used in the past years during grapevine farming, however, based on the appearance of the field and during land preparation, no FYM leftover was apparently observed in the experimental site.

3.3 Soil profile description, laboratory analysis and physicochemical properties of the soil in the study site

This section describes major approaches that were used to characterize soil properties in the study site. The holistic approach used included soil profile description, soil sampling and analytical procedure carried out in the laboratory for determination of physicochemical properties of the soil both at the furrow slice depth and across the soil horizons. Prior to the start of the experiment, soil profile (Fig. 3.1) was excavated and described.

The soil samples from different horizons were collected, air-dried and passed through a 2 mm sieve. In addition to soil profile, a composite soil sample was collected at a furrow slice depth (0-30 cm) in order to characterise soil texture and soil fertility level with reference to nutrients requirement of the sorghum crop. Both collected soil samples from soil profile and furrow slice depth were tested for physicochemical properties.



Figure 3.1: Soil profile in the study area.

Soil chemical properties including pH, electrical conductivity (EC), total nitrogen (TN), Nitrate (NO_3^-), ammonium (NH_4^+), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), total carbon (TC), cation exchange capacity (CEC) were determined following standard laboratory procedures. The soil pH was measured by a glass electrode from solution prepared at a ratio of 1:5 of soil: water and soil: 1 M of KCl, respectively. The solution prepared with soil and water was further used to determine EC of the soil. The total nitrogen and total carbon were determined by the dry combustion method (Yeomans and Bramner, 1991; Smith and Tabatabai, 2004), using NC elemental analyser (Vario Max CHN, German). The inorganic nitrogen (NH_4^+ and NO_3^-) were analysed following the flow injection analysis method (FIALab-2500, FIALab[®] Instrument. Inc. Washington, USA). Available P was determined colorimetrically by photospectrometry using the blue ammonium molybdate method with ascorbic acid as a

reducing reagent as suggested by Olsen et al. (1954), Olsen and Sommer (1982), and Sparks (1996). The basic exchangeable cations were analysed by atomic absorption spectrometer (Shimadzu, AA-840-01). The CEC was determined by Kjeldahl steam distillation apparatus after extraction of the soil sample solution by ammonium acetate method at a neutral pH condition (Thomas, 1982). Thereafter, a back titration was done with 0.01 M HCl. The tested soil physical property across the collected samples was only soil texture and clay minerals. The soil particle size distribution was determined by wet sieving and pipette methods. After destruction and removal of organic matter by hydrogen peroxide (H₂O₂) at 80°C, the complete dispersion of silt and clay particles at pH 9 condition was achieved by pulverizing soil particles with supersonic wave (Gee et al., 1986, cited by Funakawa et al., 2012).

The percentage base saturation (BS (%)), exchangeable sodium percentage (ESP (%)) and sodium adsorption ratio (SAR) were computed using the values of the basic cations and CEC as indicated in equations 3.1, 3.2 and 3.3.

$$BS (\%) = [(Ca^{2+} + Mg^{2+} + K^{+} + Na^{+})/CEC] \times 100 \dots\dots\dots (3.1)$$

$$ESP (\%) = \text{Exchangeable } [(Na^{+})/(Ca^{2+} + Mg^{2+} + K^{+} + Na^{+})] \times 100 \dots\dots\dots (3.2)$$

$$SAR (mmol_c) = Na^{+}/\sqrt{1/2 (Ca^{2+} + Mg^{2+})} \dots\dots\dots (3.3)$$

The tested physicochemical properties of soil at a furrow slice depth (0-20 cm) in the study site are indicated Table 3.1. The nutrients category levels were rated according to Cottenie (1980), Oster and Sposito (1980), McLean (1982), Rowell (1994), USDA (1998), Horneck et al. (2001), Landon (2013), FAO (2018) and Hill Laboratory (2018).

Table 3.1: Physicochemical properties of the soil at the furrow slice depth (0-20 cm) in the study area at Tanzania Agricultural Research Institute (TARI)-Makutupora Centre.

Parameter	Value measured	Category
Soil pH (1:5): (H ₂ O)	7.9	Moderately alkaline
: KCl	7.2	Neutral
EC (mS/cm)	0.14	Non- saline
%Total Nitrogen	0.16	Low
Ammonium, NH ₄ ⁺ (kg ha ⁻¹)	15.1	Very low
Nitrate, NO ₃ ⁻ (kg ha ⁻¹)	91.9	Low
Total Plant Available Nitrogen, N (kg ha ⁻¹)	107	Low
Olsen Phosphorus, P, (mg/kg soil)	15.3	Medium
%Total Carbon, C	1.5	Very low
C:N	9.4	Narrow
Basic Cations (cmol _c kg ⁻¹ soil): Na	0.05	Not a problem
: K	1.4	Very high (In low CEC)
: Ca	8.1	Very high (In low CEC)
: Mg	0.87	Very high (In low CEC)
CEC (cmol _c kg ⁻¹ soil)	11.2	Low
CEC (cmol _c kg ⁻¹ clay)	56	High
%Base Saturation	93	Highly saturated
Ca:Mg	9.3	No problem for K uptake
Sodium Adsorption Ratio, SAR (mmol)	0.08	Low (< 2 mmol)
Exchangeable Sodium Percentage, ESP	0.48	Non sodic (< 6%)
Particle size proportions: %Course sand (CS)	36.2	2.00-0.25 mm
: %Fine sand (FS)	16.9	0.25-0.05 mm
: %Course silt (CSi)	1.8	0.05-0.02 mm
: %Fine silt (FSi)	25.1	0.02-0.002 mm
: % Clay (C)	20.0	<0.002 mm
Clay type	Kaolinite and Mica	
Textural Class	Sand Clay Loam (SCL)	

The soil was neither saline nor sodic, with a neutral to moderate alkaline reaction of 7.2 and 7.9 in pH, respectively. It had a medium range of available phosphorus, but low amount of total nitrogen, inorganic nitrogen, and total carbon. The particle size distribution of the soil is 36.2% course sand, 16.9% fine sand, 1.8% course silt, 25.1% fine silt and 20% clay. Based on the soil textural classification of the United State Department of Agriculture (USDA), the soil particles distribution was classified as Sandy clay loam.

The profile description at the study site is indicated in Table 3.2. The soil profile showed an evidence of surface sealing due to presence of skin coating. It also had cutans in the pore and ped surfaces. The laboratory's analytical results of the physicochemical properties of the observed soil profile revealed the presence of an argillic horizon BA_t

Table 3.2: Observable characteristics of the soil profile horizons in the study are at TARI Makutupora Centre.

Horizon	Depth (cm)	Roots size	Structure	Consistence	Pores	Remark	Mussel colour	
							Dry soil	Wet soil
Ap	0-15	Many very fine and fine roots.	Strong fine sub-angular and course granular structure.	Slightly hard when dry, clay content is about 20%. Slightly sticky and plastic when wet.	Common medium, many very fine and fine few course pores.	Evidence of surface sealing due to presence of clay skins/coatings.	Brown (7.5YR4/4)	Dark brown (7.5YR3/4)
AB	15-25	Many very fine and fine, few medium roots.	Fine to medium strong sub-angular block structure.	Friable moist, slightly sticky and plastic when wet.	Many very fine and fine common medium, few course pores.	Cutans: Few in pore and ped surfaces.	Yellowish red (5YR5/6)	Reddish brown (5YR4/4)
BAt	25-55	Common very fine and fine, few medium, few course roots.	Moderate to strong sub-angular block structure.	Friable moist, slightly sticky and plastic when wet. Clay content is about 25-30%.	Many very fine and fine pores, few to common medium and few course pores.	Cutans: Common in pore and ped surfaces.	Red (2.5YR4/8)	Red (2.5 YR5/6)
Bt	55-130	Common very fine, few fine, few course roots.	Fine and medium moderate strong sub-angular block structure.	Friable moist, slightly sticky and plastic when wet. Clay content is about 25-30%.	Few medium and pores, common many fine pores.	Cutans: Common in pores and surface.	Red (2.5YR5/8)	Red (2.5YR5/6)
BC ₁	130-155	Few very fine and fine roots.	Fine and medium moderate sub-angular block, structure.	Friable moist, Slightly sticky and plastic when moist. Clay content is about 15%. Largely remain sandy.	Common very fine and fine, many medium and few course pores.	Cutans; Abundant, Clay and Sesquioxide of Fe and Al probably with organic matter on ped surfaces pore within soil matrix.	Red (2.5YR4/8)	Red (2.5 YR 4/6)
BC ₂	155-188	Few very fine and fine roots.	Fine and medium moderate sub-angular block, structure.	Friable moist, Slightly plastic when moist. Clay content is about 10%. Largely remain sandy.	Common very fine and fine, many medium and few course pores.	Presence of concretion, fine to hard spherical, blackish, globules (nodules), probably of Mn and Fe.	Red (2.5YR4/8)	Red (2.5YR4/6)
BC ₃	188-200	Few very fine and fine roots.	Fine and medium moderate sub-angular block, structure.	Friable moist, Slightly plastic when moist. Clay content is insignificant%. Largely sandy.	Common very fine and fine, many medium and few course pores.	Presence of concretion and evidence of fine to hard polygon Calcium carbonate, which forms effervescence with 10% HCl.	Red (2.5YR4/8)	Red (2.5YR5/6)

Table 3.3: Physicochemical properties of the soil profile in the study area at TARI-Makutupora Center.

Horizon	Depth, cm	% Soil texture					USDA Textural Classification	Clay type	pH		%		mg kg ⁻¹		C:N
		Course Sand	Fine Sand	Course Silt	Fine Silt	Clay			H ₂ O	KCl	TC	TN	NH ₄ ⁺ -N	NO ₃ ⁻ -N	
Ap	0 - 15	35.5	17.1	1.8	26.0	19.5	Sandy Loam	Mica and Kaolinite	7.8	7.0	1.7	0.16	7.6	46.0	10.3
AB	15 - 25	36.9	16.0	2.4	24.5	20.1	Sandy Clay Loam	Mica and Kaolinite	8.2	6.4	0.4	0.04	7.9	17.4	8.8
BA _t	25 - 55	33.2	16.2	2.5	14.0	34.1	Sandy Clay Loam	Mica and Kaolinite	7.4	5.7	0.3	0.04	4.7	13.2	7.4
B _t	55 - 130	34.7	14.4	3.5	13.0	34.4	Sandy Clay Loam	Mica and Kaolinite	5.6	4.2	0.2	0.03	3.6	15.6	6.3
BC ₁	130 -155	29.8	20.0	5.9	26.3	18.0	Loam	Kaolinite	6.7	5.2	0.2	0.03	9.1	8.3	5.7
BC ₂	155 - 188	40.6	28.7	8.2	17.6	5.0	Sandy Loam	Mica and Kaolinite	7.6	6.3	0.1	0.02	6.4	5.7	6.0
BC ₃	188 -200	59.3	22.9	8.9	7.5	1.4	Loamy Sand	Mica and Kaolinite	8.5	7.3	0.1	0.02	2.1	7.3	5.3

Horizon	Depth, cm	P mg kg ⁻¹ , Olsen	cmol _c kg ⁻¹ soil					CEC	%Base Saturation	Ca: Mg	ESP	SAR (mmol)
			K ⁺	Na ⁺	Mg ²⁺	Ca ²⁺	Total Basic Cation					
Ap	0 - 15	12.8	1.42	0.01	0.84	8.58	10.85	11.40	95.20	10.16	0.09	0.02
AB	15 - 25	17.0	1.19	0.19	3.27	4.69	9.35	9.55	97.93	1.44	1.99	0.30
BA _t	25 - 55	4.5	0.92	0.50	3.88	5.37	10.67	12.87	82.91	1.38	4.48	0.74
B _t	55 - 130	7.2	1.00	0.80	2.39	3.27	7.46	14.07	53.02	1.37	9.69	1.50
BC ₁	130 -155	9.2	0.16	1.06	5.29	6.72	13.23	15.70	84.27	1.27	7.41	1.37
BC ₂	155 - 188	0.3	0.20	0.77	5.81	10.48	17.27	17.70	97.53	1.80	4.27	0.85
BC ₃	188 -200	1.4	0.30	0.95	7.09	30.63	38.97	18.45	211.20	4.32	2.38	0.70

and Bt with CEC of 37.7 and 40.9 $\text{cmol}_c \text{ kg}^{-1}$ clay, respectively (Table 3.3). Based on the morphological description and analytical data, the soil was classified as an Alfisol. The soil occurs under ustic moisture regime (Ustalf) and the great group Haplustalfs as it does not fit in the other groups of Ustalfs. Focusing only on the texture, the soil is classified into Arenic Haplustalf according to USDA taxonomy. With regard to the world reference base, the soil is classified as Haplic Luvisol (Aridic, profundic).

3.4 Weather characteristics during the experiment in the study site

3.4.1 Monitored rainfall characteristics

Daily rainfall amounts and their distribution for the cropping seasons of 2015/2016 (above-average rainfall season) and 2016/2017 (below-average rainfall season) in the study site, are indicated in Fig. 3.2. The recorded annual rainfall amount for the above-average rainfall season and below-average rainfall season were 966.9 mm and 343.2 mm, respectively.

In the above-average rainfall season, the total rainfall amount exceeded the long-term average rainfall (450 mm) by 114.9%, yet its distribution, pattern and normal intensity were not guaranteed. Contrary to other years the rainfall commenced early in

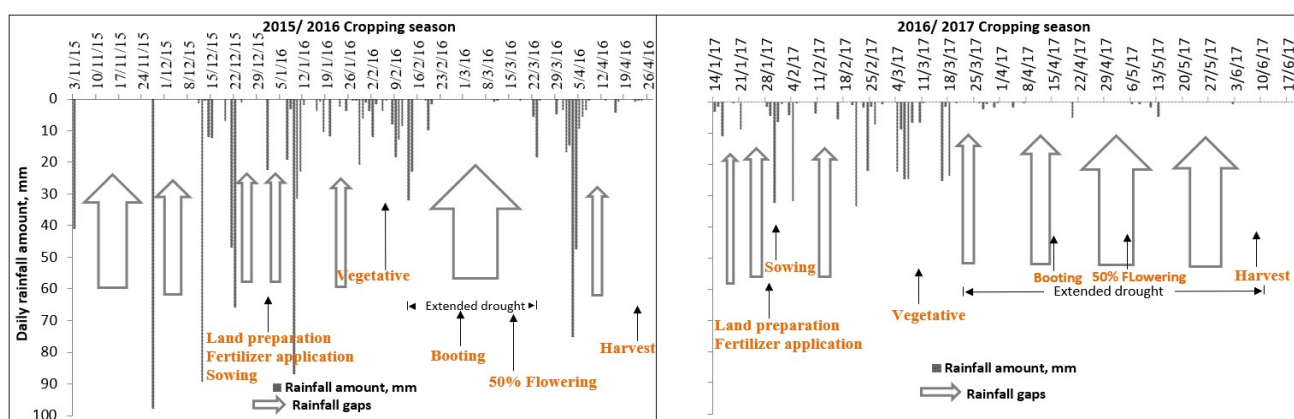


Figure 3.2: Rainfall distribution pattern and occurrences of the dry spells in the study area for the 2015/2016 and 2016/2017 cropping seasons.

Table 3.4.1: Rainfall characteristics for the first cropping season of 2015/2016 (above-average rainfall season) in the study site at TARI-Makutupora.

Storm size range (mm)	Rainfall characteristics										Total
	≤ 10	$10 < \leq 20$	$20 < \leq 30$	$30 < \leq 40$	$40 < \leq 50$	$50 < \leq 60$	$60 < \leq 70$	$70 < \leq 80$	$80 < \leq 90$	$90 < \leq 100$	
Number of rainfall days/season	40	11	4	2	3	0	1	1	2	1	65
Rainfall amount (mm/day)	107.4	157.9	88.8	63.4	135.2	0	65.6	75	175.9	97.7	966.9
Average rainfall amount, mm/120 days growing season											7.80

Table 3.4.2: Rainfall characteristics for the second cropping season of 2016/2017 (below-average rainfall season) in the study site at TARI-Makutupora.

Storm size range (mm)	Rainfall characteristics										Total
	≤ 10	$10 < \leq 20$	$20 < \leq 30$	$30 < \leq 40$	$40 < \leq 50$	$50 < \leq 60$	$60 < \leq 70$	$70 < \leq 80$	$80 < \leq 90$	$90 < \leq 100$	
Number of rainfall days/season	36	1	6	3	0	0	0	0	0	0	46
Rainfall amount (mm/day)	93.1	10.8	142.1	97.2	0	0	0	0	0	0	343.2
Average rainfall amount, mm/120 days growing season											2.86

November, debilitating the existing inconsistent in the onset of the rainfall season and the unpredictability of the cropping window's length, which often leaves farmers in a dilemma of the sowing calendar. During this season, the heaviest rainfall intensity (97.7 mm day^{-1}) was received at the beginning of the season on November 27, 2015, after the rainfall intensity of 40 mm day^{-1} on November 03, 2015, leaving agronomic and meteorological droughts in between for 23 days. The extended dry spell started 44 days later on February 15, 2016 after sowing on January 2, 2016, then ceased 37 days later on March 22, 2019 with 18 mm of rainfall after a few ineffective drizzles. In this season, heavy storms of more than 70 mm day^{-1} contributed to 36.1% of the total rainfall. This higher rainfall amount was of little significance in meeting crop water requirement in the flat cultivated land. Most of the water from the heavy rainfall intensity was observed to be lost by the surface runoff. It was further noted that a large proportion (61.5%) of the daily rainfall was ineffective ($<10 \text{ mm day}^{-1}$) but contributed to 11% of the total rainfall. The actual number of days that received effective rainfall was 25 for an entire cropping season

(Table 3.4.1), this accounted for 38.5% of the 65-days, which received rainfall. It also means out of the 120-days cropping window, 95 days did not receive rainfall.

The rainfall amount in the below-average rainfall season sharp decreased by 181.7% and 31.1% compared to the above-average rainfall season and the long-term average rainfall, respectively. The highest rainfall intensity (33.4 mm day^{-1}) was in the middle of the cropping season with several dry-spells before and after. The onset of the cropping season shifted ahead significantly and altered the sowing calendar by $\geq 25\%$ of the 120-days cropping window. The rainfall commenced with a series of ineffective showers before an effective rainfall of 32.1 mm day^{-1} on January 30, 2017. The extended dry spell started 47 days later on March 19, 2019 after sowing (January 31, 2017). There were no any further effective rainfalls from the time when the extended dry spell started until the harvest time. Rainfall of less than 10 mm day^{-1} dominated the daily rainfall frequencies by 78.3% and contributed to 93.1 mm (27.1%) of the total rainfall amount (Table 3.4.2).

The total number of days received rainfall (46 days) in the below-average rainfall season accounted for 38.3% of the 120-days growing period. Out of the rainfall receiving days, only 10 days had received effective rainfalls. Considering the length of 120-days growing period, the proportion of days which would had been supposed to be supplemented with irrigation water to surpass crop water requirement was 91.7%. This is far much higher compared to 79.2% in the 2015/2016 cropping season. The observed inter and intra-annual rainfall variability in amount, intensity, pattern and distribution just within the two consecutive cropping seasons, proved the degree of rainfall unreliability, which poses higher chance of crop failure in the dryland areas of Tanzania.

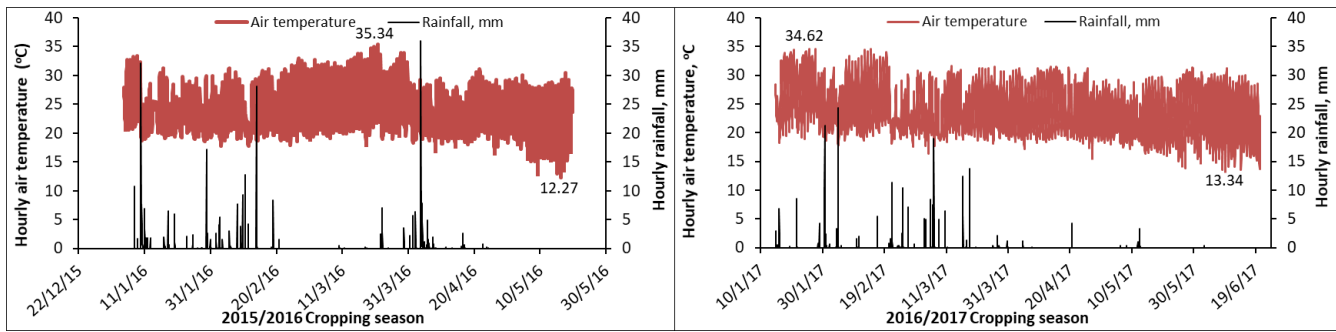


Figure 3.3: Air temperature dynamics for 2015/2016 (above-average rainfall season) and 2016/2017 (below-average rainfall season).

3.4.2 Air temperature characteristics

The registered air temperature dynamics in the study site during the experimentation period is indicated in Fig 3.3. In both cropping seasons, air temperature varied greatly between day and night times than across the seasons. The drastic drop of air temperature after rainfall events was evident in both cropping seasons. The maximum temperatures recorded were 35.34 °C and 34.62 °C for the 2015/2016 (above-average rainfall season) and 2016/2017 (below-average rainfall season), respectively. The minimum temperature for above-average rainfall season was 12.27 °C, while for the below-average rainfall season was 13.34 °C. The range in temperature between minimum and maximum temperature was higher in the above-average rainfall than in the below- average rainfall season.

CHAPTER FOUR

EFFECT OF IN SITU RAIN WATER HARVESTING TECHNIQUES AND FERTILIZER SOURCES ON SOIL MOISTURE AVAILABILITY AND GROWTH PERFORMANCE OF SORGHUM IN THE DRYLAND AREAS OF TANZANIA

4.1 Introduction

Climate change and occurrences of extreme weather events have favoured sorghum to be the main alternative food and cash crop (Mahinda, 2014; Mahinda et al., 2018b). Wheat and barley production, which prefer cool weather condition, have been decreasing yearly to meet industrial demands (Asseng et al., 2015; Liu et al., 2016). Sorghum, which has been saving as the main staple food in the marginal and prone dryland areas, has become a potential cash crop in Africa and the world in general (Odhiambo, 2011; Makindara et al., 2013; Heard, 2014). Although sorghum is in high demand as the staple food and industrial raw material (Heard, 2014; TBL, 2011; 2016), its supply to meet the demand is limited due to the decline in yield production attributed to low rainfall, a high rate of evapotranspiration, inter and intra-annual rainfall variability, surface runoff, and the inherently poor soil fertility status in the dryland areas where the crop is majorly cultivated (Mahinda et al., 2018b).

In Tanzania, the dryland areas occupy more than 61% of the available land for agriculture and sustained 61% of the country's population (Corbett, 1996; UNDP/UNSO, 1997). Dodoma region, which is located in the central part of Tanzania, is a typical dryland in the country. It is also a representative of many other dryland areas in Africa. Apart from receiving low rainfall (Mahinda et al., 2016), the area has inherently low capacity to supply crop nutrients, notably nitrogen, phosphorus and potassium (Mahinda

et al., 2018b). In improving fertility and productivity of the land, industrial fertilizers and manure have shown the potential for increasing sorghum yield. However, the soil moisture deficit, dictated by inconsistent and low rainfalls, limits the realization benefits of applied fertilizers. Drip irrigation has paved a way to increase sorghum yield production (Mahinda et al., 2018a); nevertheless, the initial cost of investment and lack of technical support have been a hindrance to many smallholder farmers (Mahinda et al., 2018b). Furthermore, different soil and water conservation techniques have been intensively employed (Christiansson et al., 1993; Ellis-Jones and Tengberg, 2000; Senkondo et al., 1998; Boyd et al., 2000; Wakindiki et al., 2007; Kilasara et al., 2015). Most of these studies have focused on areas prone to soil erosion. In areas where the focus has been on improving crop production, less attention has been paid to detailed examination of the potential contribution of ripping and tie-ridges in storing the captured rainwater at the effective root zone of the sorghum, and its subsequent availability for the crop during the extended dry spell periods. There is also limited knowledge on how different fertilizer sources, integrated with ripping and tie-ridges, would further dictate soil water availability during the critical period of moisture stress due to their different influences in stimulating crop growth and water uptake. This research, therefore, examines the combined effect of ripping and tie-ridges, with organic and inorganic fertilizers, on sorghum's growth, final biomass and grain yield, through the mitigation of the critical moisture stress period during the expected extended drought periods in the dryland areas of Tanzania, which occurs in February or March, when the sorghum is at booting or flowering stage. The management of soil water for the former and the latter growth stages, is of crucial importance, as during these growth stages, sorghum water requirement is high, but the rainfall stops, creating a hydric deficit, which affects sorghum growth and final grain yield (Mahinda et al., 2018b).

4.2 Materials and methods

This section describes major approaches that were used in this study. It has been separated into different subsections, each addressing field methods and materials used in achieving the general objective of the study. The methods and materials employed include those used for farmyard manure preparation, experimental design and layout, land preparation, treatments assignment, soil parameters sampling and soil moisture determination and quantification, crop parameters measuring and sampling, laboratory test, data computation and statistical data analysis.

4.2.1 Farmyard manure preparation and laboratory analysis

Farmyard manure (FYM) was air-dried, crushed and passed through a 3 mm wire mesh (Mahinda et al., 2018b). The aim to sieving was to increase surface area of FYM for nutrients release and uniform distribution in the field. This method is highly encouraged to enhance the effectiveness of the applied organic fertilizers in the field for improvement of both physical and chemical properties of the soil. The sieve used and the prepared FYM are indicated in Fig. 4.1 (a) and (b), respectively.

The prepared FYM was sampled, air-dried, and passed through a 2 mm sieve before

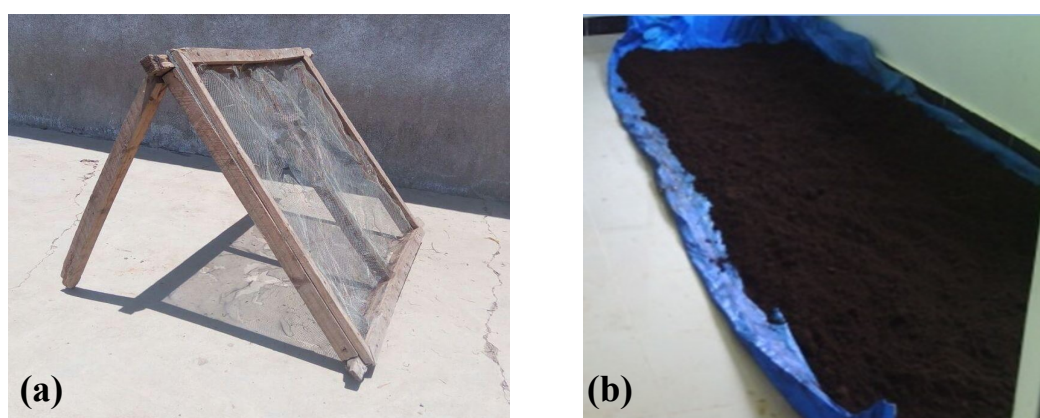


Figure 4.1: Showing (a) a 3 mm wire mesh for sieving FYM; (b) sieved FYM ready for application.

subjected to laboratory analysis for pH, total nitrogen (N), phosphorus and potassium (K^+). A mixture of FYM: water at a ratio of 1:2, respectively, was shaken by the electrical shaker for one hour, thereafter measured for its pH by the glass electrode. The total N was quantitatively determined by the modified Dumas' dry combustion method (Yeomans and Bramner, 1991; Smith and Tabatabai, 2004), in which 1g of the very fine ground, oven dried FYM (75°C), was transferred to a crucible container and quantified by NC elemental analyser (Vario Max CHN, German). The total N of the FYM was also analysed by a wet digestion method, whereby 1g mixture of catalyst (sodium sulphate, copper sulphate and selenium at the ratio of 100:10:1 was added to 1g of FYM, followed by 20 ml of concentrated H_2SO_4 and then heated in the digestion block at 360 °C for 2 hours. During the distillation stage, the escaped NH_3 was trapped by 2% boric-acid, added with an indicator. The greenish distillate collected was back titrated by 0.01 M H_2SO_4 until the colour changed to pink (Kjeldahl, 1883).

K^+ was determined by flame photometer from the filtrate made by adding 25 ml of ammonium acetate, and then shaken for 30 minutes. P was analysed colorimetrically by a spectrophotometer (Uvmin-1240) at 710 nm, following methods suggested by Olsen (1954) and Troug (1930). In Olsen method P was quantified from the 50 ml solution prepared by filtering a mixture of the extracting solution with 5g of soil. Based on the laboratory analysis and recommendation rate in the region, FYM was applied at a rate of 8 Mg ha⁻¹. The N, P and K contents of the FYM applied were 8.8, 0.4 and 5.3 kg Mg⁻¹, respectively.

4.2.2 Inorganic fertilizer computation and application

A compound inorganic fertilizer namely YaraMila-CerealTM was applied at the rate of 70 kg N ha⁻¹. The fertilizer is manufactured at the formulation ratio of 23:10:15 for the major

primary nutrients. It, therefore, contains elemental N:P:K nutrients at the ratio of 23:4.4:12.5, respectively. The amount of inorganic fertilizers, based on the computed nutrients, was broadcasted to every plot based on the treatments' requirements.

4.2.3 Experimental design, layout and treatments allocation

A split-plot design was employed in randomising experimental treatments (Fig. 4.2 (a) and (b)). Treatments were derived from the two factors, namely in situ rain water harvesting techniques (IRWHT) and fertilizer source. The IRWHT was the main factor, while the fertilizer source was the sub-factor. The IRWHT included two levels of land manipulation techniques, involving tie-ridges (TR) and ripping (RP), tested against each other and with flat cultivated land (FCL), which is a major land cultivation method in the region. Fertilizer sources had four sub-factor levels; the first, second, and third levels were inorganic (N), organic (FYM) and a half-combined N and FYM (N+FYM), respectively. The fourth level was a negative control. The twelve treatments were replicated three times for the two cropping seasons of 2015/2016 and 2016/2017, consecutively.

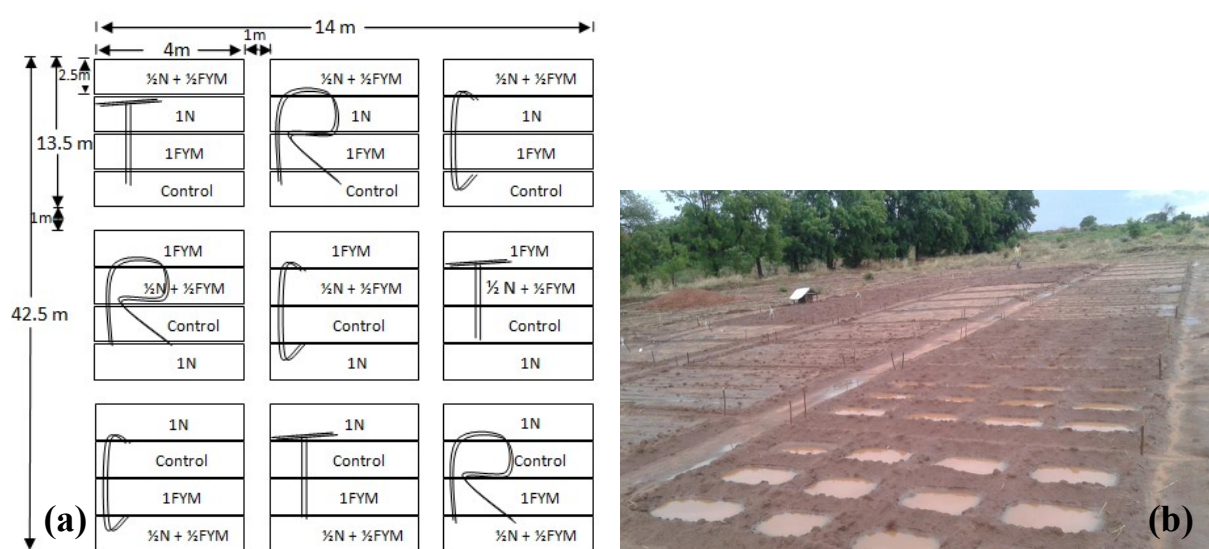


Figure 4.2: Showing (a) experimental layout design: T, tie-ridges; R, ripping; C, flat cultivated land; N, inorganic fertilizer; FYM, organic fertilizer; (b) pictorial outlook of the prepared experiment after the first rainfall event.

4.2.4 Experimental plots preparation

The experimental field was prepared based on the three main treatments, which were TR, RP and FCL. The preparation of the TR was done by earthing up soil from the opposite sides in parallel lines, forming ridges and furrows, concurrently (Mahinda et al., 2018b). The parallel ridges were tied up across at one-metre intervals with scooped soil from the furrow, creating micro-catchment basins, which captured, retained and prevented water from running along either side of the furrow (Fig. 4.3 (a) and (b)) (Mahinda et al., 2018b).

The height of the ridges from the furrow was 30 cm, and the distance from the pick of one ridge to the next was 75 cm. The inter-row distance was fixed following a recommended spacing for sorghum in the region. To take advantage of the stored soil moisture, while avoiding excessive captured rainwater from depleting oxygen at the effective root zone, sorghum seeds were sown on the sides of the ridges. As dictated by rainfalls, sorghum was sown on January 2, 2016 and January 31, 2017 for the 2015/2016 and 2016/2017 cropping season, respectively.

The RP treatments were prepared by deep piercing the soil beyond the furrow slice to a depth of 30 cm, without inverting the soil (Mahinda et al., 2018b). The aim was to break loose the soil, and to free a way for roots to penetrate the soil and access nutrients and infiltrated water; this sub-soiling would also break down any hardpan that might have

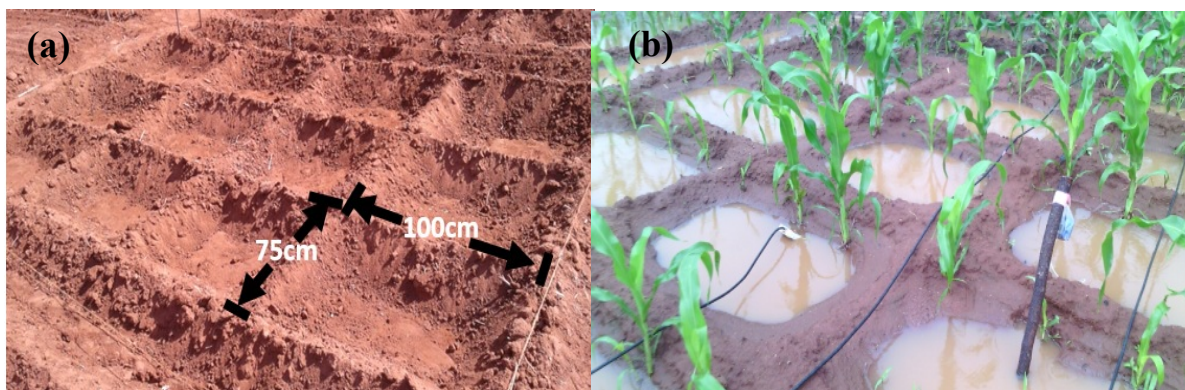


Figure 4.3: Showing (a) the prepared tie-ridges in the experimental site; (b) rainwater captured and retained in TR.

existed, hence, encouraging water percolation and reduces surface runoff. The distance from one ripped line to the next was 25 cm. Sorghum seeds were sown along the ripped lines at the same spacing as was in the TR and FCL treatments. Similarly, the plot size in TR treatments was 10m² as were for RR and FCL.

Based on the size of the plots, ripping treatments were prepared by a mattock, commonly known as the pickaxe. This is a hand tool with a strong, long, narrow spike metal head, attached perpendicular to wooden handle. The metal head has a counter-weight effect and is sharp pointed at the end of one side to easy piercing up the soil apart (Fig. 4.4 (a)). The length of the sharp pointed side is 30 cm (Fig. 4.4 (b)), and the appearance of the ripped lines are as indicated in Fig. 4.4 (c) and (d). For thorough incorporation of fertilizer sources in the soil across all the IRWHT and FCL treatments, the selected fertilizer sources were applied to their respective plots during land preparation. In the 2015/2016 cropping season, land preparation was done on January 2, 2016, while in 2016/2017, land preparation was done on January 30, 2017.

4.2.5 Soil moisture and weather parameters monitoring

The detailed soil moisture measurement at the effective root zone of the sorghum (0-20 cm depth), where most of the fine roots concentrated (Fig. 4.5 (a) and (b)), was monitored by an automated water content reflectometer, CS 616 (CS 616, Campbell Scientific Inc., Logan, USA). The real-time CS 616 was programmed to scan the soil moisture details in



Figure 4.4: Showing (a) a Mattock, with a sharp pointing end; (b) a Mattock piercing head length, 30 cm); (c) ripped plot ready for sowing sorghum in the experiment area; (d) ripped plot after several rainfalls.

every 30 minutes. Its average outputs values in microseconds were recorded at hourly intervals until the end of the day, when the process was set to repeat, automatically.

The plotted calibration curve equations in microseconds against their corresponding volumetric water contents (VWC), derived from a gravimetric method were used to compute the recorded hourly microseconds into VWC. The undisturbed soil samples for VWC calibration, were collected at varying degrees of moisture in each of the treatments from the saturated status to air dried level. Following the same pattern in time intervals, the detailed weather parameters, mainly rainfall (mm) and air temperature ($^{\circ}\text{C}$) were recorded on an hourly basis. The rainfall data was monitored by an automatic tipping rain gauge (Pulse count, mm), while the air temperature was recorded by an automated air temperature sensor (T108_C).

To comply with the standards of the meteorological data collection, the rain gauge and the air temperature sensors were installed at the height of 150 cm from the ground surface. The soil moisture sensors, rain gauge and air temperature sensors were connected to the CR 1000 data logger (CR 1000, Campbell Scientific Inc., Logan, USA). The recorded data values for soil moisture, rainfall and air temperature were retrieved, downloaded and communicated to the user interface by an aid of a pre-installed computer

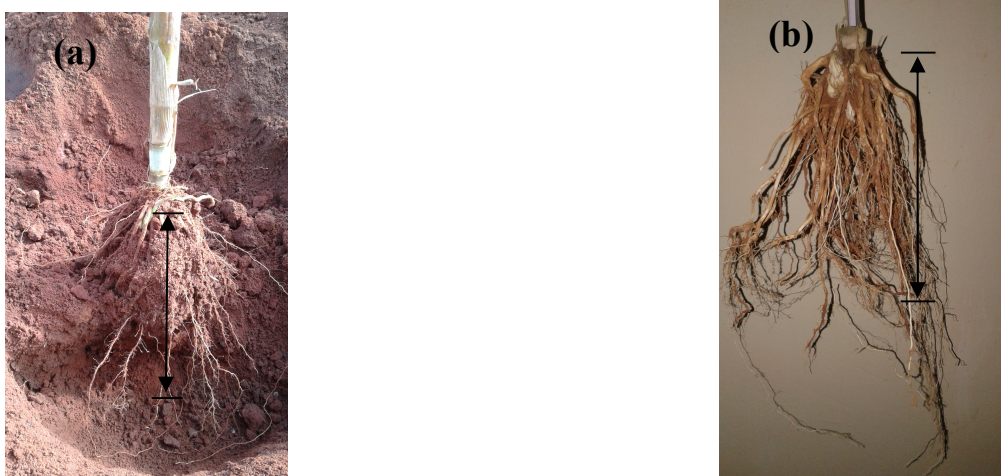


Figure 4.5: Showing area of concentration of the sorghum roots at the effective root zone (a) during excavation; (b) after excavation.

software application logger net 4.0 (Campbell Scientific. Inc., Logan, USA). Further analysis and manipulation of the collected parameters for daily and weekly VWC were computed from the average of hourly data set, while the daily rainfall was computed by summing up the hourly rainfall data values. The VWC held at different tensions against roots uptake were determined following procedures by Klute (1986) and CSSAMM (1986).

Available water content was calculated as the difference in soil water content computed from CS 616 against soil water content held at permanent wilting point (-1.5 MPa). All days with soil water content equivalent to that retained at tensions greater than -1.5 MPa, were counted as days in which sorghum was under moisture stress period, while the remaining days with water held below the -1.5 MPa tensions, were considered to be available for the normal crop evapotranspiration. An extra available soil water was computed by subtracting the available stored water volume in one treatment of interest over the other. The aim was to have a benchmark for identification and comparison of the treatments' performances, in term of the additional available stored water, at any particular point in time.

Furthermore, the drought mitigation potential was computed based on the proportional of number of days at which the soil water content was available (> -1.5 MPa) for the crop, during the entire period of the expected extended drought period, from a day after the last rainfall stopped. To convert the value to percentage, the obtained proportional was multiplied by 100. Alternatively, the drought mitigation potential was computed by subtracting the proportional number of days with soil water held below the permanent wilting point (< -1.5 MPa) from 100, then multiplied by 100, in order to convert the value to percentage for easy comparison amongst the treatments. The former 100, represented the entire length of the expected extended drought period from the last

rainfall events; in which within it, there were both days with water held below and above the -1.5 MPa. The formulated equations to compute available water content (AWC), moisture stress period (MSP), extra available water (EAW) and drought mitigation potentials (DMP) are indicated in equations 4.1, 4.2 and 4.3, 4.4 (i) and 4.4 (ii), respectively.

$$AWC (m^3 ha^{-1}) = SWC_{\bar{Y}} - WPWP \dots\dots\dots (4.1)$$

Whereby: $SWC_{\bar{Y}}$ is 24 hours mean soil-water volume ($m^3 ha^{-1}$) computed from CS 616; and WPWP is soil water volume ($m^3 ha^{-1}$) held at tension of -1.5 MPa.

$$MSP (Days) = NEDP - NASW \dots\dots\dots (4.2)$$

Whereby: NEDP is number of days of the extended drought period; NASW is number of days for the soil water held above the permanent wilting point (> -1.5 MPa).

$$EAW (m^3 ha^{-1}) = (ASW_H - ASW_L) \dots\dots\dots (4.3)$$

Whereby: ASW_H is available soil-water in a high-water storing treatment; and ASW_L is available soil water in a relatively less water storing treatment of interest for comparison.

$$DMP (\%) = 100 - ((NPWP/NEDP) \times 100) \dots\dots\dots (4.4 (i))$$

Whereby: NPWP is number of days for soil water at permanent wilting point ($\leq -1.5\text{MPa}$); and NEDP is number of days of the extended drought period.

$$\text{Alternatively, DMP (\%)} = (\text{NAWC/NEDP}) \times 100 \dots\dots\dots (4.4 \text{ (ii)})$$

Whereby: NAWC is number of days for soil water above the permanent wilting point ($> -1.5 \text{ MPa}$).

4.2.6 Determination of the sorghum's seedling emergence and growth parameters

4.2.6.1 Determination of the sorghum's seedling emergence

Seedling emergence was closely monitored at the first 5 and 15 days to observe the influence of IRWHT and fertilizer sources on seedling emergence. Across all the treatments, emerged seedlings were visually spotted and counted. The percentage of seedlings were obtained by dividing the actual number of emerged seedlings over the expected number of seedlings to be emerged. The latter directly related with the total number of holes sown by sorghum seeds. A mathematical expression of the equation used is indicated below.

$$\text{SE (\%)} = \text{ANS/ENS} \dots\dots\dots (4.5)$$

Whereby: SE (%) is percentage of seedlings emergence; ANS is actual total number of emerged seedlings in a plot; ENS = expected number of seedlings in a plot.

4.2.6.2 Determination of the sorghum's plant heights and plant heights increasing rates

Plant height (cm) was measured using a standard tape measure. The measurement was taken at each of the phenological stages of the sorghum plant, namely, vegetative, flag leaf, flowering and physiological maturity. The reference point for determining a specific growth stage was established when the total number of plants population in a stage of interest was more than 50%.

The rates at which sorghum plants heights increased, were determined based on the differences in plant heights between the two subsequent growth stages. The product of the differences in plant heights, were then divided by their respective time differences (days) between the two growth stages as indicated in the equations 4.6 (i), 4.6 (ii) and 4.6 (iii).

$$\text{PIR (cm day}^{-1}\text{)} = \delta\text{Ph} / \delta t \dots\dots\dots (4.6(i))$$

$$\text{Also; } \delta\text{Ph} = \text{Ph}_2 - \text{Ph}_1 \dots\dots\dots (4.6(ii))$$

$$\delta t = t_2 - t_1 \dots\dots\dots (4.6(iii))$$

Whereby: PIR is plant height increasing rate; δPh is a product of the difference in plant height (cm) between the two subsequent growth stages; δt is a product of the difference in time (days) between the two subsequent growth stages; Ph_2 is plant height measured at the end of the growth stage; Ph_1 is plant height measured at the beginning of the growth stage; t_2 is time at which a growth stage ends, t_1 is time at which growth stage starts.

4.2.6.3 Determination of the sorghum biomass and rainfall use efficiency

Determination of the rainfall use efficiency of sorghum under different IRWHT and fertilizer sources, involved two important parameters, namely, sorghum above ground biomass (kg) and total rainfall amount (mm) in a season. The above ground biomass was obtained by cutting sorghum shoots in each treatment at the ground level. The collected plant shoots were chopped into pieces, packed into perforated paper bags, and then oven-dried at 75°C to a constant weight (Rowell, 1994). The weight of the oven dried shoots was finally quantified by an electronic weighing balance. The rainfall amount was obtained by summing up the daily rainfall amount within a season. The rainfall use efficiency was determined by dividing the total above ground biomass (kg) from the total amount of rainfall in a season (mm) as shown in the equation below.

$$\text{RUE (kg mm}^{-1}\text{)} = \text{DM} / \text{TR} \dots\dots\dots (4.7)$$

Whereby: RUE is sorghum rainfall use efficiency; DM is above ground biomass (kg); TR is total amount of rainfall in a season (mm).

4.2.6.4 Determination of sorghum grain yield performance

The physiological matured sorghums from different treatments were harvested separately by cutting the panicles with knives (Fig. 4.6 (a)). To ease up detachment of grains from the panicles, the harvested panicles were sun dried for four days to reduce the grain moisture content. The sun-dried panicles were threshed by beating sorghum in the sack. The scaly-bracts and lodicules were detached by partial dehulling the grains in a wooden mortar and pestle.

The grains were finally cleaned by winnowing to remove chaffs, immature grains and

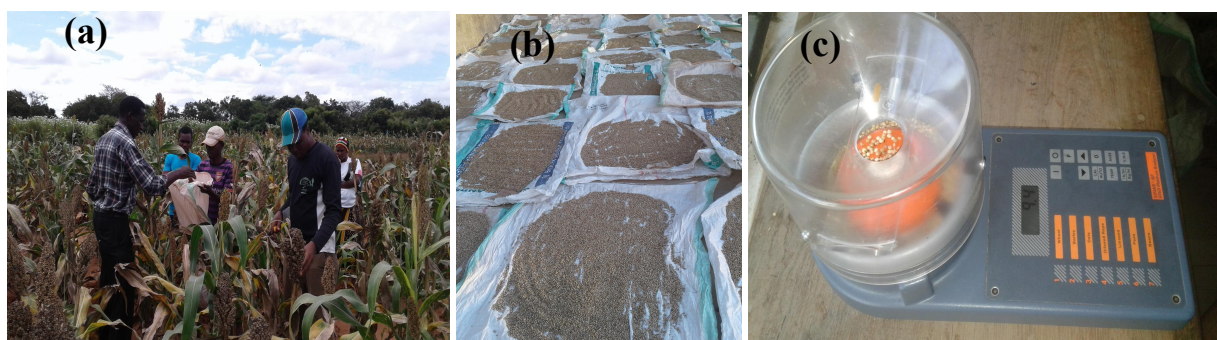


Figure 4.6: (a) Sorghum harvesting activity; (b) air drying of the sorghum grains; (c) determination of the sorghum grain.

other low-density materials by taking advantage of blowing wind. The clean grains were air dried for homogenization (Fig. 4.6 (b)), then analysed for its grain moisture content (Fig. 4.6(c)) using a digital grain moisture meter (SinarTM, Model 6060, AP Moisture Analyzer, Bracebridge, UK). The grains were subsequently weighed by an electronic balance, and its final weight was interpolated to an acceptable market equilibrium grain moisture content of 14%.

4.2.7 Statistical data analysis

Gen-Stat Discovery (16.1 version, 2000-2018 VSN. International Ltd.) was used as an aiding software tool to analyse data mainly; growth parameters, biomass, rainfall use efficiency and grain yield at 95% level of significance in two-way ANOVA. During the analysis, assumptions made were that; observations and errors were normally distributed, and all observations within and across the collected samples were independent with the same variance. The means were separated by employing Duncan's New Multiple Range Test. The weekly soil moisture data were statistically analysed by a pairwise two tailed t-test at $\alpha = 0.05$ using excel add-in software.

4.3 Results and discussion

4.3.1 Potential contribution of ripping and tie-ridges in storing the captured rainwater at the effective root zone of the sorghum

Figure 4.7 shows the potential contribution of ripping (RP) and tie-ridges (TR) against Flat cultivated land (FCL) in storing the captured rainwater at the effective root zone of the sorghum, and its subsequent availability in the sorghum field for the two consecutive cropping seasons of 2015/2016 (above-average rainfall season) and 2016/2017 (below-average rainfall season). The detailed temporal moisture dynamics showed that in the above-average rainfall season; when the rainfall was $966.9 \text{ mm year}^{-1}$, RP and TR treatments closely retained a similar volume of water during rainfall events. The soonest after the rainfall storm ceased, RP treatment drastically infiltrated and percolated the captured rainwater, while TR treatment retained the largest volume of water. The rate at which the retained water was depleted in RP treatment was marked higher at the end of the extended drought period. At this point, the retained soil moisture in RP treatment was relatively lower ($193.4 \text{ m}^3 \text{ ha}^{-1}$) compared to 212.5 and $228.6 \text{ m}^3 \text{ ha}^{-1}$ in FCL and TR, respectively.

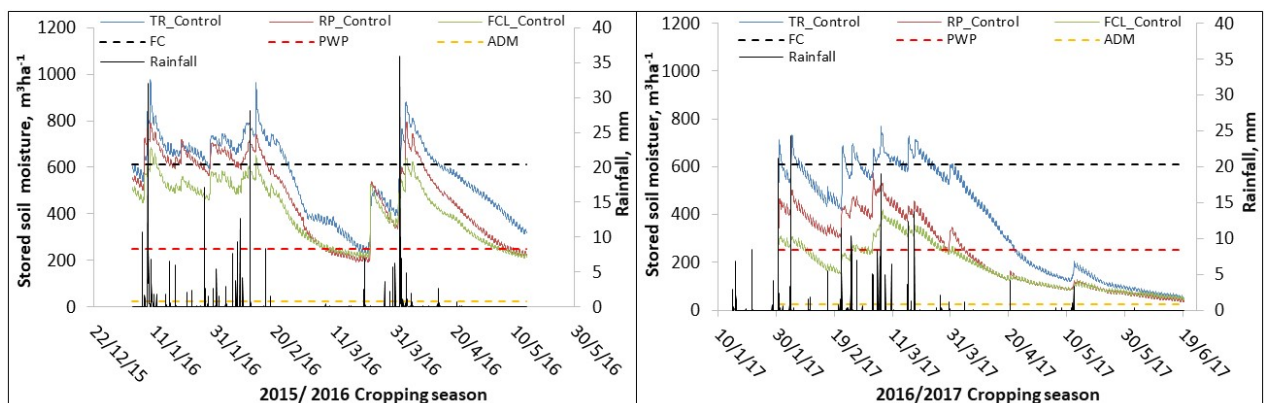


Figure 4.7: Stored water monitored hourly at the sorghum's effective root zone during 2015/2016 (above-average rainfall season) and 2016/2017 (below-average rainfall season). TR, tie-ridges; RP, ripping; FCL, flat cultivation; FC, field capacity (-3.1 kPa); PWP, permanent wilting point (-1.5 MPa); ADM, air dried moist (-31.0 MPa).

Percentagewise, FCL treatments had retained more soil-water by 9.9% over the RP treatment, while TR treatment accumulated an extra soil water by 18.2%. Although the percentage increment of soil water in TR over FCL was only 7.6%; it was enough to separate TR from RP and FCL in terms of degree of drought susceptibility for sorghum water extraction, at the end of the extended drought period. While TR treatment had retained soil water close to the range of the permanent wilting point (-1.5 MPa) by 8.8%, FCL and RP had completely exhausted all the stored water at the effective root zone. To attain the soil moisture status above -1.5 MPa, FCL and RP treatments would have needed to gain soil water of more than 15.2% and 22.8%, respectively. The moment RP and FCL held soil water below the -1.5 MPa on March 7, 2016, TR had available soil water to support sorghum for 11 more days.

As opposed to the above-average rainfall season, the performance of TR against RP in the below-average rainfall season was different in terms of capturing efficiency and the storage of soil water, at the effective root zone of the sorghum. The results showed that TR treatment had stored the captured rainwater, effectively than RP and FCL (Table 4.1). The monitored soil moisture dynamics showed that, the stored soil water in TR was high during and after the rainfall events. When the retained soil water in FCL and RP was

Table 4.1: Average soil-water volume status ($\text{m}^3 \text{ha}^{-1}$) at the effective root zone of sorghum in the two consecutive cropping seasons of 2015/2016 (above-average rainfall season) and 2016/2017 (below-average rainfall season).

Treatment	Annual Rainfall ($\text{m}^3 \text{ha}^{-1}$)	Water at the start of the extended dry spell ($\text{m}^3 \text{ha}^{-1}$)	Water at Field Capacity ($\text{m}^3 \text{ha}^{-1}$)	Water at permanent wilting point ($\text{m}^3 \text{ha}^{-1}$)	Available water at the start of extended dry spell ($\text{m}^3 \text{ha}^{-1}$)	Available water capacity ($\text{m}^3 \text{ha}^{-1}$)
Tie ridges ¹	9669	827.5	610.9	250.6	576.9	360.3
Ripping ¹	9669	707.1	610.9	250.6	456.5	360.3
Flat cultivated land ¹	9669	632.4	610.9	250.6	381.8	360.3
Tie-ridges ²	3432	708.6	610.9	250.6	458.0	360.3
Ripping ²	3432	383.2	610.9	250.6	132.6	360.3
Flat cultivated land ²	3432	346.8	610.9	250.6	96.2	360.3

¹2015/2016 cropping season (above-average rainfall season); ²2016/2017 cropping season (below-average rainfall season); tie-ridges (TR); ripping (RP); flat cultivation (FCL).

depleted below the -1.5 MPa, TR had still retained available soil water for crop uptake. The difference in the stored available soil water between RP and TR at this point was $262.2 \text{ m}^3 \text{ ha}^{-1}$, which accounted for 91.8% in a decreased capability of the later to withhold water at the effective root zone of the sorghum, where most of the active feeding roots proliferated. Past the water holding tension of -1.5 MPa, TR had still retained more water than the rest of the treatments. Even though soil water held at a tension of -1.5 MPa is practically limited for crop uptake with reference to sunflower, maize and wheat (Farre and Faci, 2006; Kirkham, 2014), and usually regarded as a general reference point for permanent wilting point to all other field crops (Kirkham, 2005, 2014); sorghum roots might have an ability to extract water beyond this tension. This is because, the observed point at which water was retained at -15 MPa in the laboratory, following Klute (1986) and CSSAMM (1986)'s procedures, was slightly high to represent soil moisture condition at the permanent wilting point in the sorghum field; nonetheless it was still useful for comparison in this study. The study showed that, differences in soil moisture levels retained in the different IRWHT at same point in time, offers important hints in foreseeing the degree of soil water availability in supporting crop growth, particularly, during the expected extended drought period, when soil moisture is limited.

Although most of the studies on TR (El-Swaify et al., 1985; Krishna, 1989; Hulugalle et al., 1990; Carter and Miller, 1991; Piha, 1993; Vogel, 1993; Wiyo et al., 1999; Araya and Stoosnijder, 2010; Biazin and Stroosnijder, 2012; Ngetich et al., 2014; Okeyo et al., 2014; Kilasara et al., 2015) had not directly quantified in detail the balance and subsequent availability of soil water at the effective root zone of the crop, the finding in this study complement most of their assumptions that TR treatment does not only inherently increase soil water status, but also it makes the stored water easily available at the effective root zone. With an increasingly impact of climate change and variability on

rainfall distribution, amount and pattern in ASALs as observed in this study, TR proved to be the best tillage option in storing available soil water, which is essential in mitigating the critical period of soil moisture stress due to meteorological and agronomic droughts on a wide range of rainfall from 343.3 mm to 966.9 mm. The findings of this study, however, deviate from the modelling works of Wiyo et al. (2000), whose simulation work based on the water balance model concluded the ineffectiveness use of TR in the rainfall season below 500 mm or above 900 mm.

4.3.2 Influence of ripping and tie-ridges integrated with organic and inorganic fertilizers on temporal soil water dynamics at the sorghum's effective root zone

Temporal soil moisture dynamics, at the effective root zone of the sorghum as influenced by RP treatment and TR treatment, integrated with organic and inorganic fertilizers are depicted in Fig. 4.8. The results showed that, there was a variation in temporal soil moisture dynamics within and across the treatments. The differences were brought by the effect of applied fertilizers on the sorghum's growth and development, which in turn triggered different water demand to match with sorghum bio-physiochemical process. Depending on the fertilizer source integrated with the RP, TR and FCL treatments, as well as the amount, pattern and distribution of the rainfalls; different temporal soil water dynamics were revealed.

In the above-average rainfall season, when FYM alone was applied, RP_FYM retained soil water volume slightly closer to TR_FYM after deep percolation. FCL_FYM stored the least amount of water than TR_FYM and RP_FYM; nevertheless, it had a comparable higher soil water volume than FCL_N+FYM and FCL_N. During the critical period of soil moisture stress in the extended drought period, RP_FYM rapidly depleted the available soil water at the effective root zone. Throughout the extended drought period,

the rate of soil water depletion in RP_FYM, increasingly deviated from TR_FYM and pooled itself for similarity with FCL_FYM. As the tension to hold water against the sorghum's roots uptake increased beyond the easily available water, RP_FYM regained soil moisture at the effective root zone by capillary rise due to upward water movement, probably from the percolated water stored beyond the 20 cm depth. The regained water by the capillary rise resulted in the availability of soil water in RP_FYM, which supported sorghum growth for eighty more days from 29th February to March 8, 2016 when FCL_FYM had already depleted water beyond -1.5 MPa.

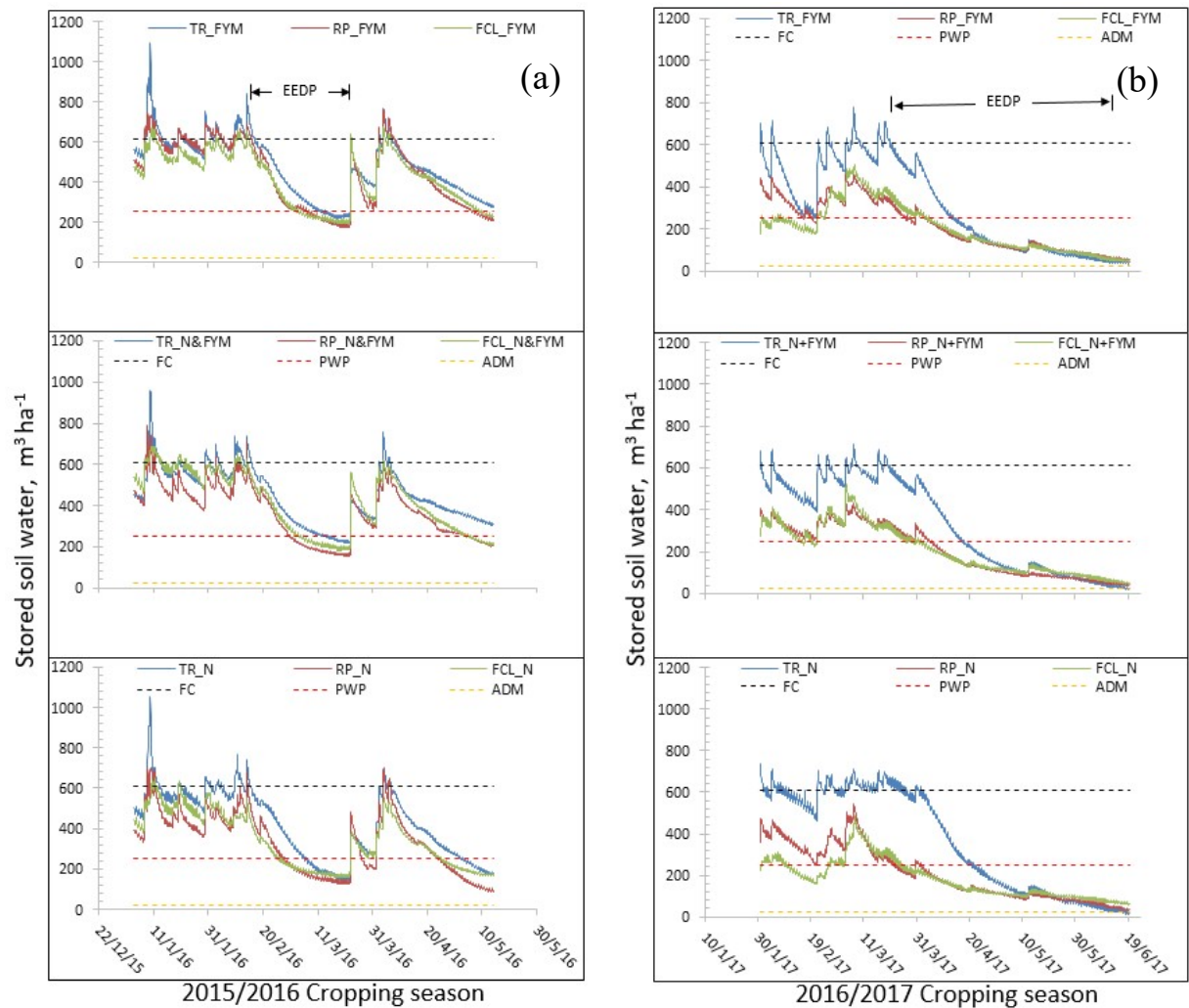


Figure 4.8: Temporal soil moisture dynamics in tie-ridge (TR), ripping (RP) and flat cultivated land (FCL) as influenced by different rates of soil water depletion to meet crop water requirement as triggered by N, FYM and N+FYM in (a) 2015/2016 cropping season (above-average rainfall season) and (b) 2016/2017 cropping season (below-average rainfall season). FC, field capacity (-3.1 kPa); PWP, permanent wilting point (-1.5 MPa); ADM, air dried moist (-31.0 MPa).

The results also showed that before soil water was held at -1.5 MPa, in the above-average rainfall season, the stored soil water volume at the effective root zone was in order: $TR_FYM > RP_FYM > FCL_FYM$. However, at the end of the extended drought period, when water was held at tensions beyond -1.5 MPa, RP_FYM treatment quickly depleted the regained soil water volume by capillary rise. The degree of soil water depletion was even higher than that in FCL_FYM ; this resulted in alteration of the soil moisture levels to the order: $TR_FYM > FCL_FYM > RP_FYM$.

The rate at which the available soil water depleted in between the rain storms and during the extended drought period, was even higher in RP_N and RP_N+FYM . Regardless of the quick depletion of the soil water volume, RP treatments were observed to regained water more quickly than FCL treatments, even under the rainfall of less than 10 mm. This rapid water regaining ability in RP treatments was attributed to overlapping effects of high infiltration rate and the upward water movement. The upward water movement, however, clearly revealed itself in the RP_FYM treatment. From the beginning to the end of the expected extended dry period, there was a distinct degree of depletion of stored available soil water in the $IRWHT$ integrated with $N+FYM$ following the order: $RP_N+FYM > FCL_N+FYM > TR_N+FYM$. This trend deviated from the $IRWHT$ integrated with N , which revealed a different pattern in soil water depletion before and after soil water was held at -1.5 MPa. Between the field capacity (-3.1 kPa) and permanent wilting point (< -1.5 MPa), the trend of soil moisture depletion followed the order: $RP_N > FCL_N > TR_N$, while at a tension greater than -1.5 MPa the order was $RP_N > TR_N > FCL_N$; indicated that there was a high crop water uptake demand, triggered by the initial vigorous sorghum growth in RP and TR treatments integrated with N .

In the above-average rainfall season, the general degree in soil water depletion at the effective root zone of the sorghum, during the extended dry spell period increased from TR_FYM and RP_FYM to TR_N and RP_N, respectively. TR_Control and RP_Control retained a relatively higher water volume than the former and the latter. This implies that, if the soil moisture stress during the extended dry spell could have been extended more, the likelihood of sorghum crop failure would have decreased in the order: IRWHT_N > IRWHT_N+FYM > IRWHT_FYM > IRWHT_Control. Such trend on the rate of soil moisture depletion sheds some light on the reluctance of the dryland areas' farmers on the use of industrial fertilizers. It also revealed some trade-off dryland areas' farmers do take to ensure less but steady sorghum grain yield rather than expecting higher yield with a high risk of crop failure. Furthermore, the results showed that an integration of either a half or full amount of FYM in TR treatment, smoothly regulated sorghum water uptake from the stored available soil water; as a result, TR_FYM and TR_N+FYM retained relatively more water volume when TR_N had already depleted the stored soil water to -1.5 MPa. The period for the retained available water volume to meet crop water requirement, increased by two-fold in TR_Control as indicated in Table 4.2.

Contrary to the above-average rainfall season, an integration of FYM in the FCL in the below-average rainfall season, enhanced more water availability than in FCL_Control and FCL_N+FYM. The amount of the available water volume increased even more when FCL_FYM was compared to FCL_N. The influence of FYM on the enhancement and regulation of the soil water availability, however, was not observed in the RP and TR treatments. While it might have been surpassed by a compounded effect of high infiltration rate and crop water requirement in RP treatment, it was observed to be influenced by the latter in TR-treatment due to vigorously sorghum growth. The integrated FYM in RP and TR treatments played a more role as a fertilizer rather than an

Table 4.2: Stored soil-water balance ($\text{m}^3 \text{ha}^{-1}$) at the effective root zone of the sorghum (0-20 cm) when any of the treatment in question was at permanent wilting point (PWP, -1.5 MPa) during the critical period of soil moisture stress.

Season	Treatment	Time when water was at the PWP	Water held at PWP	Corresponding stored soil water balance for each treatment at permanent wilting point ($\text{m}^3 \text{ha}^{-1}$)											
				Tie-ridges (TR)				Ripping (RP)				Flat cultivated land (FCL)			
				N+FYM	FYM	N	Control	N+FYM	FYM	N	Control	N+FYM	FYM	N	Control
2015/16	TR_N+FYM	12/03/2016:09:00	250.4	250.4	246.8	181.1	319.9	173.0	207.9	141.7	215.9	199.3	2019.8	170.5	229.7
	TR_FYM	12/03/2016:05:00	250.9	253.6	250.9	185.8	328.3	175.4	212.1	145.0	219.8	203.1	212.3	172.8	233.7
	TR_N	06/03/2016:16:00	250.1	289.3	307.0	250.1	387.4	207.4	271.0	186.4	249.0	245.5	249.0	198.1	275.3
	TR_Control	18/03/2016:09:00	250.4	224.3	217.9	148.9	250.4	159.06	177.9	126.0	194.4	181.2	191.9	157.5	217.2
	RP_N+FYM	29/02/2016:09:00	250.8	341.6	376.2	339.1	443.5	250.8	267.9	216.6	372.5	282.5	273.4	210.4	305.9
	RP_FYM	07/03/2016:04:00	250.8	282.1	294.6	237.8	365.6	195.08	250.3	166.3	253.1	228.1	227.8	184.3	254.9
	RP_N	27/02/2016:04:00	250.3	378.8	419.1	388.3	530.7	295.0	300.0	250.2	421.5	320.3	314.2	230.3	342.0
	RP_Control	07/03/2016:12:00	250.2	276.6	288.8	228.4	361.5	193.4	248.3	165.2	250.2	225.8	226.9	185.1	250.9
	FCL_N+FYM	03/03/2016:07:00	250.2	308.3	336.6	288.9	383.3	218.8	264.8	188.7	297.2	250.8	246.5	195.9	280.8
	FCL_FYM	06/03/2016:18:00	250.6	293.2	311.1	255.8	393.7	207.4	271.0	187.6	272.7	246.6	250.6	200.4	277.7
	FCL_N	25/02/2016:04:00	250.3	416.9	462.8	430.8	593.0	330.2	346.5	282.7	347.5	357.4	360.7	250.3	378.9
	FCL_Control	07/03/2016:07:00	250.2	278.9	290.5	232.2	358.4	192.6	245.2	161.8	247.3	223.5	222.6	180.5	250.2
2016/17	TR_N+FYM	17/04/2017:14:00	250.2	250.2	219.3	282.5	327.4	143.6	148.2	128.1	138.1	143.1	161.4	132.9	139.2
	TR_FYM	13/04/2017:06:00	250.6	302.0	250.2	340.6	384.5	167.8	167.7	147.0	163.4	161.8	181.5	146.7	159.0
	TR_N	19/04/2017:09:00	250.3	222.8	198.8	250.3	292.3	130.3	138.4	117.9	126.9	126.4	147.5	119.7	235.9
	TR_Control	22/04/2017:02:00	250.4	201.2	174.0	236.8	250.4	133.2	157.3	136.8	138.1	142.5	155.8	130.5	133.6
	RP_N+FYM	30/03/2017:06:00	250.8	478.1	446.8	557.9	531.8	250.8	222.3	187.7	239.5	237.1	259.3	206.8	236.3
	RP_FYM	03/04/2017:03:00	250.9	498.7	460.8	578.5	548.9	269.8	250.9	22.3	272.3	228.7	255.2	203.2	227.2
	RP_N	23/03/2017:00:00	250.9	569.1	561.1	641.1	630.6	309.6	302.3	250.9	364.0	296.2	337.8	277.2	306.7
	RP_Control	04/04/2017:06:00	250.7	472.2	426.3	551.7	522.3	253.1	234.6	201.3	250.7	215.2	240.6	192.4	213.1
	FCL_N+FYM	01/04/2017:13:00	250.6	531.9	509.3	597.3	579.3	299.2	282.7	250.9	324.5	250.6	276.0	220.1	250.4
	FCL_FYM	05/04/2017:16:00	250.9	458.5	401.5	531.1	517.5	253.1	241.8	211.0	249.9	224.8	250.9	202.0	222.3
	FCL_N	26/03/2017:17:00	250.1	536.8	513.6	631.3	600.2	289.4	263.2	221.9	310.3	274.4	310.8	250.1	280.0
	FCL_Control	28/03/2017:04:00	250.4	496.7	469.4	568.7	547.9	266.9	248.3	208.1	285.7	254.4	278.1	220.1	250.4

TR, Tie-ridges; RP, ripping; FCL, flat cultivated land; N, inorganic fertilizer; FYM, organic fertilizer; PWP (-1.5 MPa), Permanent wilting point; IRWHT, in situ rainwater harvesting techniques.

amendment for soil moisture enhancement. Even if it did increase soil moisture level, the rate of increment might not have been sufficient enough to offset the rate at which water was evapotranspired by the crop in TR_FYM. However, in RP_FYM both a high rate of infiltration and crop water requirement possibly decreased the retained soil water. As a result, TR_Control and RP_Control appeared to retain more available soil water balance at the effective root zone, when treatments with fertilizers had depleted soil water to -1.5 MPa.

The levels of soil moisture availability after application of fertilizer in RP in the below-average rainfall season followed the order: RP_Control > RP_FYM > RP_N+FYM > RP_N. With reference to TR treatments, application of fertilizers followed similar trend to that of RP, but with more soil water depleted earlier. The increased water depletion in TR_FYM and TR_N+FYM might have been influenced by increased mineralized FYM, which released nutrients that enhanced sorghum growth and water uptake at flag leaf growth stage toward flowering stage, before water was depleted to -1.5 MPa. The differences on soil water depletion in TR_N that pooled its soil water below the level of FCL_N and RP_N at the end of the extended dry spell period, was influenced by the earlier rapid growth rate of sorghum due to a more easily available soil moisture and nutrients. In general, the rate of depletion of available soil water at the effective root zone in the below-average rainfall season, showed a similar pattern regardless of the fertilizers integrated, but with varying degrees at which stored water was depleted based on the fertilizer source applied.

4.3.3 Interactive influence of ripping and tie-ridges with organic and inorganic fertilizers on mitigation of the critical soil moisture stress at sorghum's effective root zone during the expected extended drought period

4.3.3.1 Interactive influence of ripping and tie-ridges with fertilizers on daily basis

The drought mitigation ability of RP, TR and FCL with or without fertilizers at the effective root zone of sorghum revealed different trends. The differences at which RP_Control, TR_Control and FCL_Control mitigated the critical period of soil moisture stress at the effective root zone of the sorghum on daily basis, during the expected extended drought period is indicated in Fig 4.9 (a) and (b). The results showed that for the two consecutive cropping seasons of 2015/2016 (above-average rainfall season) and 2016/2017 (below-average rainfall season), TR treatment had highly mitigated the critical period of moisture stress by storing more volume of the available soil water than the rest of the treatments. In the above-average rainfall season, TR treatment mitigated soil moisture stress by 35 days out of 37 of the extended drought period, being ahead of RP_Control and FCL_Control by 13 and 12 days, respectively (Fig 4.9 (a)). An analysis of mitigation potential showed that TR_Control, RP_Control and FCL_Control had mitigated the extended drought period by 95%, 59% and 62%, respectively. In the below-average rainfall season, the critical soil moisture stress period was extended, this reduced the drought mitigation potential of TR_Control to 37% of 93 days of the extended drought period. Nevertheless, TR_Control was ahead of RP_Control by 17 days and FCL_Control by 23 days (Fig. 4.9 (b)).

Although after integration of the fertilizer, TR_FYM stored more water than RP_FYM and FCL_FYM (Fig.4.9 (c) and (d)), its potential to mitigate soil moisture stress at the effective root zone of the sorghum as compared to TR_Control, was reduced to 72% and 32% in the above and below-average rainfall season, respectively. However,

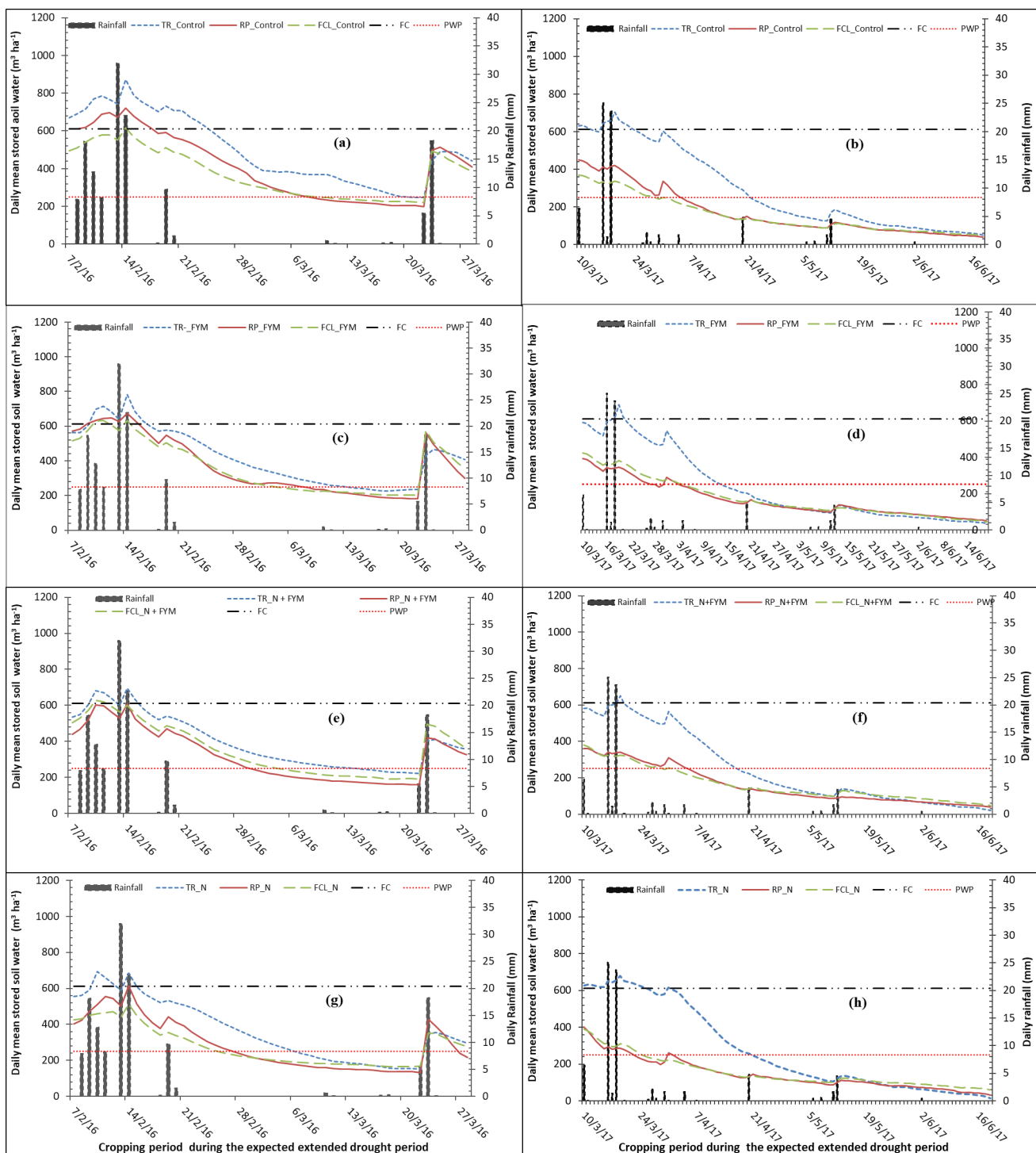


Figure 4.9: Differences in water balance at the effective root zone of sorghum in tie-ridges (TR), ripping (RP) and flat-cultivated land (FCL) as influenced by the sorghum water uptake in the treatment with: control, no fertilizer application ((a) and (b)); FYM, organic fertilizer ((c) and (d)); N+FYM, a half-combined inorganic and organic fertilizers ((e) and (f)), and N, inorganic fertilizer ((g) and (h)), for the two cropping seasons of 2015/2016 (above-average rainfall season) and 2016/2017 (below-average rainfall season). FC, field capacity (−3.1 kPa); PWP, permanent wilting point (−1.5 MPa).

in both seasons, TR_FYM held soil water at -1.5 MPa eight days earlier than TR_Control. At the end of the extended drought period in the below-average rainfall season, TR_FYM depleted more soil-water than RP_FYM and FCL_FYM. The high depletion rate of the stored soil water in TR_FYM was due to a higher water demand of the vigorously growing sorghum. This is because, the stored water in TR_FYM was initially relatively available at the effective root zone to meet sorghum water demand in the early growing stages of the crop compared to RP_FYM and FCL_FYM. Such a phenomenon was not observed in the above-average rainfall season.

The daily influence of TR_N+FYM in mitigating the critical period of soil moisture stress during the above-average rainfall season differed with TR_FYM and TR_Control by one and seven days, respectively. The mitigation potential of RP_N+FYM was reduced to 15 days from 22 days of the RP_FYM, this means the difference between the former and the latter in storing soil water volume at -1.5 MPa was 7 days. The results showed that across all the N+FYM treatments, RP_N+FYM consistently registered the lowest stored water volume (Fig. 4.9 (e)). When RP_N+FYM depleted all the water at the effective root zone to -1.5 MPa, FCL_N+FYM had an extra volume of water ($34.6 \text{ m}^3 \text{ ha}^{-1}$), which supported available soil water for three more days. Nevertheless, the latter mitigation potential over the former was low compared to an extra stored volume of water in TR_N+FYM ($87.9 \text{ m}^3 \text{ ha}^{-1}$), that mitigated the critical soil moisture stress for 13 days. In the below-average rainfall season (Fig. 4.9 (f)), TR_N+FYM was ahead in retained soil water by 13 and 19 days more compared to RP_N+FYM and FCL_N+FYM, respectively. However, comparing to TR_Control treatment, TR_N+FYM depleted the stored soil water at the effective root zone of the sorghum, four days earlier.

Integration of N in the above-average rainfall season influenced sorghum growth, which led to a rapid depletion of the available soil water at the effective root zone and

decreased the mitigation potential of TR_N (57%) over TR_N+FYM and TR-FYM by 19% and 16%, respectively. Although TR_N had stored an extra soil water volume of 127.2 m³ ha⁻¹ and 164.2 m³ ha⁻¹, mitigating soil moisture stress for 8 and 10 days longer than RP_N and FCL_N, respectively (Fig. 4.9 (g)); its available soil water was rapidly evapotranspired 14 days earlier than in the TR_Control. Compared to RP_N and FCL_N treatments, RP_Control and FCL_Control retained 153 m³ ha⁻¹ and 112 m³ ha⁻¹ more, which supported crop growth for 9 and 12 days, respectively.

In the below-average rainfall season, the difference in days for available soil water between TR_Control and TR_N was remarkably reduced, with the former treatment assuring one extra day to mitigate soil moisture stress over the latter. The highest water depletion was observed in the TR_FYM and TR_N+FYM, which had mitigation potentials of 28% and 32%, respectively, over TR_Control (37%). Within the RP and FCL treatments, the lowest mitigation potentials were registered in RP_N (14%) and FCL_N (7%). Following a similar trend to other IRWHT integrated with fertilizer; in all the N integrated treatments, TR_N had stored more water than RP_N and FCL_N as depicted in Fig. 4.9 (h). The result showed that at the end of the extended drought period, in the below-average rainfall season; TR_FYM and TR_N+FYM had depleted more water than TR_N, FCL_N and RP_N. This higher water depletion in TR_N, FCL_N and RP_N was influenced by lately sorghum height increasing rate, influenced by mineralized FYM under the appreciable stored soil moisture. Although such depletion showed little agronomic implications on final sorghum growth, it provided important information in understanding complexity interactions of soil-water-plant-nutrients relationship, which saves as a benchmark in tracking suitability of different land management and fertilizer source options in dryland areas. The drought mitigation potentials of the IRWHT as influenced by fertilizer sources are shown in Fig. 10.

Irrespective the proof that soil water at the effective root zone was depleted beyond -1.5 MPa, sorghum continued to grow but at a reduced rate, most of the lower leaves withered and died. The few remaining upper leaves were rolling in daytime and opened in night hours. Such a survival in a limited water condition strengthen an evidence about sorghum's ability on counteracting cohesive force at which water is held against root uptake at tension greater than -1.5 MPa, which often referred to as a permanent wilting point for most annual crops. Furthermore, the survival of the sorghum at -15 MPa might

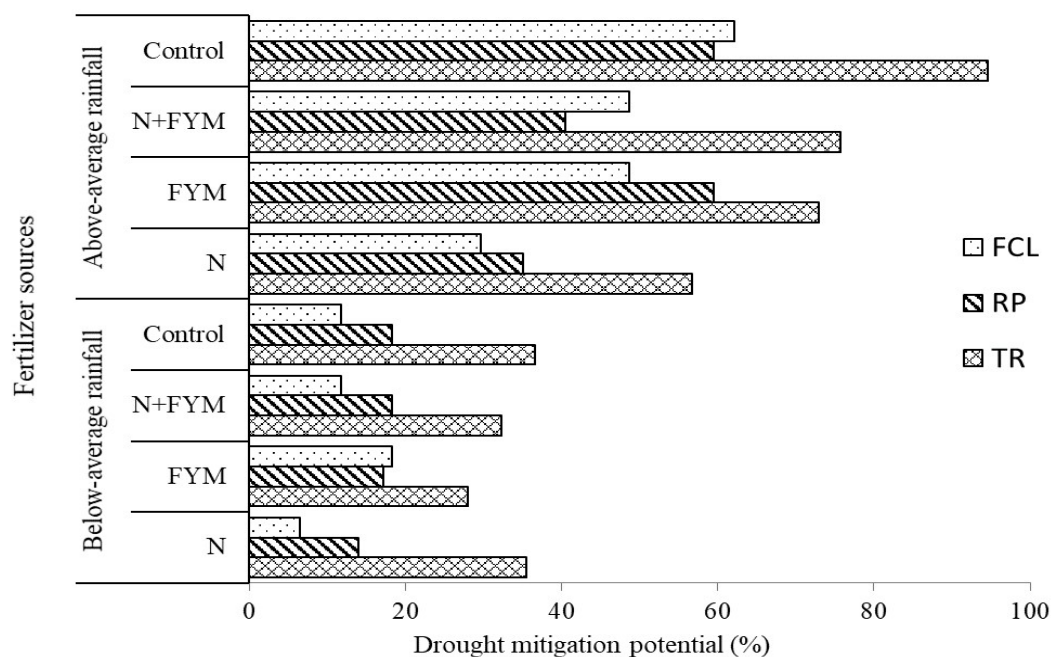


Figure 4.10: Drought mitigation potentials (%) as affected by sorghum water uptake under tie-ridges (TR), ripping (RP) and flat-cultivated land (FCL) with and without fertilizers, for the two-consecutive cropping seasons of 2015/2016 (above-average rainfall season).

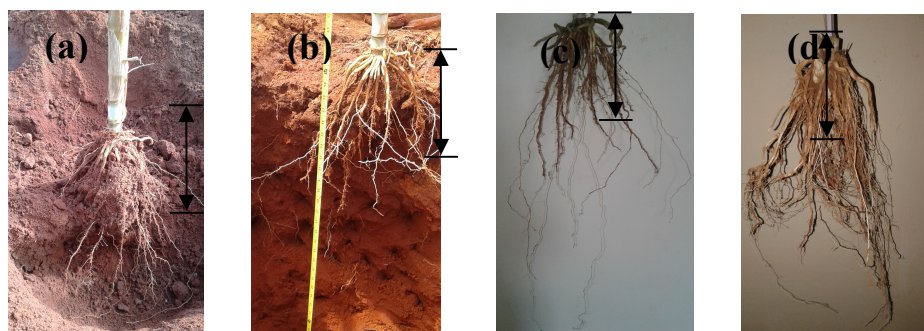


Figure 4.11: Showing area of sorghum roots concentration at the effective root zone; during excavation (a) and (b); and after excavation (c) and (d).

have also influenced by few roots, which extended beyond the effective root zone (Fig. 4.11 (a), (b), (c) and (d)). It is possibly that these roots played a significant role in soil water exploitation during the extended drought period. Such possibility of deep root in enabling sorghum to complete its life cycle has also been reported by Kaigama et al. (1977), Eck et al. (1979) and Myers (1980).

4.3.3.2 Interactive influence of ripping, tie-ridges with fertilizer on water balance at the effective root zone of the sorghum on weekly basis

The stored soil water balance at the effective root zone of the sorghum, and its subsequent availability to mitigate the critical period of soil moisture stress on weekly basis, during the extended dry spell period, was higher in the IRWHT with no fertilizer applied compared to the ones with different fertilizer source. Statistical analysis by paired t-test showed that in both seasons, TR_Control had significantly ($P < 0.05$) retained a large volume of water compared to FCL_Control and RP_Control. The analysis, however, could not reveal any remarkable differences ($P > 0.05$) in the stored soil water at the effective root zone between RP_Control and FCL_Control.

Evaluation of drought mitigation potentials on weekly basis across all the treatments, showed the highest percentage values compared to those in daily basis in the above-

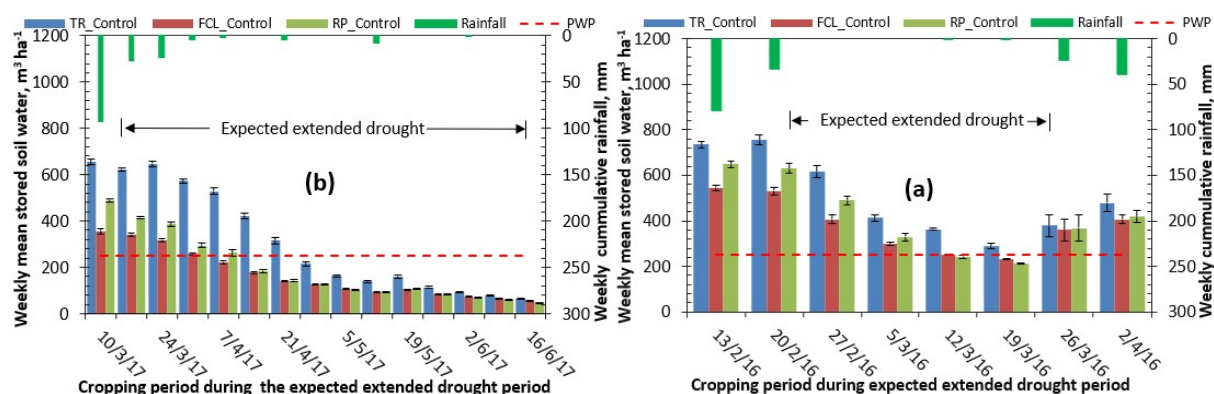


Figure 4.12: Weekly mean soil water balance at the effective root zone of the sorghum without fertilizer in (a) 2016/2017 (the above-average rainfall season); (b) 2016/2017 (below-average rainfall season).

average rainfall season and below-average rainfall season. The results indicated that in the above-average rainfall season, TR_Control had effectively mitigated the critical period of soil moisture stress by 100%. The mitigation potential decreased to 80% in FCL_Control and 60% in RP_Control (Fig. 4.12 (a)).

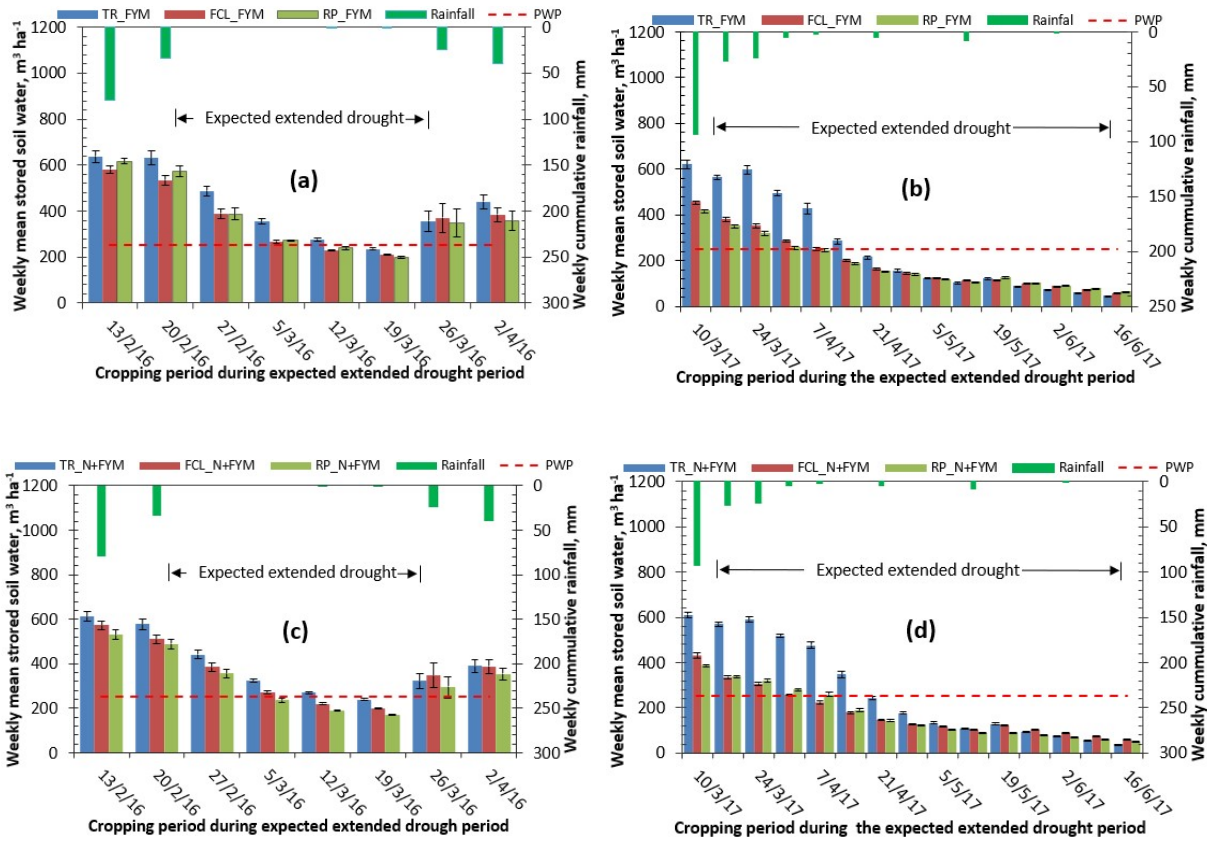


Figure 4.13: Weekly mean soil water balance at the effective root zone of the sorghum in the IRWHT integrated with: FYM, organic fertilizer in (a) above-average rainfall season; (b) below-average rainfall season; N+FYM, combined inorganic and organic fertilizer in (c) above-average rainfall seasons (d) below-average rainfall season.

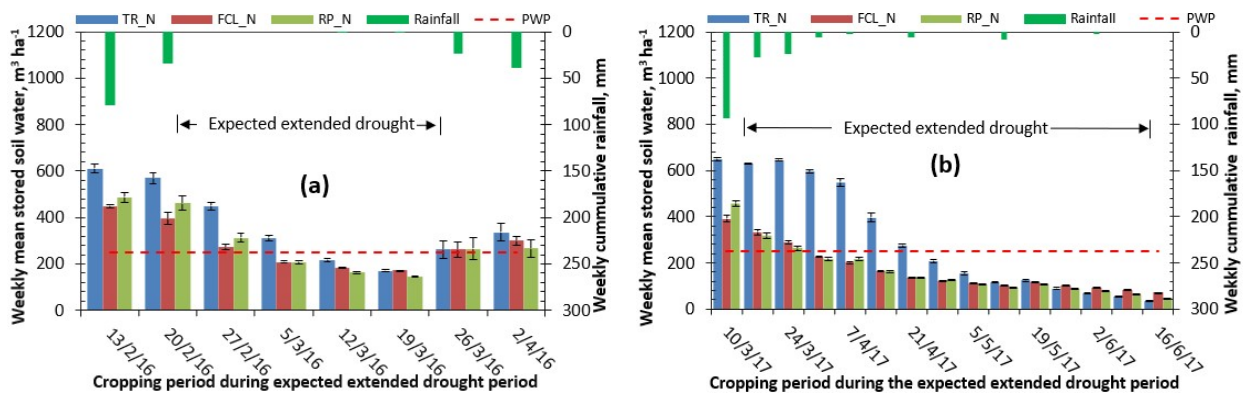


Figure 4.14: Weekly average soil water balance at the effective root zone in the IRWHT integrated with N, inorganic fertilizer, in (a) the above-average rainfall season and (b) the below-average rainfall season.

In the below-average rainfall season (Fig. 4.12 (b)), the registered drought mitigation potentials were 43%, 29% and 21% for TR_Control, RP_Control and FCL_Control, respectively. Based on the number of weeks, TR_Control had mitigated the critical period of soil moisture stress for the first 6 weeks from March 17, 2017, when sorghum was growing toward booting stage to early flowering stage on April 21, 2017. On the 7th week, the retained soil water in TR_Control was held at permanent wilting point (-1.5 MPa). At this point, FCL_Control and RP_Control had already exhausted the available soil water earlier on the 4th and 5th week, respectively; thereafter, the tension of the soil moisture against crop water uptake steadily increased until the harvest time.

The results showed that in the above-average rainfall season, both TR_FYM and TR_N+FYM depleted the available soil water below -1.5 MPa only in the last week of the extended drought, while FCL_FYM and FCL_N+FYM depleted all the available water one week earlier than the former and the latter. This accounted reduction of drought mitigation potentials by 20% in TR_FYM, TR_N+FYM, FCL_FYM and FCL_N+FYM with reference to their respective control treatments. It was also noted that RP_N, R_N+FYM and FCL_N depleted the available soil water to -1.5 MPa, for the three consecutive weeks during the extended drought period. With exception of the TR_N in the last week of the extended drought, the t-test showed that throughout the extended drought period, TR_FYM and TR_N+FYM had retained a significantly ($P < 0.05$) large volume of soil water than RP and FCL with similar fertilizer sources (Fig. 4.13 (a) and (c)).

Furthermore, the results indicated that in the above-average rainfall season, water uptake in N applied treatments could not reveal any significant difference ($P > 0.05$) in the stored water balance at the effective root zone between FCL_N and RP_N; however, it resulted in a rapid water depletion to -1.5 MPa in the former and the latter for three

weeks, consecutively (Fig. 4.14 (a)). It should be noted though, in this season, TR_N had depleted water to -1.5 for only two weeks consecutively. In the below-average rainfall season (Fig. 4.14 (b)), the stored soil moisture at the effective root zone in RP_N and FCL_N was depleted to -1.5 MPa at the third week of the extended drought period, and water was not available to meet the crop demand for 12 consecutive weeks.

4.3.4 Effect of ripping and tie-ridges with organic and inorganic fertilizers on growth and development of sorghum

4.3.4.1 Effect of ripping and tie-ridges with organic and inorganic fertilizers on sorghum seedling emergence

Table 4.3 shows the effect of different IRWHT with organic and inorganic fertilizers on seedling emergence in the above-average rainfall season and below-average rainfall season. The result did not show any significant difference ($p>0.05$) neither between TR and RP nor RP and FCL at 15th day after sowing during the above-average rainfall season. Such unclear differences were appreciably attributed by a higher soil moisture level in the above-average rainfall season. Although at 5th day after sowing, a high moisture level stimulated the initial seedling emergence in the above-average rainfall season compared to the below-average rainfall season by 11.0% and 13.6% in TR and RP treatments, respectively, it reduced the final seedling emergence at 15th day by 22.2% and 12.8% compared to the latter season. Such a reduction of seedling emergence in the above-average rainfall season was due to a prolonged waterlogged condition, which starved seeds from oxygen, thereby led to seed rotting before germination and emergence. Oxygen is essential for seed germination, as it plays a significant role in seed metabolism for energy release that would support seedlings before developed leaves for

photosynthesis (Siegel and Rosen, 1962; Raven et al., 2005; Chaffey, 2014), therefore, its presence apart from soil moisture and suitable temperature is important.

Table 4.3: Means separation table for the percentage seedling emergence of sorghum as affected by different IRWHT, organic and inorganic fertilizer in the above-average rainfall season and below-average rainfall season.

IRWHT and Fertilizer Source		% Seedling emergence			
		2015/2016		2016/2017	
		5 DAS	15 DAS	5 DAS	15 DAS
IRWHT	TR	46.1b	65.5b	35.1b	87.7c
	RP	44.9b	61.2ab	31.3b	74.0b
	FCL	12.2a	54.5a	14.9a	55.3a
FERTILIZER	N	34.9ab	59.7a	31.8bc	68.6a
	FYM	32.1ab	57.3a	26.7b	75.0a
	N+FYM	44.4b	69.4b	35.7c	74.6a
	Control	26.2a	55.0a	14.1a	71.2a
TR x FERTILIZER	TR_N	48.8cd	63.7bcd	41.0ef	85.9de
	TR_FYM	40.5bcd	62.5abcd	32.1cde	89.1e
	TR_N+FYM	66.7d	75.0d	50.0f	87.8de
	TR_Control	28.6abc	60.7abcd	7.3abc	87.8de
RP x Fertilizer source	RP_N	50.0cd	66.7cd	32.1cde	69.9bc
	RP_FYM	38.1bc	50.6abc	34.6def	77.6cde
	RP_N+FYM	50.0cd	69.1d	39.1ef	75.6cd
	RP_Control	41.7bcd	58.3abcd	19.2abcd	73.1c
FCL x Fertilizer Source	FCL_N	6.0 a	48.8ab	22.4bcd	50.0a
	FCL_FYM	17.9ab	58.9abcd	13.5ab	58.3ab
	FCL_N+FYM	16.7ab	64.3bcd	18.0abc	60.3ab
	FCL_Control	8.3a	45.8a	5.8a	52.6a
LSD	IRWHT	12.0	7.6	7.3	5.9
	FERTILIZER	13.9	8.8	8.4	6.8
	IRWHT*FERT	24.1	15.3	14.6	11.9
CV		41.3	15.0	31.9	9.7
F. STAT	IRWHT	***	*	***	***
	FERTILIZER	ns	*	***	ns
	IRWHT*FERT	ns	ns	ns	ns

p>0.05, nonsignificant (ns); p=0.05 – 0.01, significant (*); p=0.01– 0.001, very significant (**); p< 0.001, very highly significant (***); IRWHT, in situ rainwater harvesting technique; ¹above-average rainfall season; ²below-average rainfall season; N, inorganic fertilizer; FYM, organic fertilizer; and N+FYM, a half-combined inorganic and organic fertilizers.



Figure 4.15: (a) Tracing if seed germinated; (b) Seed found germinated, (c) surface crusting/ sealing in FCL.

In the below-average rainfall season, the lowest and highest final seedling emergence at 15th day after sowing were 55.3% and 87.7% for FCL and TR, respectively. The lowest final seedling emergence in FCL was caused by a limited soil moisture that was required for seed imbibition and germination, and for softening surface crusting to ease up seedling emergence. The highest overall final seedling emergence (89.1 %) in TR, in the below-average rainfall season was influenced by appreciable soil moisture level, which provided conducive environment for seed imbibition, germination and easy seedling emergence. However, these supportive conditions, could not clearly differentiated seedling emergence in TR over RP treatments, across the two seasons at 5th day after sowing, proving that some seeds continued to germinate in the soil, notwithstanding, the final seedlings emergence was affected by the limited soil moisture and surface sealing. Field observation showed that, some seeds had germinated but failed to emerge above the soil surface (Fig. 4.15 (a), (b) and (c)). Nevertheless, both TR and RP had a significantly ($p<0.05$) higher seedling emergence than FCL at 5th day after sowing.

Although fertilizer source influenced seedling emergence in the above-average rainfall season with N+FYM registering higher percentage in seedling emergence than in the control treatments at the 5th and 15th days after sowing, the control treatment could not differ significantly ($p>0.05$) with either N nor FYM at the 15th day after sowing. In the

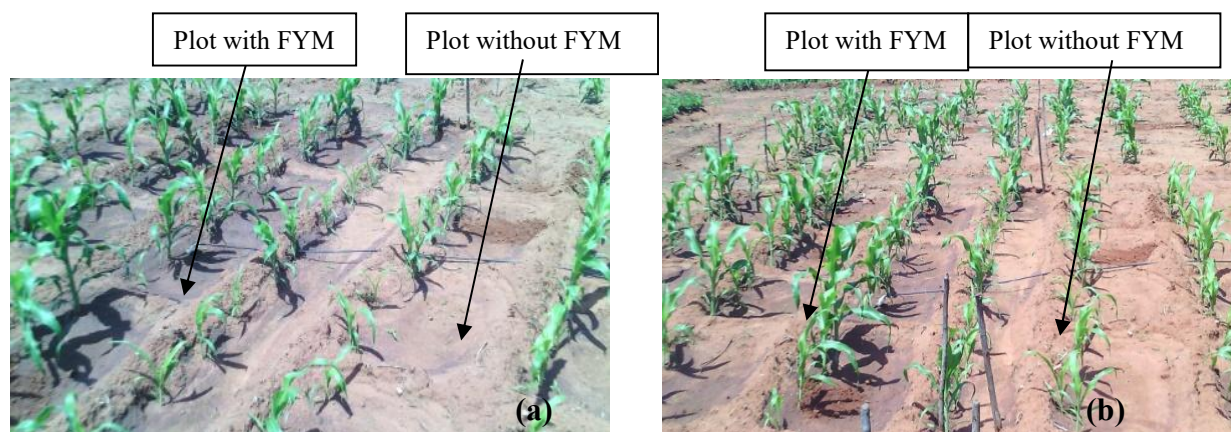


Figure 4.16: Field observation in the treatment with and without FYM soil moisture retention in the below-average rainfall season (a) when soil moisture is relatively high (b) when soil moisture is relative decreased.

FYM and Control at the 5th day after sowing, however, it registered a similar percentage below-average rainfall season, N+FYM fertilizers had the highest emerged seedlings than of seedlings emergence to the ones in N treatment. At the 15th days after sowing, the influence of fertilizer source on seedling emergence was suppressed across all the fertilizer treatments; nonetheless, FYM treatment ranked the first for the numerical value order: FYM > N+FYM > N > Control. The first numerical ranking in FYM treatment could have been due to its influence on soil moisture holding ability (Fig. 4.16 (a) and (b)) and improvement of soil properties, which reduced the effect of surface sealing on seedlings emergence.

The interactive effect of the IRWHT and fertilizers showed that the highest seedling emergence in the above-average rainfall season was in TR_N+FYM (75.0 %) and the lowest value was in FCL_Control (45.8 %). TR_N+FYM treatment revealed a significant ($p < 0.05$) difference with RP_FYM, FCL_N, and FCL_Control, however, it did not differ with the rest of the IRWHT integrated with different fertilizer source. Contrary to the above-average rainfall season, the highest seedling emergence (89.1 %) in the below-average rainfall season was counted in TR_FYM treatment, which differed significantly ($p < 0.05$) with RP_N, R_N+FYM, RP_Control, CL_N, FCL_FYM, FCL_N+FYM and FCL_Control, but could not differ with TR_Control, TR_N+FYM and TR_N. The results showed that different fertilizer sources have different effect on the sorghum seedlings emergence depending on the moisture level in the season and the IRWHT integrated. In the above-average rainfall season the final seedlings emergence is influenced by both soil IRWHT and fertilizer, but in the below-average rainfall season, soil moisture level is the dominant factor influencing for final seedling emergence.

4.3.4.2 Effect of ripping and tie-ridges with organic and inorganic fertilizers on sorghum plants heights and plant heights increasing rates

The responses of sorghum plant heights as influenced by the selected IRWHT and fertilizer sources in the above-average rainfall season and below-average rainfall season are shown in Fig. 4.17 and their relationship between final plant growth heights and plant heights increasing rates are indicated in Fig. 4.18. In the above-average rainfall season, the overall shortest (32.4 cm) and tallest (136.6 cm) plant heights were recorded in FCL_Control and TR_N+FYM at vegetative and flowering stage, respectively (Fig. 4.17 (a)). There were no significant differences in plant heights at vegetative stage amongst TR, RP and FCL treatments with different fertilizer sources, and all the TR treatments with fertilizers differed significantly ($p < 0.05$) with TR_Control; however, treatments applied with FYM in RP and FCL, had statistically similar plant heights with their respective control treatments. With exception to RP_N+FYM at flag leaf stage, TR with N+FYM significantly ($p < 0.05$) outperformed the rest of the treatments across all the IRWHT and fertilizer sources. This indicated that the nutrients supply from N+FYM was much far effective than a single application of either FYM or N. At both vegetative and flag leaf

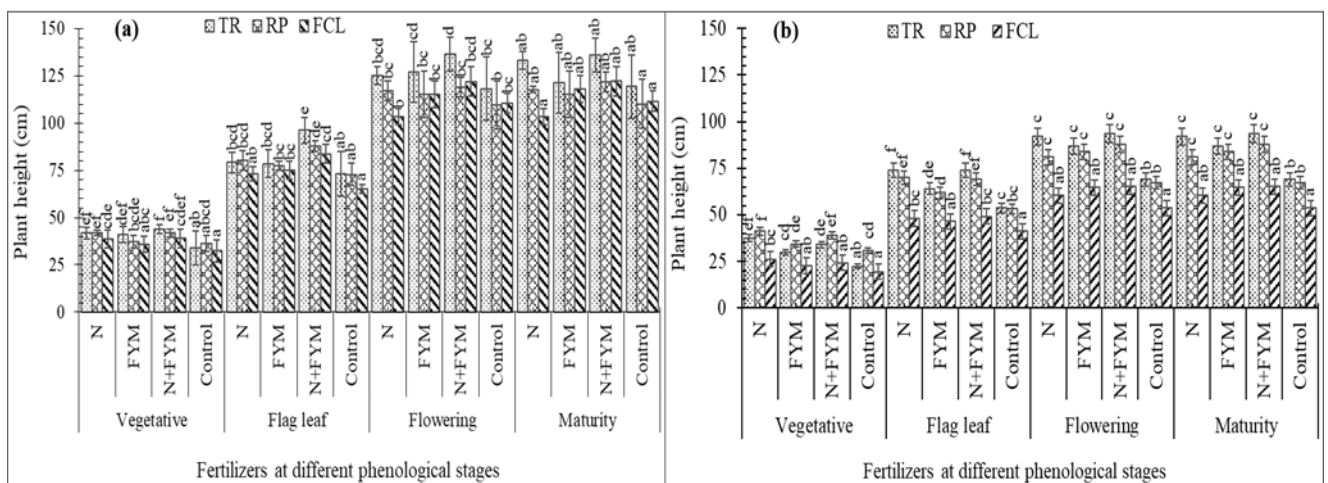


Figure 4.17: Final plant height at every growth stage as influenced by different IRWHT and fertilizers fertilizer sources in (a) above-average rainfall season (b) below-average rainfall season.

stages, plants heights in TR and RP applied with N slightly exceeded ($p>0.05$) the ones integrated with FYM, but the opposite was true at flowering and maturity growth stages.

The results showed that within the TR treatments at flowering stage, only TR_N+FYM resulted in a significantly ($p<0.05$) higher plant height than TR_Control, however, it did neither differ with TR_FYM nor TR_N. The similarity in plant heights amongst the TR with N, FYM and N+FYM at flowering stage was due to merged effects of switched differences in plant heights increasing rates across the treatments at different

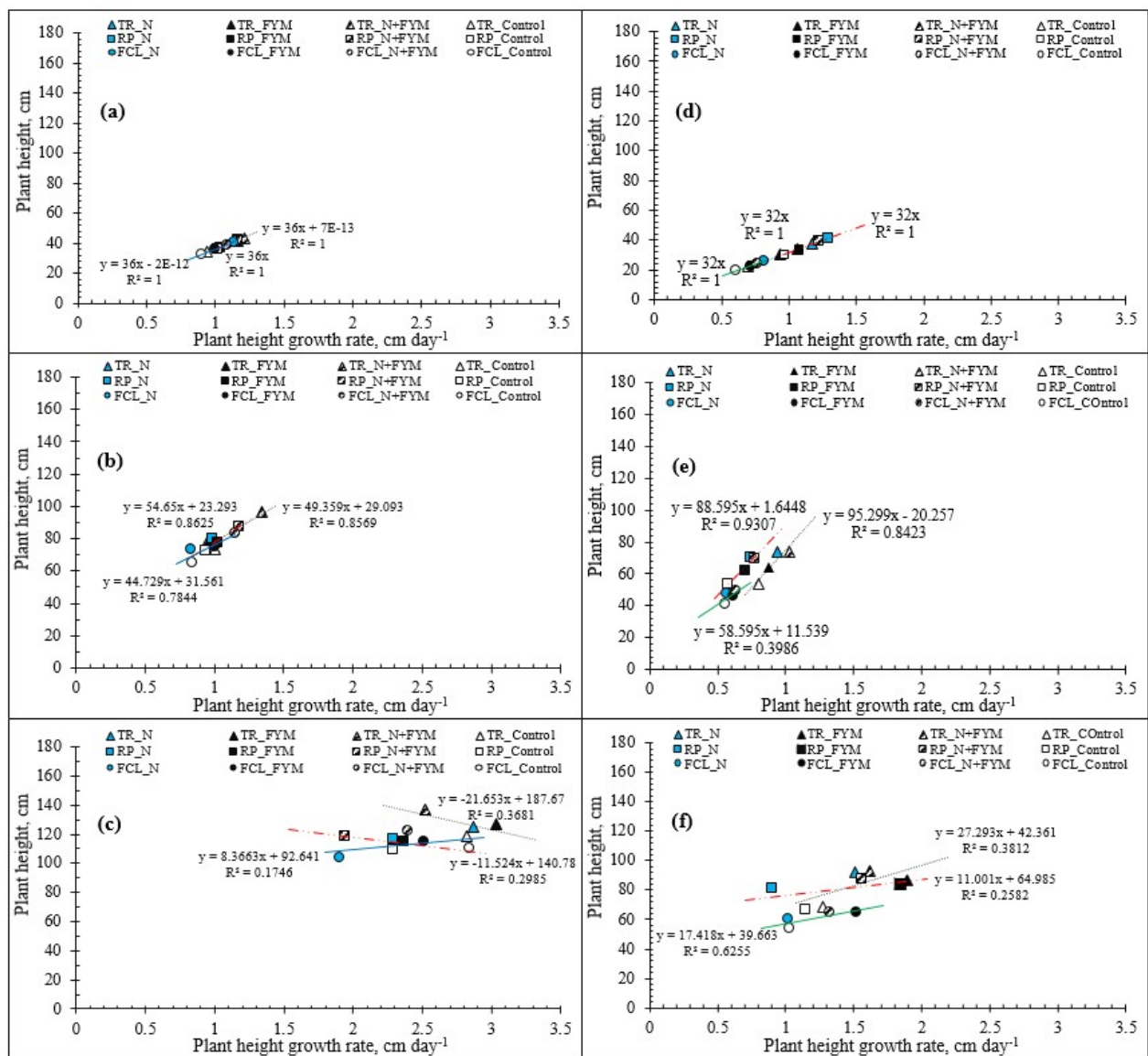


Figure 4.18: Relationship between sorghum plant heights and plant heights increasing rates in the above-average rainfall season at (a) vegetative stage; (b) flag leaf stage and (c) flowering stage; and in the below-average rainfall season at (d) vegetative stage; (e) flag leaf and (f) flowering stage.

growth stages. It was noted that within the TR treatments, the highest plant height increasing rate from flag leaf to flowering stage (Fig. 4.18 (c)) was in TR_FYM (3.03 cm day⁻¹) followed by TR_N (2.88 cm day⁻¹). The difference in plant height increasing rate in TR_N+FYM (2.53 cm day⁻¹) was 0.56 cm day⁻¹ and 0.35 cm day⁻¹ compared to the TR_FYM and TR_N, respectively. The plant height increasing rate in TR_FYM and TR_N from the flag leaf stage to flowering stage was three folds compared to their increasing rate of 0.96 cm day⁻¹ from vegetative to flag leaf stage (Fig 4.18 (b)), when TR_N+FYM had the highest plant height increasing rate of 1.35 cm day⁻¹. Since the growth period from vegetative stage to flag leaf stage (39 days) was longer than that from flag leaf stage to flowering stage (16 days), TR_N+FYM, resulted in the highest numerical plant height growth at flowering stage in the order: TR_N+FYM > TR_FYM > TR_N > TR_Control. The observed plant heights trend at the flowering stage differed from its plant height increasing rate from flag leaf stage to flowering stage, which showed the order: TR_FYM > TR_N > TR_Control > TR_N+FYM.

As was not expected, TR_Control, which had a significantly ($p<0.05$) shorter plant height by 16.8 cm than TR_N+FYM, exceeded plant height increasing rate of TR_N+FYM from flag leaf to flowering by 0.29 cm day⁻¹. In a similar way and at the same growth stage, RP_Control surpassed plant height increasing rate in RP_N+FYM by 0.35 cm day⁻¹; however, the plant height increasing rate in FCL_Control had the highest value amongst the FCL treatments, with the exceeding values of 0.94, 0.33 and 0.45 cm day⁻¹, beyond those attained in FCL_N, FCL_FYM and FCL_N+FYM, respectively. The observed high plant height increased rate in TR_Control, RP_Control and FCL_Control with reference to their corresponding fertilizers applied treatments, were influenced by a relatively higher stored water at the effective root zone of the sorghum, which mitigated the critical period of soil moisture stress during the expected extended drought period,

when sorghum water demand was high, but the rainfall stopped. This shows that it is possible for water to compensate the effects of fertilizer on plant height increasing rates during the critical period of soil moisture competition, as during this time fertilizer alone in a limited water condition could not influence a high plant height increasing rate. The results showed that in FCL treatments, FCL_Control had mitigated soil moisture stress for 23 days out of 37 days of the extended drought period compared to 18, 11 and 18 days in FCL_FYM, FCL_N and FCL_N+FYM, respectively. This means that sorghum plant in FCL_N rapidly depleted stored water at the effective root zone during booting stage, and it was under soil moisture stress 12 days earlier before TR_Control. Such a stress period was more than two folds compared to FCL_FYM and FCL_N+FYM, which depleted the stored water at the effective root zone to -1.5 MPa five days earlier before FCL_Control. Irrespective of the fact that FCL_N had a numerical taller plants than FCL_FYM at vegetative, a high water depletion in FCL_N at booting stage resulted in a lower plant height increasing rate (1.9 cm day^{-1}) in FCL_N from flag leaf to flowering stage compared to FCL_N+FYM (2.39 cm day^{-1}), FCL_FYM (2.51 cm day^{-1}) and FCL_Control (2.84 cm day^{-1}). The maximum attained plant heights at flowering stage were maintained until maturity stage, however there were some discrepancies in increase and decrease in plant height due to tiller formation and bending of the sorghum stems near the peduncle resulted by the overweight of the sorghum's panicles.

A decrease in soil moisture in the below-average rainfall season reduced the plant height performances across all the treatments compared to the above-average rainfall season. Although the shortest (19.5 cm) and tallest (93.4 cm) plants were still recorded in the same treatments and at the same growth stages as in the above-average rainfall season, they were shorter by 39.8 and 31.6% in the FCL_Control and TR_N+FYM at vegetative and flowering stage, respectively (Fig. 4.17 (b)). Contrary to the above-average rainfall

season, plants height in TR_N at vegetative stage, significantly ($p<0.05$) exceeded the ones in TR_FYM by 7.4 cm, but it could not differ with TR_N+FYM for its marginal difference of 3.3 cm; notwithstanding both TR_N (37.4 cm), TR_FYM (30 cm) and TR_N+FYM (34.1 cm) registered a significantly ($p<0.05$) taller plants than TR_Control (22.3 cm). A short plant in TR_FYM compared to TR_N was attributed to a compounded effect of limited released nutrients from FYM, and easily availability of nutrients from the applied inorganic fertilizer at the beginning of the season. Although FYM was considered limited in nutrients supply compared to N and N+FYM, it was relatively high enough to stimulate crop growth compared to TR_Control (Fig. 4.19).

The difference in plant height between TR_N and TR_FYM at the vegetative stage was not observed in the above-average rainfall season, suggesting that the prolonged excessive soil moisture at the effective root zone in the above-average rainfall season, created unfavourable conditions, which suppressed the expressive ability of TR_N over TR_FYM in enhancing primary growth. In the TR treatments with fertilizers during the above-average rainfall season, chlorosis was observed (Fig 4.20), indicating that sorghum plant was being affected by ammonium toxicity, but the degree of chlorosis was relatively more obvious in TR_N. However, this condition was quickly recovered as sorghum plant was growing toward a flag leaf stage. Although ammonium toxicity has been identified to



Figure 4.19: Showing visual performance of TR_FYM versus TR_Control during the below-average rainfall season.

reduce plant growth in several crop species (Nommik and Thorin, 1972; Torres de Claasen and Wilcox, 1974; Allen and Smith, 1986; Chaillou et al., 1986; Cramer and Lewis, 1993; Deignan and Lewis, 1988; Magalhães and Huber, 1989a;1989b; Feng and Barker, 1992; Bligny et al., 1997; Cao and Tibbits, 1998; Dou et al., 1999; Britto, D.T. and Kronzucker 2002; Millar and Crammer, 2004; Roosta and Schjoerring, 2007; Wang et al., 2010; Takushi et al., 2012; Cen et al., 2013; Bornman, 2013), it is likely that Macia sorghum variety (SDS 3220) is less susceptible and has a quick recovering mechanism. This is because, irrespective of the observed chlorotic plants in TR treatments with fertilizers, TR_N, TR_FYM and TR_N+FYM had still resulted in a significantly ($p<0.05$) higher sorghum growth than TR_Control.

Amongst the FCL and RP treatments at vegetative stage in the below-average rainfall season, only FCL_N (26.1) had a significantly higher plant height than FCL_Control (19.5 cm), and that in RP_N (41.2 cm) and RP_N+FYM (39.1 cm) had taller plants than in RP_Control (30.7 cm); however, the plant height in RP_Control and FCL_Control did not differ with the one in RP_FYM (34.4 cm) and FCL_FYM (22.7 cm), respectively; indicating that N was responsible in triggering vigorous sorghum growth by taking advantage of the initial available soil moisture condition. At flag leaf stage, the plant



Figure 4.20: Appearance of the chlorosis in TR_N at vegetative stage in the above average rainfall.

height in FCL_N+FYM (49.1 cm) significantly ($p<0.05$) deviated from the FCL_Control (41.3 cm), but it was statistically similar ($p>0.05$) with FCL_N (48.1 cm) and FCL_FYM (46.5 cm). At this stage, the influence of the latter on plant height was still statistically unnoticeable from FCL_Control. At flowering stage, regardless of the earlier influence of different fertilizer sources, none of the FCL treatments differed significantly ($p>0.05$) from FCL_Control (53.6 cm), however, numerically, FCL_N+FYM (65.1 cm) > FCL_FYM (64.7 cm) > FCL_N (60.3 cm) > FCL_Control (53.7 cm). This trend differed from the one at flag leaf stage, whereby, FCL_FYM was less than FCL_N, and that at vegetative stage, the plant in FCL_N numerically ranked the first before FCL_N+FYM.

The rates at which sorghum plants were growing to attain the final plant heights at each of the stages and their correlation in the below-average rainfall season are indicated in Fig.4.18 (d), (e) and (f). The results showed that, across all the treatments, the rate at which plant heights increased from sowing to vegetative stage was higher in the treatments applied with N than others. As plant was growing from vegetative to flag leaf stage, the plant heights increasing rates in treatments with N were reduced, while those with N+FYM increased. When the plant was growing from flag leaf stage to flowering stage the plant heights increasing rates in FYM applied treatments were higher than that in N+FYM. Notwithstanding, they could not attain the highest final plant height. The reduced plant height increasing rate from flag leaf to flowering in RP_N and FCL_N, corresponded to the lowest detected stored water volume; implying that their earlier plant growth rates were subjected to the higher water demand, which rapidly depleted the stored water volume at the effective root zone of the sorghum, and reduced the drought mitigation potential during the critical period of soil moisture stress from flag leaf to flowering growth stages, therefore, impaired the observed sorghum plant height. The increased plant height rate in FYM treatments were ascribed to the influence of FYM in

balancing and maintaining soil moisture and nutrients release, which helped in regulating slow sorghum growth, hence reduced the degree of the crop vulnerability to drought during the expected extended period. Moreover, the results showed that, across the flag leaf stage, flowering and maturity stages, the lowest plant height in TR_Control and RP_Control were significantly ($p < 0.05$) taller than plants in FCL_Control, but similar with those in FCL with different fertilizer sources. This shows that the increment rates in plant heights due to application of different fertilizer sources in FCL were surpassed by more available stored soil water in TR and RP treatments.

4.3.5 Influence of ripping and tie-ridges integrated with organic and inorganic fertilizer on rainfall use efficiency

The rate at which rainwater was converted into biomass during the above-average rainfall season, differed significantly ($p < 0.05$) across the IRWHT and fertilizer source; however, in the below-average rainfall season, only IRWHT resulted in a significantly ($p < 0.05$) higher water use efficiency (WUE) (Fig. 4.21). Application of fertilizers in the IRWHT in

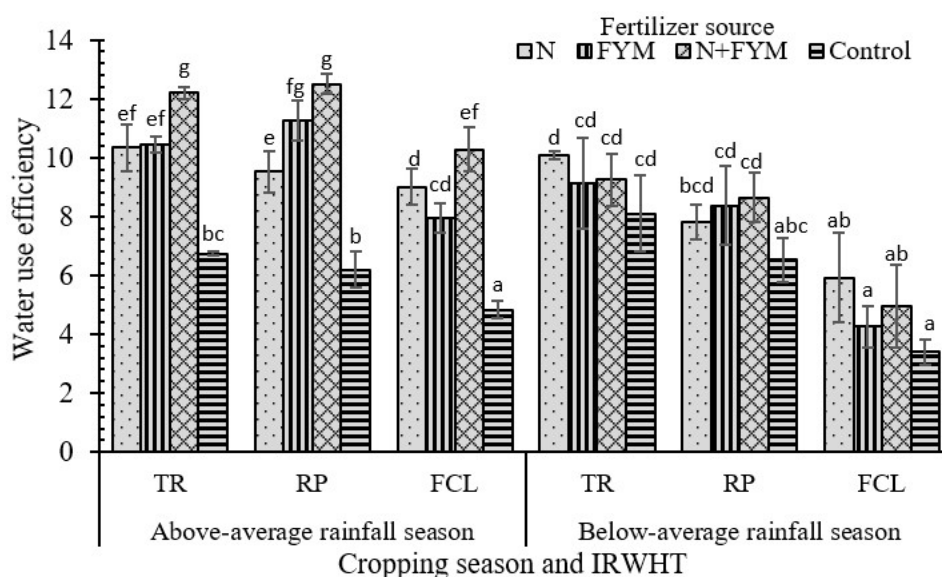


Figure 4.21: Rainfall use efficiency of sorghum under tie-ridges (TR), ripping (RP) and flat-cultivated land (FCL) integrated with different fertilizer sources for the two cropping seasons of 2015/2016 (above-average rainfall season) and 2016/2017 (below-average rainfall season).

the below-average rainfall season leveraged WUE, with TR treatments clearly transforming higher ($p<0.05$) rainwater into biomass than FCL_Control, FCL_N, FCL_FYM and FCL_N+FYM. Although the influence of RP_Control had no significant ($p<0.05$) difference with FCL applied with or without fertilizer, application of FYM and N+FYM in RP treatments significantly ($p<0.05$) improved WUE than any of the FCL treatments. This shows that application of the FYM and N+FYM in the FCL, in the below-average rainfall season had little contribution on the overall biomass accumulation compared to RP treatment. Regardless of the statistical difference ($p<0.05$) between RP_N and FCL integrated with N and N+FYM, TR treatments had clearly outperformed all the FCL treatments, irrespective of the fertilizer source integrated. However, it should also be noted that amongst the TR treatments, only TR_N significantly registered higher WUE than RP_Control. Within the TR, RP and FCL treatment, application of either N, FYM or N+FYM in the below-average rainfall season, could not result in any difference ($p>0.05$) in WUE. Such insignificance in water productivity was caused by a low rainfall and prolonged drought spell, which limited soil-water availability for fertilizer dissolution. The limited soil water availability also resulted into insufficient water supply to meet crop water demands at the critical growth stages, hence suppressed the expressive influence of the applied fertilizers on WUE that otherwise could have significantly manifested ($p<0.05$) as it was observed in the above-average rainfall season (Table 4.4).

The results showed that, the highest WUE (12.5 kg mm^{-1}) in the above-average rainfall season was in RP_N+FYM, however, this did not differ significantly ($p>0.05$) with TR_N+FYM (12.2 kg mm^{-1}) and RP_FYM (11.3 kg mm^{-1}). In the below-average rainfall season, the highest WUE (10.1 kg mm^{-1}) was in the TR_N; nonetheless, it did not differ with TR and RP with FYM and N+FYM. Across the two seasons, FCL_Control registered the lowest WUE of 4.8 and 3.4 kg mm^{-1} in the above-average rainfall season

Table 4.4: Multiple comparison for water use efficiency in the selected IRWHT integrated with organic and/or inorganic fertilizers.

IRWHT and fertilizer source		Water use efficiency (kg mm ⁻¹)	
		2015/2016 ¹	2016/2017 ²
IRWHT	TR	9.9b	9.1b
	RP	9.9b	7.8b
	FCL	7.8a	4.3a
Fertilizer	N	9.3b	7.6a
	FYM	9.9b	7.3a
	N+FYM	11.7c	7.6a
	Control	5.9a	6.0a
TR x Fertilizer source	TR_N	10.3ef	10.1d
	TR_FYM	10.4ef	9.1cd
	TR_N+FYM	12.2g	9.3cd
	TR_Control	6.7bc	8.1cd
RP x Fertilizer source	RP_N	9.5e	7.8bcd
	RP_FYM	11.3fg	8.4cd
	RP_N+FYM	12.5 g	8.6cd
	RP_Control	6.2b	6.5abc
FCL x Fertilizer source	FCL_N	8.2d	4.8ab
	FCL_FYM	8.0cd	4.3a
	FCL_N+FYM	10.3ef	4.9ab
	FCL_Control	4.8a	3.4a
CV		8.1	23.8
F. STAT, p=0.05	IRWHT	***	***
	Fertilizer	***	Ns
	IRWHT*Fertilizer	ns	Ns

p>0.05, nonsignificant (ns); p=0.05 – 0.01, significant (*); p=0.01– 0.001, very significant (**); p< 0.001, very highly significant (***); IRWHT, in situ rainwater harvesting techniques; ¹above-average rainfall season; ²below-average rainfall season; N, inorganic fertilizer; FYM, organic fertilizer; and N+FYM, a half-combined inorganic and organic fertilizers.

and below-average rainfall season, respectively. Considering the IRWHT alone, across the two seasons, the results suggest that manipulation of land to capture every single raindrop in prone dryland area is important on enhancing WUE. The results showed that either TR or RP treatment offers the viable option for enhancing water productivity in both seasons; nonetheless, the differences in TR and RP as compared to FCL, was higher in the below-average rainfall season than in the above-average rainfall season.

In the above-average rainfall season, the highest WUE in TR treatment (9.1 kg mm⁻¹) exceeded FCL (7.0 kg mm⁻¹) by 2.1 kg mm⁻¹ (21%), while in the below-average rainfall season the difference (4.8 kg mm⁻¹) was more than doubled (53%). This indicates that the efficiency of TR treatment is much higher in the below-average rainfall season than in the

above-average rainfall season. Notwithstanding, the latter rainfall resulted in more biomass amount than the former.

Regardless of the fertilizer sources applied in the below-average rainfall season, the results revealed that application of either N, FYM or N+FYM alone does not result in a remarkable difference ($p>0.05$) in WUE. Contrary to the below-average rainfall season, application of fertilizer in above-average rainfall season results in a significant ($p<0.05$) WUE, with N+FYM registering the highest biomass (11.7 kg) for every millimetre of rainwater used. The results did not reveal any significant difference ($p>0.05$) in WUE between N and FYM; however, it should be clearly noted that the former had a significant ($p<0.05$) higher WUE compared to their respective control treatments.

4.3.6. Influence of ripping and tie-ridges integrated with organic and inorganic fertilizers on the sorghum grain yield and aboveground biomass performance

The response of sorghum aboveground biomass and grain yield within and across the IRWHT and FCL integrated with different fertilizer sources for the two consecutive cropping seasons are indicated in Table 4.5. In both seasons, FCL registered the lowest sorghum biomass and grain yield. The lowest biomass and grain yield were 7.6 and 2.3 Mg ha⁻¹, respectively, in the above-average rainfall season, while in the below-average rainfall season were 1.5 and 0.7 Mg ha⁻¹, respectively. Further analysis by the Duncan multiple range test could not reveal any statistical difference ($p>0.05$) in biomass and grain yield between TR and RP. However, in the above-average rainfall season, the highest biomass in TR (9.6 Mg ha⁻¹) did not contribute to the highest grain yield (4.1 Mg ha⁻¹). Instead, the highest grain yield was harvested in RP treatment, which had less biomass by 0.1 Mg ha⁻¹. Moreover, TR treatment that had the highest biomass, partitioned and translocated low grain yield's photosynthates, which was less by 0.5 Mg

Table 4.5: Multiple comparison for water use efficiency in the selected IRWHT integrated with organic and/or inorganic fertilizers.

IRWHT and fertilizer source		Sorghum yield (Mg ha ⁻¹)			
		2015/2016 ¹		2016/2017 ²	
		Grain yield	Biomass	Grain yield	Biomass
IRWHT	TR	3.6b	9.6b	1.9b	3.1b
	RP	4.1b	9.5b	1.5b	2.7b
	FCL	2.3a	7.6a	0.7a	1.5a
FERTILIZER	N	3.1b	9.0b	1.4a	2.6a
	FYM	3.7b	9.6b	1.4a	2.5a
	N+FYM	4.7c	11.3c	1.6a	2.6a
	Control	1.9a	5.7a	1.1a	2.1a
TR x Fertilizer source	TR_N	3.3bcd	10.0ef	2.0d	3.5d
	TR_FYM	3.8cde	10.1ef	1.9d	2.9cd
	TR_N+FYM	5.1ef	11.8g	2.0d	3.2cd
	TR_Control	2.3b	6.5bc	1.6bcd	2.8cd
RP x Fertilizer source	RP_N	3.7bcd	9.2e	1.4abcd	2.7bcd
	RP_FYM	4.5def	10.9fg	1.6bcd	2.9cd
	RP_N+FYM	5.7f	12.1g	1.8cd	3.0cd
	RP_Control	2.4b	6.0b	1.2abcd	2.2abc
FCL x Fertilizer source	FCL_N	2.5bc	7.9d	0.9ab	1.6ab
	FCL_FYM	2.7bc	7.7cd	0.7ab	1.5a
	FCL_N+FYM	3.1bcd	9.9ef	0.9abc	1.7ab
	FCL_Control	0.9a	4.7a	0.5a	1.2a
CV (%)		22.1	8.1	36.9	23.8
F_STAT, p, 0.05	IRWHT	***	***	***	***
	Fertilizer	***	***	ns	ns
	IRWHT*Fertilizer	ns	ns	ns	ns

p>0.05, nonsignificant (ns); p=0.05 – 0.01, significant (*); p=0.01– 0.001, very significant (**); p< 0.001, very highly significant (***); IRWHT, in situ rainwater harvesting techniques; ¹above-average rainfall season; ²below-average rainfall season; N, inorganic fertilizer; FYM, organic fertilizer; and N+FYM, a half-combined inorganic and organic fertilizers.

ha⁻¹ than that in RP treatment. Different phenomenon was revealed in the below-average rainfall season, where the highest biomass in TR (3.1 Mg ha⁻¹), which exceeded RP treatment (2.7 Mg ha⁻¹) by 0.4 Mg ha⁻¹, contributed to the highest grain yield (1.9 Mg ha⁻¹) that was more than that in the RP treatments (1.5 Mg ha⁻¹) by 0.4 Mg ha⁻¹. These easily overlooked differences in the relationship between biomass and grain yield are important in understanding the likeness influence of water levels in allocation of photosynthetic materials to the grain part of the sorghum, when rainfall is either above or below the average, along with their compounded effects due to water logging and extended droughts, dictated by climate change and variability. The slight biomass increments in TR, in the above-average rainfall season, was associated with its high drought mitigation potential

during the critical growth stages, which compensated for the decreased grain yield caused by frequent water lodging condition; nevertheless, it failed to transform the additional biomass into the grain yield.

Depending on the rainfall amount and fertilizer source integrated with the IRWHT, the response of sorghum biomass and grain yield, deviated from the earlier observed trends and levels when either IRWHT or fertilizer sources were considered alone. Integration of FYM or N+FYM with TR, RP and FCL, in the above-average rainfall season, increased grain yield and biomass significantly ($p < 0.05$). In this season, both the highest sorghum biomass and grain yield were harvested in TR_N+FYM and RP_N+FYM, respectively. However, the latter had no significant ($p > 0.05$) difference with RP_FYM in sorghum biomass and grain yield. As oppose to RP_N+FYM treatment, TR_N+FYM treatment had a significantly ($p < 0.05$) higher biomass than TR_FYM, TR_N and TR_Control. Although FYM and N did not reveal any significant ($p > 0.05$) difference in biomass and grain yield when fertilizer sources were considered alone without IRWHT; integration of FYM in RP treatment, resulted in a significantly ($p < 0.05$) higher biomass (10.9 Mg ha^{-1}) than in RP_N (9.2 Mg ha^{-1}). FCL treatment suppressed the influence of N+FYM on grain yield, and it had no any significant ($p > 0.05$) difference with either FCL_N or FCL_FYM; however, compared to FCL_Control, all the FCL treatments with fertilizers, significantly ($p < 0.05$), registered high biomass and grain yields.

The highest overall drought mitigation potential (95 %) on daily basis in TR_Control, in the above-average rainfall season, could neither resulted in the highest biomass (Fig. 4.22 (a)) nor the highest grain yield (Fig. 4.22 (b)). This indicated that the highest water availability in the TR_Control was due to low rate of crop water depletion, hindered by inadequate nutrients supply to stimulate crop growth at vegetative and flag leaf stage,

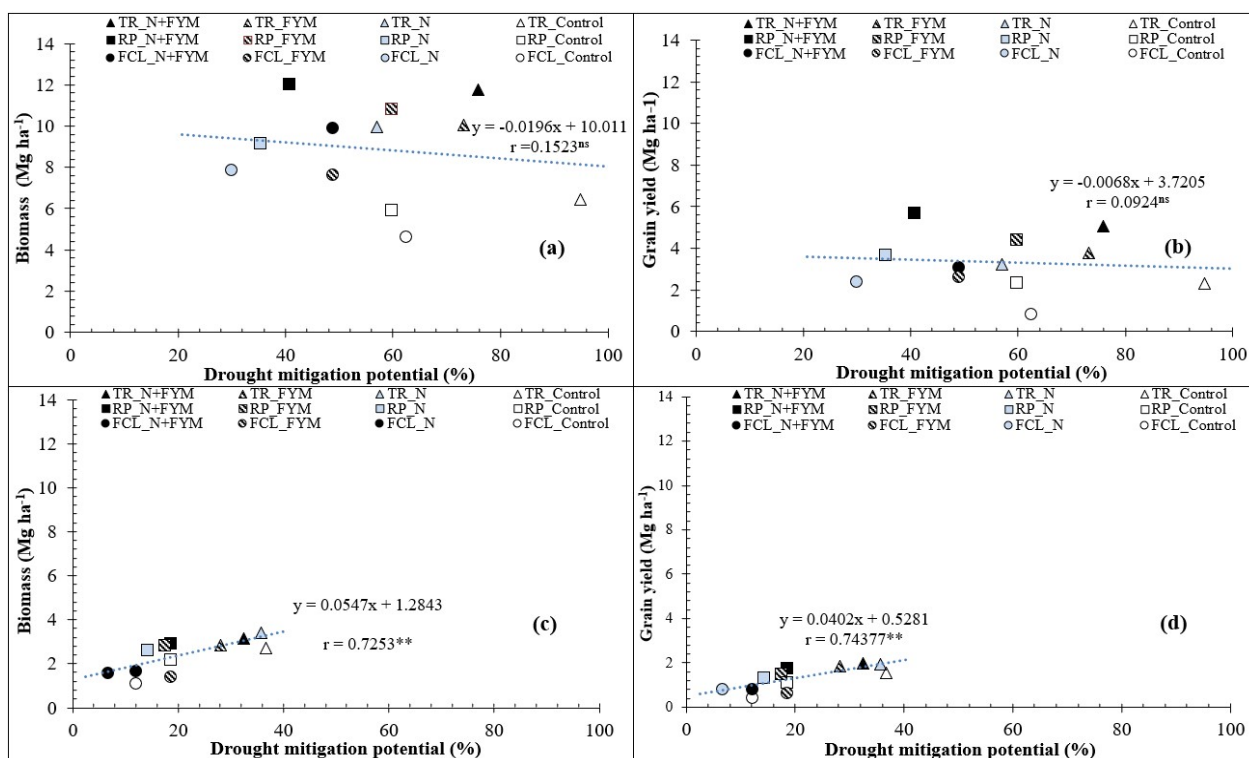


Figure 4.22: Combined influence of IRWHT and FCL with N, FYM and N+FYM on biomass and grain yield, and their relationship with drought mitigation potentials (%), for the two cropping seasons of 2015/2016 (above-average rainfall season, (a) and (b)) and 2016/2017 (below-average rainfall season, (c) and (d)).

which could have triggered high crop water demands, as observed in the fertilizers applied treatments. Although the higher drought mitigation potential in TR_Control compensated for the plant height increasing rate from flag leaf to flowering growth stage, it still registered the similar shortest ($p < 0.05$) plant height and the lowest biomass amongst the TR treatments. However, it was statistically similar with TR_N in terms of the grain yield. Integration of N+FYM in TR, in the above-average rainfall season, reduced the drought mitigation potential by 19% from TR_Control, but it yielded the highest sorghum biomass amongst the TR treatments.

On the other hand, within the same season, RP_N+FYM, which mitigated drought by 41%, increased both sorghum biomass (12.1 Mg ha^{-1}) and grain yield (5.7 Mg ha^{-1}) significantly ($p < 0.05$) compared to RP_Control, which mitigated drought by 59%, but resulted in less biomass (6.0 Mg ha^{-1}) and grain yield (2.4 Mg ha^{-1}). The results showed

that water availability alone does not guarantee the highest sorghum biomass and grain yield, unless fertilizer is integrated. The results revealed the plasticity of the sorghum crop in balancing and regulating biomass accumulation, partitioning and allocation of photosynthates to form the grain part of the sorghum plant based on the nutrient source and soil moisture levels. The results further showed that frequent water ponding in TR treatments during rainfall events and the high moisture content in the above-average rainfall season have an effect on depletion of oxygen at the effective root zone, which causes impairment in root respiration, physiological functions of the sorghum and reduction in grain yield and biomass. This explains the reason to why TR should not be recommended in high rainfall receiving areas.

Regardless of the low mitigation potentials in RP_N+FYM treatments in the above-average rainfall season, its highest grain yield (5.7 Mg ha^{-1}) and biomass (12.1 Mg ha^{-1}), revealed that, the water-air balance at the effective root zone was sufficiently regulated for the overall bio-physiochemical processes of the sorghum plant. The regulated water-air condition was attributed by inherently ability of the RP treatments to quickly drain excess water out of the effective root zone. Furthermore, the applied integrated fertilizer source regulated nutrients release and availability differently, which enhanced grain yield increment ($p>0.05$) in RP_N, RP_FYM, RP_N+FYM and RP_Control over TR_N, TR_FYM, TR_N+FYM and TR_Control by 0.5, 0.7, 0.6 and 0.1 Mg ha^{-1} , respectively. A similar phenomenon was also observed with biomass, which posed a relatively less linear correction between sorghum biomass and grain yield performance in the above-average rainfall season as compared to below-average rainfall season (Fig. 4.23). The highest biomass and grain yield were not observed in RP_N, suggesting that the low water retention capacity and initial vigorous sorghum growth triggered by N depleted more soil water, which intensified the critical moisture stress for sorghum five days

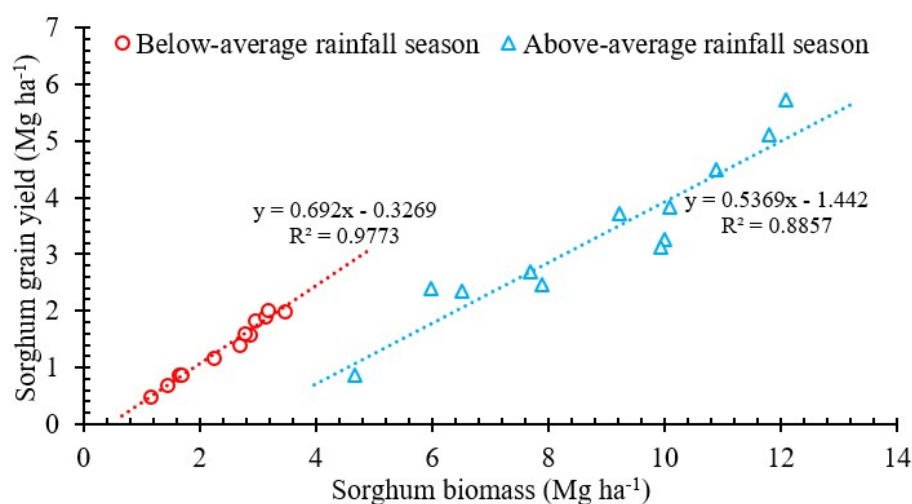


Figure 4.23: Relationships between biomass and grain yield performance in the above-average rainfall season and below-average rainfall season.

earlier, before flag leaf stage to three days later after 50% flowering. This also caused a reduction in plant height increasing rate in RP_N.

A decrease in soil moisture, and hence drought mitigation potentials in the below-average rainfall season, corresponded to the lowest harvested biomass and grain yield. Fertilizer integration did not result in an increased sorghum biomass and grain yield neither within the FCL nor in the selected IRWHT. Across the treatments, integration of fertilizers in TR, significantly ($p < 0.05$) maintained higher sorghum biomass and grain yield than FCL treatments. Contrary to TR_N, application of N in RP suppressed its grain yield differences with all the FCL treatments; however, when RP was integrated with N+FYM, it resulted in a higher ($p < 0.05$) grain yield than FCL_N, FCL_FYM and FCL_Control. In all the IRWHT either with or without fertilizers, there were an increase in sorghum biomass and grain yield following the order: FCL < RP < TR. Fertilizer application within the RP treatments, increased grain yield performance's margins in the order: Control < N < FYM < N+FYM, this fertilizers performance order differed with the one in TR, which had less margins in grain yield; nevertheless, TR with N+FYM

registered a significantly higher ($p < 0.05$) grain yield than FCL_N+FYM. It was also noted that FCL and TR interchangeably the grain yield performance order, with sorghum in FCL_N yielding slightly more grain than in FCL_FYM. Such an alteration in yield performance order could have been due to easy dissolution and accessibility of the N, influenced by the appreciable soil moisture at the beginning of the season.

CHAPTER FIVE

EFFECT OF TEMPORAL INTERCROPPING PATTERNS OF SORGHUM-GROUNDNUT ON SOIL MOISTURE AVAILABILITY AND RISK IN CROP FAILURE IN THE DRYLAND AREAS OF TANZANIA

5.1 Introduction

Sorghum (*Sorghum bicolor* L.) and groundnut (*Arachis hypogaea* L.) are the most grown annual crops in the prone dryland area of Sub-Saharan Africa. While the former is grown as the main staple food (Carson, 1989; Odhiambo, 2011; Makindara et al., 2013; Heard, 2014; Mahinda, 2014; Mahinda et al., 2016; 2018a; 2018b), the latter is grown as a cash crop (Mhango et al., 2013; Snapp et al., 2018). Across the Sub-Saharan Africa, groundnut is the fifth most widely grown crop after maize, sorghum, millet and cassava (Snapp et al., 2018) and it serves as the primary source of oil and protein for many smallholder farmers in African communities (Rusinamhodzi et al., 2012; Mhango et al., 2013; Janila et al., 2013).

Although in humid and sub-humid regions, groundnut can be grown as a sole crop, farmers usually prefer to intercrop groundnut with main crops, either maize or sunflower as a way of intensifying land use (Waddington et al., 2007; Snap, 2018). In dryland areas, however, sunflower and maize are usually not intercropped with groundnut due to limited rainfall amount coupled by a high crop water requirement of the two main crops. Therefore, sorghum, pearl millet and finger millet are the optional main crops for intercropping, because these crops have the ability to tolerate low soil moisture stress compared to sunflower and maize (Mhango et al., 2013; Mahinda, 2014; Abdalla et al., 2015; Farm Progress, 2017).

In dryland areas of Tanzania, particularly the central zone regions (Dodoma and Singida), Shinyanga and Tabora, sorghum and groundnut are grown in the same piece of land within the same season, a practice called intercropping. Just as intercropping of any other crops, most farmers prefer intercropping sorghum and groundnut as a way of diversifying farm income and yield. This practice is increasingly preferred particularly under this challenging era of climate change and weather variability, with anticipation that a failure of one crop due to incidence of drought or pest, would be compensated with the other intercropped crop. As oppose to mix cropping, whereby crops with similar feeding characteristics are grown together in the same piece of land at the same time, intercropping of sorghum with groundnut is assumed to counteract the negative nutrients balances. Therefore, it is expected to enhance land productivity in the long run due to involvement of the two different crops with different phenotypical characteristics but compatible root depth architecture, feeding behaviours and preferences to N species to be utilized by the crops (Ronner and Giller, 2012) In such a compatible interactive system, the excessive nutrients uptake by sorghum is counterbalanced by groundnut, which fix nitrogen from the atmosphere. In addition to this, groundnut has also inherently low rate of nutrients uptake but fast rate of mineralization (Barrios et al., 1999; Mubarak et al., 2002; Kaewpradit et al., 2009; Timsina et al., 2010; Yu et al., 2016). This type of intercropping saves as an important self-sufficient ecological and agronomic pathway for replenishing nutrients and organic matter in the field, provided that crops residues are not removed away from the field (Ncube et al., 2009; Peoples et al., 2009).

Realizing the importance of intercropping sorghum with groundnut in sustaining the livelihood in the dryland areas and its ecological functions in replenishing nutrients to the soil as well as improvement and protection of the soil structure, much of the efforts have been done by research centres, non-governmental organization and government's

institutions to disseminating knowledge for intercropping and associated agronomic practices. However, the yield of sorghum and groundnut under intercropping have never been promising as anticipated due to poor crop growth performance. The main reason attributed to poor crop performance and low yields is limited soil moisture due to low rainfall, and the combined effect of soil moisture depletion by the two companion crops grown together. Although this could be generally agreed based on the field evidence, there was no clear research evidence to show the rate of soil moisture depletion at the effective root zone of the sorghum when intercropped with the groundnut. In trying to improve the water productivity under the existing sorghum-groundnut intercropping in dryland area, it was hypothesised that given the same amount of water, the time at which groundnut is introduced to the sorghum field might have an influence on the rate at which soil moisture is depleted at the effective root zone of the sorghum. This research, therefore, was examining the effects of temporal intercropping pattern of sorghum-groundnut on soil moisture availability and percentage risk in crop failure due soil moisture competition in the prone dryland areas of Tanzania.

5.2 Materials and Methods

This section describes major approaches that were used in this study. It has been separated into different subsections, each addressing field methods and materials used in achieving the general objective of the study. The methods and materials employed include those used for designing and laying out of the field experiment, treatment allocation, soil sampling for soil water determination, soil water quantification, data computation and analysis.

5.2.1 Experimental design, layout and treatment allocation

A complete randomised block design was employed to randomise experimental treatments (Fig. 5.1). Treatments were derived from a single factor with five different levels assigned to the field where sorghum was already sown. The levels of the treatments were based on the time at which the groundnut was intercropped in the sorghum field. The treatments were: intercropping sorghum and groundnut in the same day (0SG_DAS), followed by intercropping groundnut at 15th day (15G_DAS), 30th day (30G_DAS) and 45th day (45G_DAS) later after sowing sorghum (DAS). One of the treatment plots was only sown by the sorghum and left without being intercropped with groundnut. The aim of this sole sorghum cropping was to serve as a control treatment. The five treatments (0SG_DAS, 15G_DAS, 30G_DAS, 45G_DAS and Control) were replicated three times for the two consecutive cropping seasons of 2015/2016 (above-average rainfall season) and 2016/2017 (below-average rainfall season).

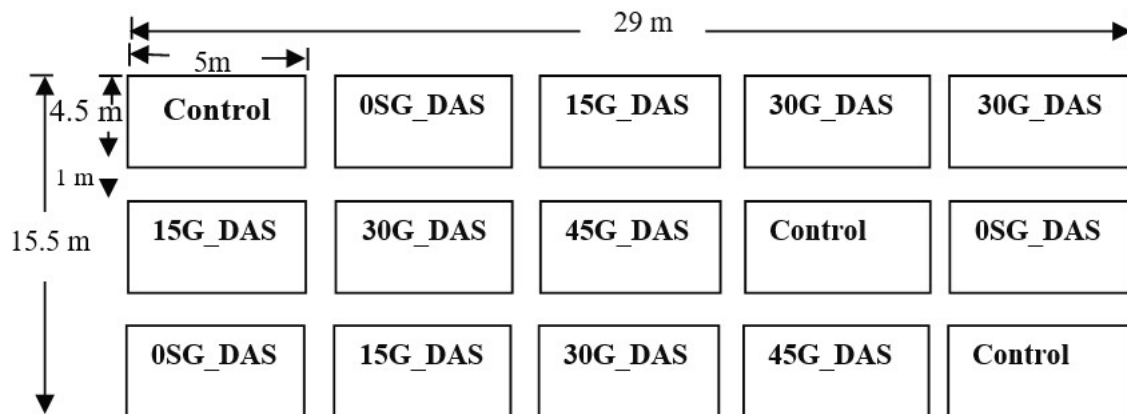


Figure 5.1: Experimental layout design for the temporal intercropping pattern of the sorghum intercropped with groundnut intercropped in the same day (0SG_DAS); sorghum intercropped with groundnut at 15th (15G_DAS), 30th (30G_DAS) and 45th (45G_DAS) days after sowing sorghum; and a sole sorghum cropping (Control).

5.2.2 Soil water monitoring

The detailed soil moisture measurement at the effective root zone of the sorghum (0-20 cm depth), where most of the fine roots concentrated was monitored by an automated water content reflectometer, CS 616 (CS 616, Campbell Scientific Inc., Logan, USA). The real-time CS 616 was programmed to scan the soil moisture details in every 30 minutes. Its average outputs values in microseconds were recorded at hourly intervals until the end of the day, when the process was set to repeat, automatically.

The plotted calibration curve equations in microseconds against their corresponding volumetric water contents (VWC), derived from a gravimetric method were used to compute the recorded hourly microseconds into VWC. The undisturbed soil samples for VWC calibration, were collected at varying degrees of moisture in each of the treatments from the highest soil moisture status to air dried level. Following the same pattern in time intervals, the amount of rainfall (mm) was recorded on an hourly basis. The soil moisture sensors and rain gauge were connected to the CR 1000 data logger (CR 1000, Campbell Scientific Inc., Logan, USA). The recorded data values for soil moisture and rainfall were retrieved, downloaded and communicated to the user interface by an aid of a pre-installed computer software application logger net 4.0 (Campbell Scientific. Inc., Logan, USA). Further analysis and manipulation of the soil moisture data to daily values VWC was computed from the average of hourly data set, while the daily rainfall was computed by summing up the hourly rainfall data values.

The VWC held at different tensions against roots uptake were determined following procedures by Klute (1986) and CSSAMM (1986). Available water content was calculated as the difference in soil water content computed from CS 616 against soil water content held at permanent wilting point (-1.5 MPa). All days with soil water content equivalent to that retained at tensions less than -1.5 MPa were counted as days in

which sorghum was under moisture stress period, while the remaining days with water held above the -1.5 MPa tensions were considered to be available for the normal crop evapotranspiration. An extra available soil water was computed by subtracting the available stored water volume in one treatment of interest over the other. The aim was to have a benchmark for identification and comparison of the treatments' performances for additional available stored water at any particular points in time.

Furthermore, the risk of crop failure due to soil moisture stress was computed based on the proportional number of days at which the soil water content was unavailable (< -1.5 MPa) for the crop during the expected extended drought period. To convert the value to percentage, the obtained proportional was multiplied by 100. Alternatively, the risk of crop failure was computed by subtracting the proportional number of days with soil water held above the permanent wilting point (> -1.5 MPa) from 100, then multiplied by 100. The former 100 represented the entire length of the expected extended drought period from the last rainfall event; in which within it, there were both days with water held below and above the -1.5 MPa. The formulated equations to compute available water content (AWC), moisture stress period (MSP), extra available water (EAW) and percentage risk of crop failure due to soil water stress (RCF) are indicated in equation 5.1, 5.2 and 5.3, 5.4 (i) and 5.4 (ii), respectively.

$$AWC (m^3 ha^{-1}) = SWC_{\bar{Y}} - WPWP \dots\dots\dots (5.1)$$

Whereby: $SWC_{\bar{Y}}$ is 24 hours mean soil-water volume ($m^3 ha^{-1}$) computed from CS 616; and WPWP is soil water volume ($m^3 ha^{-1}$) held at tension of -1.5 MPa.

$$MSP (Days) = NEDP - NASW \dots\dots\dots (5.2)$$

Whereby: NEDP is number of days of the extended drought period; and NASW is number of days for the soil water held above the permanent wilting point (> -1.5 MPa).

$$\text{EAW (m}^3 \text{ ha}^{-1}\text{)} = (\text{ASW}_\text{H} - \text{ASW}_\text{L}) \dots\dots\dots (5.3)$$

Whereby: ASW_H is the available soil-water in a high-water storing treatment; and ASW_L is the available soil water in a relatively less water storing treatment of interest for comparison.

$$\text{CFR (\%)} = (\text{NAWC}/\text{NEDP}) \times 100 \dots\dots\dots (5.4 \text{ (i)})$$

Whereby: NAWC is number of days for soil water below the permanent wilting point (< -1.5 MPa); NEDP is number of days of the extended drought period.

$$\text{Alternatively, RCF (\%)} = 100 - ((\text{NPWP}/\text{NEDP}) \times 100) \dots\dots\dots (5.4 \text{ (ii)})$$

Whereby: NPWP is number of days for soil water above the permanent wilting point (≥ -1.5 MPa); NEDP is a number of days of the extended drought period.

5.3 Results and Discussion

5.3.1 Influence of temporal intercropping pattern of sorghum-groundnut on soil water dynamics at the effective root zone

The temporal soil moisture dynamics at the effective root zone of the sorghum as influenced by temporal intercropping of sorghum-groundnut for the two consecutive

cropping season of 2015/2016 (Above-average rainfall season) and 2016/2017 (below-average rainfall season) is indicated in Fig. 5.2 ((a) and (b)). The results showed that in both the above-average rainfall season and below-average rainfall season, the levels of soil water across the treatments were higher in sole sorghum cropping (control) compared to the rest of the treatments.

In the above-average rainfall season, sorghum treatment intercropped with groundnut in the same day (OSG_DAS) on January 5, 2016 registered the lowest amount of stored soil water at the effective root zone of the sorghum almost throughout the cropping season. The amount of stored soil ^a r at the effective root zone of the sorghum across the treatments was observed to be more or less similar to the control treatment before groundnut was intercropped. However, after intercropping groundnut in the sorghum field, the degree of depletion of the stored soil water at the effective root zone of the sorghum increasingly deviated from the control treatment. Such an increased depletion in the stored soil water was attributed to an increased crop water uptake dictated by the groundnut intercropped in the sorghum field. The rate at which the water was depleted at

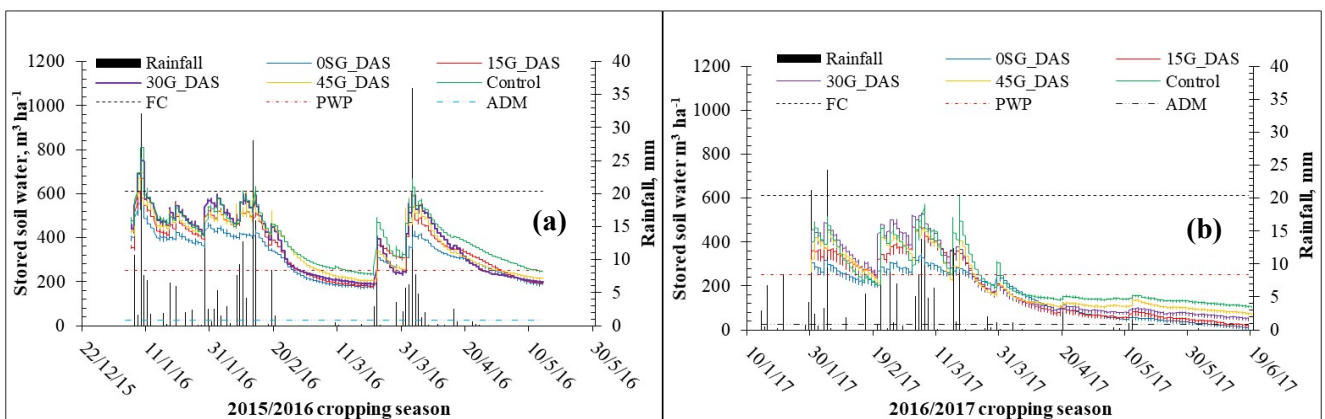


Figure 5.2: Differences in water dynamics at the effective root zone as influenced by sorghum intercropped with groundnut in the same day when sorghum was sown (OSG_DAS), 15 days later after sowing sorghum (15G_DAS), 30 days later after sowing sorghum (30G_DAS), 45 day later after sowing sorghum (45G_DAS), and sole sorghum cropping (Control) for the two cropping season of (a) 2015/2016 (above-average rainfall season) and (b) 2016/2017 (below-average rainfall season). FC, field capacity (−3.1 kPa); PWP, permanent wilting point (−1.5 MPa); and ADM, air dried soil moisture (−31.0 MPa).

the effective root zone of sorghum in the sorghum-groundnut field, as opposed to Control treatment (Sole sorghum cropping) during the above-average rainfall season, is indicated in Fig. 5.3 ((a) (b), (c) and (d)). Amongst the temporal intercropped sorghum-groundnut treatments in the above-average rainfall season, 0SG_DAS and 45G_DAS had the lowest and highest stored soil water amount at the effective root zone of the sorghum, respectively. The amount of stored soil water in 30G_DAS was in between 15G_DAS and 45G_DAS. The lowest stored amount of soil water in the 0SG_DAS treatment was due to a continued increase in water uptake at the effective root zone since at the beginning of the cropping season. Because the rest of the temporal sorghum-groundnut treatments were later on sequentially intercropped at 15 days interval, the latest intercropped treatment at 45th day on February 19, 2016 (45G_DAS) had the least water extracted from the soil. This resulted 45_DAS to have the closest similar amount of water

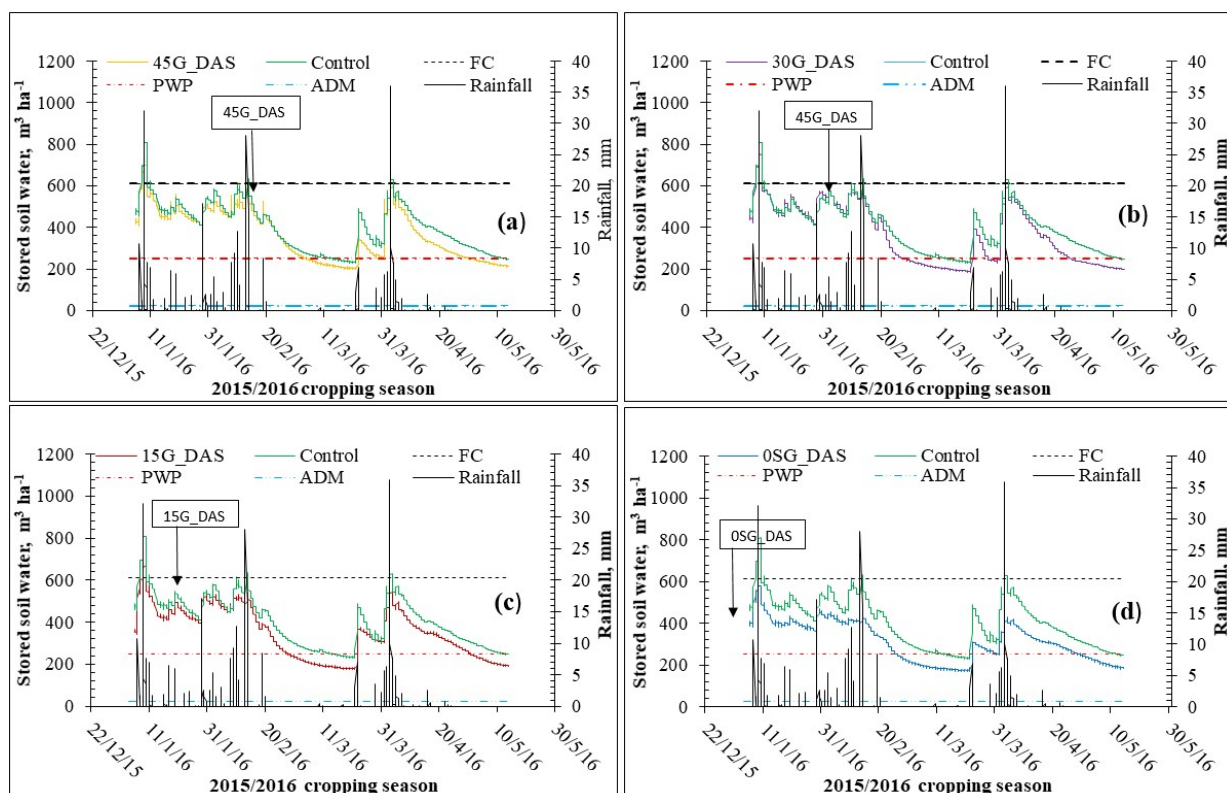


Figure 5.3: Differences in soil water depletion monitored hourly at the effective root zone of the sorghum as influenced by temporal intercropping pattern of (a) 45G_DAS, (b) 30G_DAS (c) 15G_DAS and (d) 0SG_DAS as opposed to control treatment in 2015/2016 (above-average rainfall season). FC, field capacity (−3.1 kPa); PWP, permanent wilting point (−1.5 MPa); and ADM, air dried moist (−31.0 MPa).

level to that in sole sorghum cropping (Control). As the groundnut was growing up, the amount of stored water in 45G_DAS, started decreasing steadily and deviating from the sole sorghum cropping. Nonetheless, it still had retained more stored soil water than 30G_DAS, 15G_DAS and 0SG_DAS. The general trend indicates that throughout the cropping season in the above-average rainfall season, the amount of stored soil water at the effective root zone of the sorghum across all the treatments followed the order; Control > 45G_DAS > 30G_DAS > 15G_DAS > 0SG_DAS

Although in the below-average rainfall season, Control treatment (Sole sorghum cropping) still outperformed the rest of the treatments (Fig 5.4), the amount of the stored soil water at the effective root zone of the sorghum substantially decreased. This decrease in the stored soil water was not associated with the effects of temporal intercropping pattern, but a compounded influence of the insufficient rainfalls and possibly a high soil

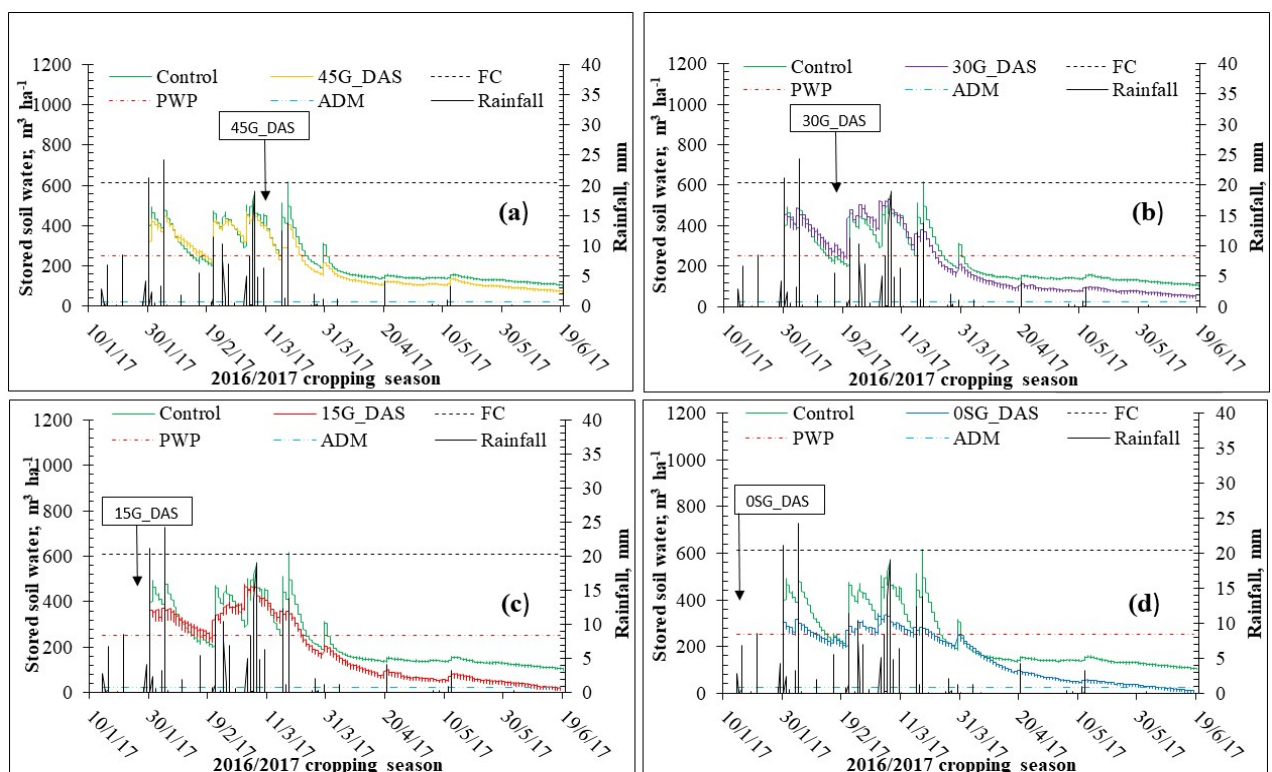


Figure 5.4: Differences in soil water depletion monitored hourly at the effective root zone of the sorghum as influenced by temporal intercropping pattern of (a) 45G_DAS, (b) 30G_DAS (c) 15G_DAS and (d) 0GS_DAS as opposed to control treatment in 2016/2017 (below-average rainfall season). FC, field capacity (−3.1 kPa); PWP, permanent wilting point (−1.5 MPa); and ADM, air dried moist (−31.0 MPa).

temperature. It should be noted that during the below-average rainfall season, the rainfall amount decreased by 181.7 and 33.1% compared to the above-average rainfall season and the long-term average rainfalls, respectively (Mahinda et al., 2018b). Nevertheless, the result showed that within the below-average rainfall season, 30G_DAS and 45G_DAS treatments had the nearest similar stored amount of soil water to that in the control. The stored soil water in 15G_DAS treatment pulled itself closer to 0SG_DAS treatment, and it showed a higher rate of water extraction at the effective root zone than 0SG_DAS from March 27, 2017 to April 17, 2017 when groundnut in this treatment was at flowering stage heading to podding stage. However, at the end of the season, 0SG_DAS masked 15G_DAS in term of the rate at which water was extracted at the effective root zone of the sorghum. Comparing 15G_DAS and 0SG_DAS treatments with the other treatments in term of the retained soil water at the effective root zone of the sorghum throughout the

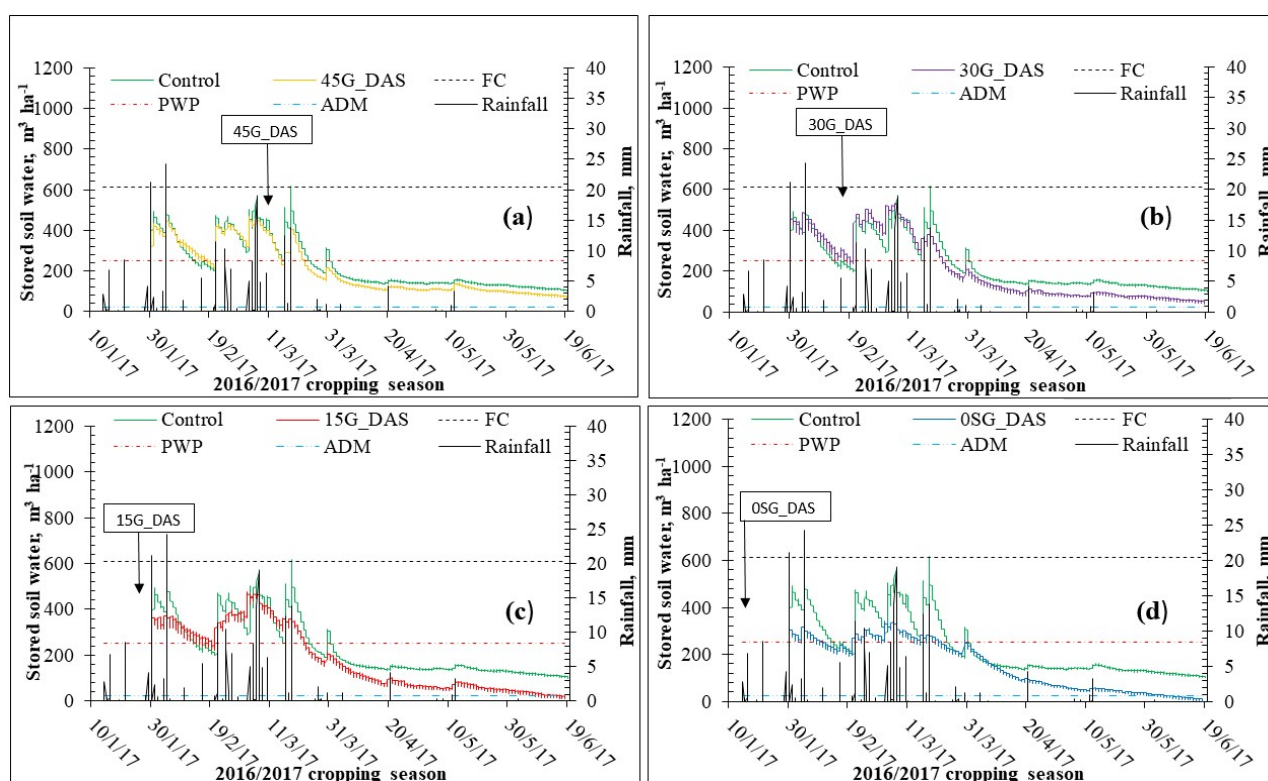


Figure 5.5: Differences in soil water depletion monitored hourly at the effective root zone of the sorghum as influenced by temporal intercropping pattern of (a) 0SG_DAS, (b) 30G_DAS (c) 45G_DAS (d) and control in relation to 15G_DAS in the 2016/2017 (below-average rainfall season). FC, field capacity (-3.1 kPa); PWP, permanent wilting point (-1.5 MPa); and ADM, air dried moist (-31.0 MPa).

below-average rainfall season, the temporal sorghum-groundnut patterns followed the order: $0SG_DAS \leq 15G_DAS < 30G_DAS < 45G_DAS$ (Fig.5.5). Furthermore, the results showed that during the rainfall events before the critical period of soil moisture stress, 15G_DAS, 30G_DAS, 45G_DAS and Control treatments had more or less similar amount of soil water stored at the effective root zone of the sorghum from the percolated rainwater. However, 0SG_DAS had still having the lowest retained soil water. The lowest amount of soil water in 0SG_DAS was directly linked to the lowest prevailed soil water balance at the effective root zone, due to increased soil water uptake triggered by the groundnut, since early at the beginning of the season when sorghum and groundnut were sown in the same plot. Such a similar phenomenon was also observed in the above-average rainfall season. The lowest water level in 0SG_DAS could have also possibly been contributed by the early formed groundnut cover, which prevented direct contact of the ineffective rainfalls to the soil. It should be remembered that the ineffective rainfalls in the below-average rainfall dominated by 78.3% of the rainfall frequencies (day). In this season, effective rainfalls had only rained for 10 days out of the 46 rainfalls' days, with 33.4 mm day^{-1} being the highest recorded rainfall in the 120 days cropping window. Under the arid environment, with high air temperature and atmospheric moisture demand, the water on the leaves could easily lost by evaporation.

5.3.2 Interactive influence of temporal intercropping patterns of sorghum-groundnut on the rate of soil moisture depletion at the effective root zone of the sorghum and risk of the sorghum crop failure during the critical period of soil moisture stress

The rate of soil water depletion on daily basis at the effective root zone of the sorghum in 0SG_DAS, 15G_DAS, 30G_DAS, 45G_DAS and Control treatments revealed different

trends. Figure 5.6 (a) and (b) represents the differences at which soil water was depleted during the critical periods of soil moistures stress, for the two consecutive cropping season of 2015/2016 (Above- average rainfall season) and 2016/2017 (below-average rainfall season). The associated risk of the sorghum crop failure is indicated in Table 5.1. The results showed that for the two consecutive cropping seasons, 0SG_DAS treatment had depleted more soil water at the effective root zone of the sorghum and increased the percentage risk of the sorghum crop failure than the rest of the treatments.

In the above-average rainfall season, the percentage risk of sorghum crop failure in 0SG_DAS, during the expected extended drought period was 70.3%. The results revealed that out of the 37 days of the extended drought period, only 11 days had the available soil water to meet a combined crop water demands of sorghum and groundnut. The risk of sorghum crop failure in 0SG_DAS treatment was higher by almost three-fold compared to sole sorghum cropping (Control), which had the lowest percentage risk of crop failure (24.3%). Throughout the extended dry spell period of 37 days, Control treatment had 9 days with hydric deficit at the effective root zone of the sorghum, while 0SG_DAS treatment had 26 days of hydric deficit. When the amount of soil water in Control treatment was held at -1.5 MPa on March 14, 2016, the crops in 0SG_DAS, 15G_DAS, 30G_DAS and 45G_DAS treatments had already depleted the available soil water 17, 15

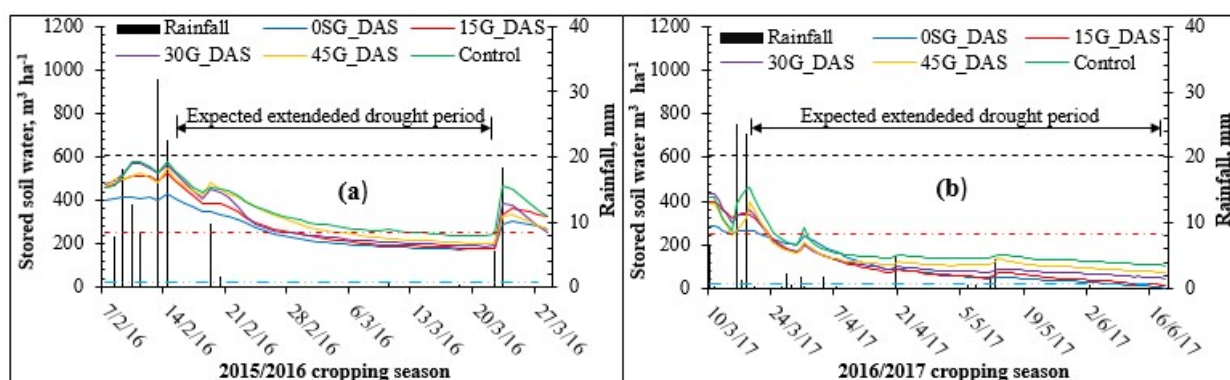


Figure 5.6: The rate of depletion of the soil water at the effective root zone of the sorghum on daily basis as influence by the temporal intercropping pattern of sorghum-groundnut for the two cropping seasons of 2015/2016 (above-average rainfall season) and 2016/2017 (below average rainfall season).

Table 5.1: Number of days with available soil water (> -1.5 MPa) and unavailable soil water (< -1.5 MPa) for the crop at the effective root zone of the sorghum during the expected extended drought period and the associated risk of crop failure due to soil moisture stress during the critical period of soil moisture competition.

Cropping season	Treatment	Number of days			Differences in days for soil moisture stress from control	Risk in crop failure (%)
		Extended drought period	Moisture stress (< -1.5 MPa)	Available water (> -1.5 MPa)		
2015/2016	0SG_DAS	37	26	11	17	70.3
2015/2016	15G_DAS	37	24	13	15	64.9
2015/2016	30G_DAS	37	24	13	15	64.9
2015/2016	45G_DAS	37	18	19	9	48.6
2015/2016	Control	37	9	28	0	24.3
2016/2017	0SG_DAS	93	90	3	3	96.8
2016/2017	15G_DAS	93	89	4	2	95.7
2016/2017	30G_DAS	93	89	4	2	95.7
2016/2017	45G_DAS	93	88	5	1	94.6
2016/2017	Control	93	87	6	0	93.5

0SG_DAS, sorghum and groundnut intercropped in the same day; 15G_DAS, groundnut intercropped at 15th day after sorghum; 30G_DAS, groundnut intercropped at 30th day after sorghum; 45G_DAS, groundnut intercropped at 15th day after sorghum; Control, Sole sorghum cropping.

and 9 days earlier, respectively. The result could not reveal any differences in the percentage risk of crop failure between 15G_DAS (64.9%) and 30G_DAS (64.9%) treatments (Table 5.1). This is because the soil water in 15G_DAS and 30G_DAS treatments were held below the permanent wilting point on the same day (February 28, 2016). Nonetheless, the daily soil water data showed that when the water ($249 \text{ m}^3 \text{ ha}^{-1}$) in Control treatment was just held at -1.5 MPa, the amount of soil water ($200 \text{ m}^3 \text{ ha}^{-1}$) retained in 30G_DAS was slightly higher by $12 \text{ m}^3 \text{ ha}^{-1}$ than that in 15G_DAS ($188 \text{ m}^3 \text{ ha}^{-1}$). Although it could be easily concluded that this difference was of no significance to the crops as soil water was already held at -1.5 MPa, it still gives important hints on the rate at which water was still extracted from the effective root zone of the sorghum due to soil moisture competition influenced by the differences in time for intercropping.

In the below-average rainfall season, the critical soil moisture stress period was extended more by 56 days compared to those in the above-average rainfall season (37 days). This increased the risk of crop failure across all the treatments regardless of whether they were intercropped or not. However, compared to the above-average rainfall

season, the highest (96.8%) and lowest (93.5%) risk of sorghum crop failure in the below-average rainfall season were recorded in 0SG_DAS and Control treatment, respectively. The results indicated that by practicing sole sorghum cropping (Control treatment) in the below-average rainfall season, a farmer could have made use of the stored available water only up to six days before the crop was subjected to soil moisture stress. Notwithstanding, this number of days in Control treatment were the maximum number of days with the available soil water at the effective root zone across all the temporal sorghum-groundnut intercropping treatments. If a farmer would have chosen to intercrop groundnut in the sorghum field within the same day (0SG_DAS), the stored available soil water could have been depleted two days earlier compared to the control. In a similar way to the above-average rainfall, there were no differences in days for the available soil water at the effective root zone of the sorghum between 15G_DAS and 30G_DAS. However if the sorghum would have been intercropped with groundnut at the 45th days later after sowing sorghum (45_DAS), the 251 m³ ha⁻¹ in the 45G_DAS treatment would have met the crop water demand for one more day compared to 15G_DAS and 30G_DAS, and 2 more extra days with reference to 0SG_DAS.

CHAPTER SIX

GENERAL DISCUSSION AND CONCLUSION

Nutrients deficiency, high rate of evapotranspiration, insufficient and erratic rainfalls are the critical challenges for crop production in prone dryland areas of Tanzania. In enhancing climate change resilience and productivity capacity of the land under the challenging weather and climate variability, through mitigating the critical period of low soil moisture stress at the effective root zone of the sorghum, TR proved to be an effective IRWHT in higher and lower rainfalls than the average. Holding IRWHT constant, the depletion of the soil moisture at the effective root zone of the sorghum through crop water uptake depends on the fertilizer types applied and rainfall amount in the season. N application leads to a more rapid depletion of the stored available soil water than N+FYM and FYM in the appreciable soil moisture condition. This decreases the mitigation potential of the IRWHT to match with the crop water demand during the critical period of soil moisture stress. Although this does not always lead to a decrease in biomass in FCL, it results in a relative decrease in grain yield in all the treatments compared to N+FYM and FYM. In the below-average rainfall season, the maintenance in soil water due to FYM is regulated and counteracted by the released mineralized nutrients that encourage crop growth and more depletion of the available soil water. Regardless of the high soil moisture levels in the above-average rainfall season, practicing either TR or RP alone does not influence the final biomass and grain yield. An addition of N+FYM results in a remarkable increase in sorghum yield. Application of N alone should be the last option as it results in only a marginal increase in sorghum grain yield. The same principle applies to RP treatments in the lower rainfall season. The rule is reversed in TR and FCL in the latter season, whereby FYM should be the last option over N. Contrary to

the higher rainfall season, application of fertilizer alone without IRWHT in a below-average rainfall season does not increase sorghum grain yield and biomass. Manipulating flat land to TR increases grain yield, significantly. Although RP_N+FYM registered the highest grain yield in the high-rainfall season, this study recommends practicing TR_N+FYM as this has great potential to mitigate against the critical period of soil moisture stress and results in the highest grain yield in the low rainfall seasons, which are typical rainfall characteristics of the marginalised dryland areas of Tanzania.

In tracking soil water balance at the effective root zone for the best management of the crop at the farm level, it is important to quantify soil water balance on daily basis. Quantification of soil moisture level on weekly basis tends to overestimate the available soil moisture at the effective root zone. Such an estimate is likely to cause a hidden soil moisture stress and consequently decrease in sorghum grain yield.

Since crop production is a business like any other, in order to put the findings of this research into action, it will be more viable to carry out an economic analysis of the IRWHT and fertilizer management options to test their profitability performance. Because of the contradicting relationship in soil moisture levels and the overall grain yield performance in RP treatments, it could be of significant importance to explore more on the soil moisture dynamics beyond the effective root zone of the sorghum to understand the storage potential of RP treatments against TR. This could probably go in line with studying of roots growth pattern and behaviour in ripping and TR under different fertilizer sources management.

The results revealed that early intercropping of groundnut in sorghum field increases the rate of soil water depletion at the effective root zone of the sorghum. This depletion in soil water, increases the risk of crop failure during the extended dry spell when the crop water demand is higher, but the soil moisture is limited due to insufficient rainfall and

higher rate of evaporation. Across the two seasons, the highest and lowest risk in crop failure due to moisture stress was recorded in OSG_DAS and sole cropping, respectively. The risk in crop failure in OSG_DAS was 70.3% in the above-average rainfall season. However, it increased to 97% in the below-average rainfall season. Although the sole sorghum cropping had the least (94%) comparable risk in crop failure, it still had a low influence in enhancing crop productivity under the low and unreliable rainfalls in the prone dryland areas of Tanzania. In order to enhance crop productivity, it is recommended to grow groundnut and sorghum separately to avoid the increasing risk of crop failure. Even if the size of the land might be a problem in some places, under good land management practices this could still be achieved. It should be noted that, since the risk in crop failure was still higher even in sole sorghum cropping, practicing in situ rainwater harvesting techniques, could help mitigating the risk of crop failure during the expected extended drought period in the dryland areas of Tanzania.

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Appendix

Summary of the soil nutrients rating criteria

Table S1: Summary of total nitrogen rating levels in the soil for annual crops: Sourced from Oster and Sposito (1980) and Landon (2013).

Level	Total nitrogen (%)
Very Low	< 0.1
Low	0.1 - 0.2
Medium	0.2 - 0.5
High	0.5 - 1.0
Very High	> 1.0

Table S2: Summary of the mineralized nitrogen nutrients rating levels in the soil for annual crops: Sourced from Cottenie (1980) and Hill Laboratories (2018).

Level	Mineralizable nitrogen (mg kg ⁻¹)	Available nitrogen (kg ha ⁻¹)
Very Low	<35	< 50
Low	35 – 50	50 - 150
Medium	50 – 80	150 - 250
High	80 – 240	250 - 350
Very High	>240	> 350

Table S3: Summary of the organic carbon and organic matter rating levels in the soil: Sourced from Horneck et al. (2001), Rollins (2007) and Hill Laboratories (2018).

Level	Organic Carbon	Organic Matter
Very Low	<2	<3
Low	2-4	3-7
Medium	4-10	7-17
High	10-20	17-35
Very High	>20	>35

Table S4: Summary of the C:N rating levels in the soil for annual crops: Sourced from Rollins (2007), Landon (2013) and Hill Laboratory (2018).

level	C/N
Very Low	<8
Low	8-10
Medium	10-15
High	15-25
Very High	>25

Table S5: Summary of the Olsen phosphorous nutrients rating level in the soil for annual crops: Sourced from Cottenie (1980).

Class	Olsen phosphorous
Very Low	<5
Low	5-9
Medium	10-17
High	18-25
Very High	>25

Table S6: Summary of the basic cations (K^+ , Mg^{2+} and Ca^{2+}) rating levels in the soil for annual crops: Sourced from Cottenie (1980), Rollins (2007) and Landon (2013).

CEC ($cmol_c kg^{-1}$ soil)	Level	K	Mg	Ca
Low CEC	Very Low	<0.04	<0.04	<0.5
	Low	0.04-0.1	0.04-0.1	0.5-1
	Medium	0.1-0.2	0.1-0.2	1.0-2.5
	High	0.2-0.3	0.2-0.5	2.5-4
	Very High	>0.3	>0.5	>4
Medium CEC	Very Low	<0.1	<0.2	<2.5
	Low	0.1-0.3	0.2-0.3	2.5-5
	Medium	0.3-0.5	0.3-0.7	5-8
	High	0.5-0.8	0.7-1.5	8-12
	Very High	>0.8	>1.5	>12
Higher CEC	Very Low	<0.2	>0.3	<5
	Low	0.2-0.4	0.3-0.5	5-10
	Medium	0.4-0.8	0.5-1	10-15
	High	0.8-1.3	1-2.5	15-20
	Very High	>1.3	>2.5	>20

Table S7: Summary of the cation exchange capacity (CEC) rating levels in the soil for annual crops: Sourced from Oster and Sposito (1980), and Hill Laboratories (2018).

Level	CEC ($cmol_c kg^{-1}$ soil)
Low	5-12
Medium	12-25
High	25-40
Very High	>40

Table S8: Summary of the salinity rating levels in the soil for annual crops: Sourced from FAO (1988).

Soil Salinity Class	EC ($dS m^{-1}$)	Effect on crop Plant
Non saline	0-2	Saline Effect Negligible
Slightly Saline	2-4	Yield of sensitive crops may be affected
Moderately Saline	4-8	Yields of many crops are restricted
Strongly Saline	8-16	Only tolerant crops yield satisfactory
Very strongly Saline	>16	Only a few very tolerant crops yield satisfactory

Table S9: Summary of electrical conductivity (EC), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR) rating levels and pH range for most nutrients availability in the soil: Sourced from Rowell (1994).

Soil Test Measurement	Soil test interpretation ranges		
	Low	Medium	High
Electrical conductivity (EC): (dS/m^{-1})	<0.75	0.75-4	>4
Exchangeable Sodium percentage (ESP)	5	5-15	>15
Sodium Adsorption Ratio (SAR)	<5	5-13	>13
pH	<7.5	7.5-8.5	>8.5

Table S10: Summary of the exchangeable sodium percentage rating level in the soil for annual crops: Sourced from Landon (2013) and FAO (2018).

Classification	ESP (%)
Non sodic	<6
Sodic	6-10
Moderately sodic	10-15
Strongly Sodic	15-25
Very strongly sodic	>25

Table S11: Summary of pH rating levels in the soil for annual crops: Sourced from McLean (1982) and USDA (1998).

Level	pH
Extremely acid	3.5 – 4.4
Very strongly acid	4.5 – 5.0
Strongly acid	5.1 – 5.5
Moderately acid	5.6 – 6.0
Slightly acid	6.1 – 6.5
Neutral	6.6 – 7.3
Slightly alkaline	7.4 – 7.8
Moderately alkaline	7.9 – 8.4
Strongly alkaline	8.5 – 9.0

