# WATER PRODUCTIVITY OF SELECTED SORGHUM VARIETIES

**by**

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# PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Crop Science, School of Agricultural, Earth and Environmental Sciences, in the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially supported by the Water Research Commission (WRC) of South Africa through WRC Project No. K5/2272//4 'Determining water use of indigenous grain and legume food crops'.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: Professor Albert T. Modi

Date: 15 November, 2014

# DECLARATION

I, Thobeka Manyathi, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

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# ABSTRACT

The majority of people living in rural communities rely on rain-fed farming for their agricultural production. Under these conditions, water stress through drought or uneven rainfall distribution is a major limitation to crop production. Sorghum is drought tolerant and has the ability to produce reasonable yields under water limited conditions. The aim of this study was to evaluate crop growth and development under varying water regimes and determine water use of three sorghum varieties (PAN8816, Macia and Ujiba landrace). Two pot trial studies were conducted under controlled environment conditions. The first study evaluated the responses of three varieties (PAN8816, Macia and Ujiba) to water stress imposed at different growth stages [no stress (NS), vegetative stress (VS), reproductive stress (RS) and yield formation stress (YS)]. Thereafter, harvested seeds were subjected to seed quality tests. The second study determined the water productivity of three sorghum varieties (PAN8816, Macia and Ujiba). Results showed that the reproductive and yield formation stages were the most sensitive to stress. Sorghum demonstrated a degree of phenological plasticity in response to water stress imposed at different growth stages. Ujiba performed similar to the hybrid and open–pollinated varieties under all water regimes and better under water limited conditions. Under optimum conditions, PAN 8816 used water more productively compared to Ujiba and Macia. The high water productivity was associated with the high leaf area. Progeny from the NS and VS water regimes showed high germination capacity with the exception of progeny from plants subjected to water stress (RS and YS). It can be concluded that the Ujiba landrace may be recommended for cultivation by farmers in water limited areas because of its ability to produce reasonable yields under water stress. Water stress during reproductive and yield formation stages results in yield losses and poor seed quality in subsequent seed.

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# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# CHAPTER 1

# INTRODUCTION

## 1.1 Rational for The Research

South Africa appears to be food secure at national level but not at household level (van der Merwe, 2011). Food security is based on four pillars of food availability, accessibility, utilization and stability (Hanson, 2013). Achieving food security requires adequate food availability to the population and this could be achieved through agriculture which plays a key role in food production (du Toit, 2011). Agriculture is practiced by mainly subsistence and commercial farmers under rainfed conditions (Aliber and Hurt, 2011). However, they encounter challenges in terms of increasing productivity since they often experience periodic droughts that have a significant effect on yield (Edmeades, 2013). Crop failure further propagates the problem of food insecurity especially for subsistence farmers and rural households (Baiphethi and Jacobs, 2009).

Therefore, it is crucial that the crop choice of farmers is chosen wisely to be suitable for prolonged drought. Cereals are principal food sources because of their adaptability to many climates, soils and handling methods hence can be a desirable crop choice (Vilakati, 2009). Main cereal crops produced in South Africa are maize, wheat, oats, barley, rye and sorghum (du Toit, 2011). South Africa is one of the regions which have arid, semi–arid and dry sub-humid regions hence varying micro–climates influence the crops grown in these regions (Hanson, 2013). Water is a key challenge for food production due to the extreme variability of rainfall, long dry seasons and recurrent droughts, floods, and dry spells (Hamdy and Giuliana, 2010). It is crucial that the available water is used productively to increase production hence the need to grow drought tolerant cereal crops. Furthermore, the choice of crop and its ability survive under drought conditions in terms of producing optimal yields will enhance food security.

## 1.2 Justification

Unlike maize, rice, wheat, oats, rye and barley which are susceptible to drought and heat stress, sorghum has the ability to withstand such conditions and still produce reasonable yields (Mutisya et al., 2010). Even though sorghum is widely reported to be drought tolerant (Sabadin et al., 2012; Schittenhelm and Schroetter, 2014), water stress occurring at particular growth stages has a negative effect on yield (Yared et al., 2010). There is lack of information reporting on the response of sorghum at different stages of growth for South African sorghum varieties. Furthermore, differential responses of major varieties (local landraces, open pollinated varieties and hybrids) in terms of physical yield of a crop per amount of water consumed (crop water productivity) is not known. Therefore, studies aimed at quantifying water use and determining water use efficiency and water productivity specifically for drought tolerant cereals like sorghum have become important. This is particularly true of South Africa whereby 80% of the country is classified as being semi– to arid (Schulze, 2000). Strategies aimed at improving crop water productivity; aim at addressing not only food security but also improving crop yields. These strategies will thus contribute towards alleviating poverty and hunger, which are part of the Millennium Development Goals (Statistics South Africa, 2013).

## 1.3 Aims and Objectives

This study focused mainly on evaluating crop growth and development under varying water regimes and determining water use and water productivity of three sorghum varieties (PAN8816, Macia and Ujiba landrace). The specific objectives of study were to;

- determine crop growth and development of three different sorghum in response to varying water regimes,
- determine effect of water stress imposed at the vegetative, flowering and yield formation stages of growth on final yield of three sorghum varieties,
- determine the reference harvest index ($HI_o$) parameter and key water stress factors for the three sorghum varieties,
- determine water productivity (WP) for each of the three sorghum varieties, and
- to determine the effect of water stress imposed on maternal plants on subsequent seed quality.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 History, Origin and Production of Sorghum

Sorghum is believed to have been initially domesticated in east Africa (Ethiopian region) with secondary origins in India, Sudan and Nigeria (Devries et al., 2001). The early domesticated sorghum spread throughout Africa and Asia. Furthermore, plants were selected and distributed throughout a broad range of environments and this gave rise to a widely adapted gene base which has been further manipulated by agriculturists and plant breeders (Sukamaran et al., 2012). In Africa, sorghum is principally grown in the Sahel region (a large belt that spreads from the Atlantic coast to Somalia and Ethiopia), bordering the Sahara in the north, and the equatorial forest in the south (Food and Agriculture Organisation, 2008; Berenji et al., 2011). Sorghum is generally widely cultivated in the drier regions of eastern and southern Africa where rainfall levels are too low to support maize production (Demeke and Marcantonio, 2013).

In South Africa, sorghum has various common names. Sorghum is known as graansgorghum in Afrikaans, mabele in Pedi, siSotho and isiNdebele, amabele in isiZulu and amazimba in isiXhosa. The cultivation of sorghum played a crucial role in the spread of the Bantu (black) group of people across sub-Saharan Africa (Taylor and Robbins, 1993). Currently, sorghum is cultivated across the world in the warmer climatic areas. Sorghum is the world’s fifth largest most important cereal grain, after wheat, maize, rice and barley (Taylor and Robbins, 1993).

In many rural areas in Africa sorghum is a dual-purpose crop: both grain and stems are highly valued outputs. Sorghum is grown by two broad groups. The first group, primarily in Asia and Africa, production by farmers is traditional, subsistence and small-scale (National Agricultural Marketing Council, 2007). In this group, sorghum is mainly used for food consumption. The challenge is yields are generally low and can vary considerably from year to year. Both yield and quality of the grain are affected by biotic and abiotic stresses such as drought and low fertility soils (International Crops Research Institute for the Semi-Arid-Tropics, 2008). The second group which comprises industrialized countries and some developing countries production is modern, mechanized, high-input and large-scale and sorghum is primarily used for animal feed, and yields are relatively higher (ICRISAT, 2007).

## 2.2 Classification of Sorghum

Sorghum (*Sorghum bicolor* (L.) Moench) belongs to the tribe Andropogoneae of the family Poaceae. Linnaeus described a group of sorghums under the name Holcus in 1753 (Dahlberg et al., 2011). In 1794 Moench differentiated between the general Sorghum and Holcus (Dahlberg et al., 2011). There are five commonly used races of cultivated sorghum, including: *bicolor*, *durra, kafir*, *guinea* and *caudatum* (Doggett, 1988; Devries et al., 2001). These species are believed to have originated in Africa and continue to be cultivated in the continent, often in conjunction with one another for different uses (Devries et al., 2001). *Kafir* types originate from eastern and southern Africa (National Research Council, 1996; Olembe et al., 2010). According to Vinall et al. (1936), *Durra* sorghums are spread across a wide area of Nigeria and west-African savannah, although they developed primarily in Ethiopia. *Guinea* varieties are cultivated heavily in west and central Africa, although some landraces have spread as far south as Mozambique (Vinall et al., 1936; Devries et al., 2001). *Caudatum* sorghums were domesticated in Kenya and Ethiopia while *bicolor* varieties are lightly spread across east Africa and form the least important cultivated races in Africa (Devries et al., 2001).

The varieties grown in South Africa can be grouped in three classes: grain sorghum – malting (Class GM), which has low tannin content and is used for malting and milling; grain sorghum low tannin content (Class GL) which has low tannin content and used for malting and animal feed and; grain sorghum – high tannin content (Class GH) which has high tannin content and is used for industrial milling (NAMC, 2007).

## 2.3 Economic Importance

In South Africa, sorghum is mainly produced in the Free State and Mpumalanga provinces. The annual production fluctuates from 100 000 to 180 000 tons per annum (Department of Agriculture Forestry and Fisheries, 2013). Sorghum can survive very high temperatures and water-logged conditions which makes it suitable to be grown in tropical African climates (Blum, 2004). In many parts of the world, sorghum is mainly planted to be used by people living in semi–arid or subtropical areas as an alternative source of starch (Shergo et al., 2012). According to Taylor and Robbins (1993), since most cereal grain crops cannot withstand extreme weather or climatic conditions, sorghum has acted as a great substitute crop in many arid regions. Sorghum is used for food in Africa and many parts of Asia, cattle feed in the United States and Australia, bio–energy, brewing beer and for the manufacture of starch (Prasad and Staggenborg, 2009). Sorghum is nutritionally rich in nutrients hence it is an important part of the diets of many people in the world. Sorghum predominantly contains carbohydrates in which starch and dietary fibre are the main components (Vilakati, 2009). Sorghum is also rich in iron, magnesium, potassium, and calcium and phosphorous. These minerals play an important role in bodily processes such as hormone functioning, tissue building and enzyme functioning (Vilakati, 2009). Therefore, the consumption of the sorghum could contribute significantly to human nutrition and socio–economic status, especially in rural communities.

## 2.4 Sorghum Growth and Development

The minimum temperature for germination varies from 7 to 10°C. At a temperature of 15°C, 80% of seed germinate (du Plesis, 2008). If the soil temperatures are too low this often results in poor emergence and crop stand. Water stress has been shown to decrease both percentage and rate of germination in numerous crops. Water stress tolerance during germination, emergence and early seedling growth are particularly important traits for a successful establishment of crop as these traits determine stand establishment and affect the final yield (Safiatou, 2012).

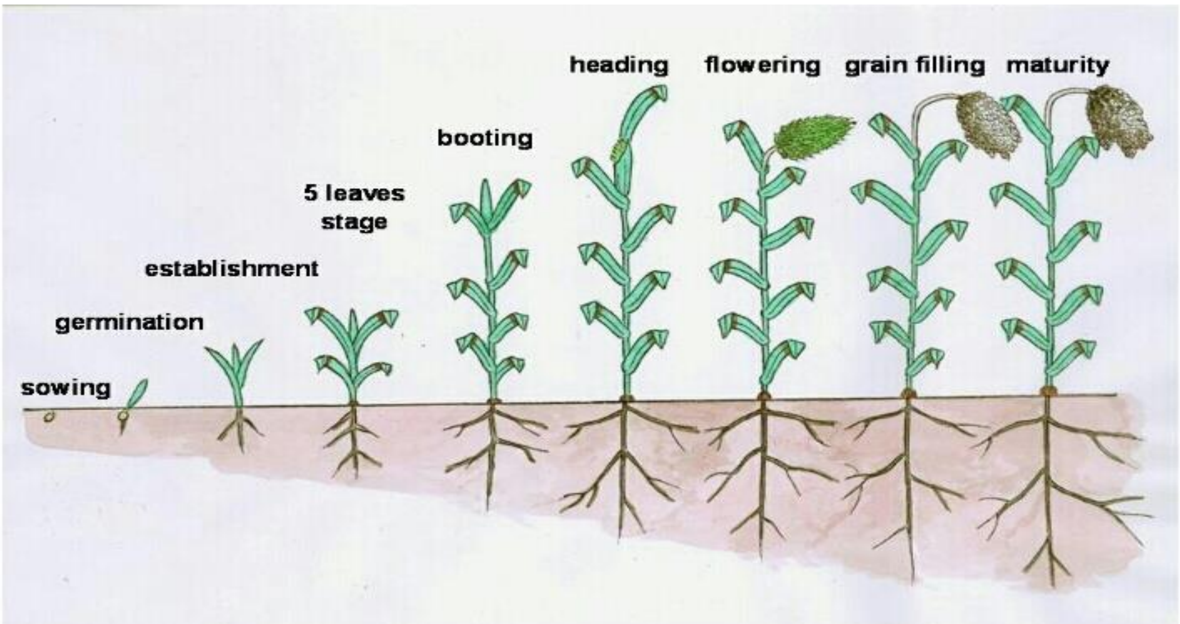

**Figure 2.1:** Sorghum growth stages from emergence to maturity according to Vanderlip (1993).

From the three leaf stage until the flag leaf sorghum is at its vegetative stage (Figure 2.1). Generally a sorghum plant produces leaves which are arranged in an alternate fashion on the culm and the most top leave is called a flag or boot leaf; however, there are cultivar differences (Bennet et al., 2010). Leaf initiation and development processes associated with the axillary branches are not severely affected as compared with main stem leaf development, resulting in whole plant leaf area reductions. Leaf area is the measure of the photosynthetic system (Mabhaudhi, 2009), furthermore it is used to predict photosynthetic primary production, evapotranspiration and as a reference tool for crop growth. Leaf area index influences photon capture, photosynthesis, assimilate partitioning, growth, and yield formation (Jones, 1992; Rajcan and Tollenaar, 1999; Narayanan, 2013). According to Kumari and Khannachoppra (1995), water stress results in a reduction in the total amount of leaf area developed thus less growth (leaf area formation) during the later stages of sorghum growth. Reduced leaf area is a drought avoidance mechanism, aimed at reducing plant water consumption and hence conserving water during periods of drought (Bimpong et al., 2011). It is achieved through inhibition of leaf expansion and initiation, reduced branching and plant height as well as accelerated leaf senescence (Belaygue et al., 1996; Pic et al., 2002). Sorghum's inflorescence is known as a panicle and can be compact or open (Figure 2.1). Sorghum panicle formation begins at the fourth leaf stage (Figure 2.1) and begins to enlarge at the six leaf stage (Narayanan, 2007).

Seed development progresses from milk to soft dough to hard dough to physiological maturity (Warrick, 2000). During the milk stage the seed is still soft and a white milk-like liquid is obtained when kernels are squeezed. The soft dough stage occurs when the kernel can be squeezed between the fingers with little or no liquid present (Charyulu et al., 2013). The hard dough stage occurs when the grain cannot be compressed between the fingers. Sorghum seed varies in shape, colour and size depending with cultivar (Charyulu et al., 2013).

## 2.5 Sorghum Responses to Water Stress

Plants experience water stress either when the water supply to their roots becomes limiting or when the transpiration rate exceeds the rate of supply from the roots (Taiz and Zeiger, 2006).Water stress is primarily caused by soil water deficit, whether intermittent, temporal or permanent. According to Blum (1996), drought is a multidimensional nature that affects plants at various levels of organization. It is commonly accepted as the most prevalent abiotic stress, as well as a major crop limiting factor in many areas of the world (Quarrie et al., 1999). Plants respond differently to water stress and their response is dependent on the type of crop, stage at which the stress is imposed, intensity and duration of the stress (Prassad and

Staggenborg, 2010). Sorghum is better suited to bio-chemically and physiologically withstand high temperatures and limited water conditions than C3 crops and maize (Downs, 1992).

### 2.5.1 Effect of water stress at different phenological stages

Water stress effects have an impact on canopy growth, stomatal conductance, canopy senescence and harvest index. Stomatal conductance is a numerical measure of the rate of passage of either water vapour or carbon dioxide through the stomata (Steduto et al., 2012). The closure of stomata decreases the flow of $CO_2$ into the leaves, followed by a parallel decline in net photosynthesis, and eventually plant growth (Chaves et al., 2003; Prasad and Staggenborg, 2009). According to Ahmed (2013), sorghum accumulates solutes and osmotically adjusts in response to developing water stress, this allows sorghum to maintain stomatal opening and carry on photosynthesis longer even as soil water depletes and delaying canopy senescence induced by water stress.

Canopy cover (green canopy cover) is a crucial feature of plant growth. Canopy expansion, ageing, senescence and stomatal conductance control the amount of water transpired which determines the amount of biomass that will be produced. According to Steduto et al. (2012), leaf expansion is most sensitive to water stress than stomatal conductance. The canopy obtains greater absorptivity than the individual leaves due to the distribution and orientation of leaves within the canopy (Campbell and Norman, 1998). Under severe water stress, canopy development might be brought to cessation and canopy senescence might be triggered depending on how severe the stress is and if crop transpiration is fully inhibited (Steduto et al., 2012).

Harvest index, defined as the ratio of grain yield over total above ground biomass (Steduto et al., 2012), is also affected by water stress. The impact of water stress on harvest index can be dependent on the timing and the extent of stress during the crop’s life cycle. If the duration of the stress is long and severe the number of grains will be reduced which results in reduced harvest index and yield. According to Borrel et al. (2010), lack of photosynthetic assimilates could cause reduction and abortion of flowers and this is likely to occur in the youngest flowers. Furthermore, in sorghum post–flowering water stress decreases seed filling duration, seed size and seed number leading to reduction in grain yield or even total crop loss. Moderate water stress would reduce leaf growth substantially because it is most sensitive to water stress, while stomata, being substantially less sensitive, would remain open to maintain photosynthesis (Mkhabela, 1995).

It is generally recognized that during the vegetative stage, sufficient leaf area and functional root systems are necessary to support maximum grain production (Mastrorilli et al., 1994). For the duration of this phase, sorghum water requirements are not particularly high, the crop has the ability attain an adequate leaf area index. In the reproductive phase, if sorghum is temporarily exposed to soil water stress there are negative consequences to final yield (Ludlow and Muchow, 1990). Yared et al. (2010) reported that water stress occurring during the vegetative stage alone could reduce yield by more than 36%. Water stress at the reproductive stage can reduce yield by more than 55%. Therefore, the most sensitive stage to water stress is at flowering as the water stress may cause delay in flowering (Sakhi et al., 2014). This brings emphasis to the fact that water stress occurring between pre– and post–flowering decreases seed filling duration, seed size and seed number and hence causing significant yield reduction.

Plant height, leaf area and stem height are significantly affected by water stress hence affecting the grain yield (Taiz and Zeiger, 2006). According to Craufurd and Peacock (1992), sorghum grain yield was affected by both the timing and severity of the stress. The most reduction (87%) in grain yield resulted from stress imposed during booting and flowering (late stress) in the early flowering the same stress treatment on vegetative plants had no effect on grain yield. An increase in severe stress duration on vegetative plants (early plus late stress) reduced grain yield by 50–60%.

Even though sorghum tolerates and avoids drought more than many other cereal crops, this does not come without any yield losses. Sorghum's drought tolerance is attributed to a dense and prolific root system that is capable of extracting soil water deep in the soil profile, its ability to maintain stomatal opening at low levels of leaf water potential through osmotic adjustment and its ability to delay reproductive development (Singh and Singh, 1995; Farre and Faci, 2006). Furthermore, sorghum restrains transpirational loss of water through upright leaf habit and also contributes to its ability to escape drought.

### *2.5.2 Varietal responses of sorghum to water stress*

Responses to water stress are generally dependent on duration and intensity of stress and different species and genotypes tend to respond differently (Ahuja et al, 2008). Studies by Gardner et al. (1981) on two sorghum varieties showed that applying varying levels of irrigation at different developmental stages resulted in no differences on phenological responses in both cultivars but the development of one cultivar was delayed for about 10 days under the most severe water stress. The delay is believed to have been caused by delayed emergence.

Hybrids are reported to show a yield advantage of 20-60% when compared to improved open pollinated varieties and local landraces (ICRISAT, 2007). Across the four years and eight study countries, the average sorghum yields for hybrids were consistently higher than those for open pollinated varieties by more than 0.6 t/ha (ICRISAT, 2007).

### 2.6 Crop Water Productivity

Ahmad (2004) defines crop water productivity as the ratio of the physical yield of a crop and the amount of water consumed. Crop water productivity (WP) can be calculated as (Steduto et al., 2009):

$$\mathbf{WP = B / \sum T} \qquad \textbf{Equation 2.1}$$

where WP = water productivity,

B = biomass, and

$\sum T$ = cumulative transpiration.

Water productivity is a useful indicator for quantifying the impact of irrigation scheduling decisions with regard to water management (Steduto et al., 2009). The main challenge in calculating rain fed water productivity lies in determining the denominator, how much water was consumed in order to produce a given output (Molden et al., 2001). Better estimates of water supply in rain fed systems can be obtained by interpolation of rain gauge data against elevation and over space (Molden et al., 2001).

The relationship between agricultural production and water consumption through evapotranspiration is complex. It is affected by numerous growing conditions, such as climate, agronomic practices, soil type and fertility and crosses scales varying from individual plants to farmer fields, river basins, nations and the global level (Sadras and Angus, 2006). Water productivity has shifted from being a by-product of the developed strategies for maximizing crop yields per unit land, to a means to express the efficiency of plants or farmers to use scarce water resources for food production (Sakthivadivel, 1999). This can be done by purposely reducing irrigation water applications and stressing crops to achieve higher water productivity as a means of saving water (Mod and Mabhaudhi, 2013). The water productivity concept is important for food security in a world where water resources are rapidly being exhausted (Zwart, 2010). Water productivity is affected by various factors, such as crop cultivar type, applied water, soil factors and management practices (Ali and Talukder, 2008).

### 2.7 Conclusion

Water remains the key challenge in agricultural production. It is crucial that this resource is used efficiently. Occurrences of drought events are likely to affect food security worldwide hence the production of drought tolerant crops like sorghum should be encouraged. Understanding sorghum water productivity would contribute in formulation of strategies to promote the crop in dry and marginal areas of agricultural production.

# CHAPTER 3

# MATERIALS AND METHODS

## 3.1 Plant Materials

Ujiba (local landrace) seeds were obtained from small-scale farmers of Tugela Ferry (28.45’ S; 30.27’ E). Ujiba produces dark brown grains. Detailed information for this variety including phenological, morphological and physiological characteristics was lacking. PAN8816 is a bronze–grained hybrid. It is a medium late maturity variety and is classified under class GM: good malting quality. It is known to have good leaf disease resistance and head smut resistance. Generally it takes 79 – 81 days to reach flowering under optimum conditions. PAN8816 seeds were purchased from Pannar Seeds, Greytown, South Africa. Macia is a white grained open–pollinated variety. It is an early to medium maturing variety. It takes 60 – 65 days to heading and 115 – 120 days to maturity under optimal growing conditions. It can be characterized as dwarf to semi– dwarf with 1.3 – 1.5 m plant height. Macia seeds were purchased from Capstone Seeds, Mooi River, South Africa.

## 3.2 Description of Controlled Environment

Two separate pot trial experiments were conducted in growth tunnels of the University of KwaZulu-Natal Controlled Environment Facility, Pietermaritzburg, South Africa (29°37'12"S; 30°23'49"E) in March 2014. The meteorological conditions in the tunnel were semi-controlled. Temperatures (~18/33°C day/night) and relative humidity (60 – 80%) the tunnels are designed to resemble those of a warm subtropical climate (Modi, 2007).

## 3.3 Experimental Design

### *3.3.1 Determination of growth, development and yield responses of sorghum to water stress imposed at different growth stages*

The first pot trial experiment was a factorial experiment consisting of three cultivars (PAN8816, Marcia and Ujiba) and four water stress regimes (no stress, vegetative stress, reproductive stage stress and yield formation stress) replicated three times. The experiment was laid out in a completely randomized design.

### *3.3.2 Determination of sorghum crop water productivity*

The second pot trial experiment was a factorial experiment which comprised three cultivars (PAN8816, Marcia and Ujiba), six destructive sampling time intervals (35, 49, 63, 77, 91 and 168 days after planting) replicated three times. The experimental design was arranged in a completely randomized design. The total number of pots was 54. Day 35 coincided with the sorghum plants three leaf stage which is when first sample was taken. Day 168 coincided with sorghum harvest maturity. Destructive sampling was carried out by cutting the base (where the plant stem meets the soil surface) of the plant. The resulting shoot was then defined as aboveground biomass. All 54 pots were watered to 80% FC from planting until harvest.

### *3.3.3 Determination of Gravimetric Field Capacity*

5 kg of soil was filled in three pots, each pot represented a replicate. Each pot was filled with water until the soil was saturated. The pots were then left to drain for 4 days to drain out excess water. Thereafter the soil was taken out from the pots and put in brown bags and placed in the oven at 80 ˚C. After 3 days the mass of dry soil was measured. The following formula was used to calculate gravimetric field capacity (Mabhaudhi, 2009):

$$\boldsymbol{\theta m} = \left(\frac{\boldsymbol{\theta w - \theta d}}{\boldsymbol{\theta d}}\right) \boldsymbol{x}\ \mathbf{100\%} \qquad \textbf{Equation 3.1}$$

where, $\theta_m$ = gravimetric field water capacity,

$\theta_w$ = wet mass of soil, and

$\theta_d$ = dry mass of soil.

### *3.3.4 Potting procedure*

Ninety two pots were filled with soil to a height of 33 cm each. Thirty six pots were used for determining the response of sorghum to water stress imposed at different growth stages. Fifty-six pots were used for determining crop and nutritional water productivity of sorghum. Fifty-four pots were allocated to treatments and two pots acted as controls for calculating weekly evaporation. The experiment was conducted in large (20 L) pots with a circumference of 89.54 cm.

All pots were irrigated to 80% field capacity after planting to facilitate seed germination. The positions of experimental pots were shifted randomly at each irrigation event to ensure that no pot ever occupied the same position continuously. Sorghum seeds were planted using the broadcasting method in all 90 treatment pots. At crop establishment (90% emergence) for each treatment, all pots were thinned to one seedling per pot. Emergence was defined as when hypocotyl protrusion was above 2 cm above soil surface. After crop establishment, a single layer of quartz was applied to cover the entire soil surface for all treatments. Quartz application was to limit soil evaporation in treatment pots, and permit water loss only by plant transpiration.

### *3.3.5 Irrigation scheduling and watering procedure*

#### *3.3.5.1 Determination of growth, development and yield responses of sorghum to water stress imposed at different growth stages*

Irrigation was done once a week for all the experimental plants. For the no stress (NS) treatment, plants were irrigated to 80% gravimetric field capacity (FC) from planting until harvest maturity. Vegetative stage stress (VS) involved watering plants to 80% FC from planting until half the treatment population had reached vegetative state (first true leaf formation), followed by  irrigating to 30% FC, thereafter irrigating to 80% FC from flowering to harvest maturity. Flowering was defined as when half the treatment population exhibited inflorescence. Reproductive stage stress (RS) involved irrigating plants to 80% FC from sowing until end of juvenile phase. Followed by irrigating to 30% FC until yield formation, thereafter irrigating to 80% FC from yield formation to harvest maturity.

Juvenile phase was observed visually as when half the treatment populations exhibited stem bulging after flag leaf formation. Yield formation was described when half the treatment population exhibited grain formation. For yield formation stress, pots were irrigated to 80% FC from planting until crop establishment, thereafter irrigated to 30% FC from crop establishment until harvest maturity. The pots were irrigated once a week according to their respective treatments.

#### *3.3.5.2 Determination of crop water productivity of sorghum*

Irrigation was done once a week. Weekly water lost from pots was measured as difference in pot mass between two consecutive weeks. After which pots were refilled back to 80% field capacity for all the experimental plants. Soil water content was taken between irrigation events which was 4 days after data collection. Soil water content, irrigation and evaporation were measured to calculate plant transpiration. Transpiration was calculated as the residual of a modified soil water balance using equation 2. Evaporation was measured using bare pots, which were irrigated to remain at 80% field capacity. The amount of water lost was considered evaporation since water was lost from bare soil. The loss of water was measured gravimetrically by the difference in weight of the pots before and after irrigation. The difference between the weeks was considered as water lost by evaporation. Soil was refilled with water to 80 % FC after each measurement.

## 3.4 Data Collection

### *3.4.1 Growth and physiology*

#### *3.4.1.1 Determination of growth, development and yield responses of sorghum to water stress imposed at different growth stages*

Weekly data was collected for seedling emergence, chlorophyll content index, and plant height and leaf number. Seedling emergence was collected from the onset of the trial up to 14 days after planting. Data collection was conducted during periods between irrigation events, from crop establishment until harvest maturity. Plant height was measured from crop establishment until harvest, using a tape measure as distance from soil surface to the tip of second youngest leaf. Leaf number was counted weekly from establishment until harvest for fully expanded and fully exposed leaves with at least 50% green leaf area (Mabhaudhi and Modi, 2013). Chlorophyll content index was measured using the CCM-200 (Opti-Sciences, USA) on the adaxial surface of the second youngest, fully expanded and fully exposed leaf of each plant. Measurements were taken during midday (12h00-14h00 hours).

Soil water content was monitored weekly between irrigation events using an ML2x theta probe connected to an HH2 handheld moisture meter (Delta-T, UK). Irrigation in the pot trial was done once a week using the gravimetric method. Briefly, individual pots were weighed. The mass of the pot was then subtracted from a known reference mass corresponding to 80% of field capacity. The difference was considered as what the plant had evapotranspired (ET). The pots were then refilled back to 80% field capacity. As part of the design, there were pots that were filled with soil but not covered with quartz and that had no plants planted in them. The purpose was to obtain an estimate for soil evaporation (E) from an uncovered soil surface. Transpiration was calculated as the residual of a modified soil water balance equation (Eq 3.2) below (Steduto et al., 2009):

$$\boldsymbol{ET = I + P - RO - DP + CR \pm SF \pm \Delta SW}$$ **Equation 3. 2**

Where: ET = evapotranspiration (mm),

I = irrigation (mm),

P = rainfall (mm),

RO = surface runoff (mm),

DP = deep percolation (mm),

CR = capillary rise,

SF = soil water lateral flow, and

ΔSWC = change in soil water content

Since the experiments were conducted in pots (without holes for drainage) with irrigation never reaching saturation, deep percolation, capillary rise, lateral flow and irrigation were considered negligible. The resultant residual equation was:

$$\boldsymbol{T = I - \Delta SWC - E}$$ **Equation 3.3**

where; T = crop transpiration,

ΔSWC = weekly changes in soil water content monitored gravimetrically by pot weighing, and

E = evaporation.

### *3.4.1.2 Leaf area and reference harvest index*

Leaf area was measured fortnightly on destructively sampled plants using a portable leaf area meter (LICOR®, USA). All individual leaves per plant were separated from the main stem. Thereafter, leaves were inserted into the leaf area meter to obtain leaf area per plant. Three plants per cultivar were destructively sampled for dry above–ground biomass at aforementioned sampling dates. From panicle formation (63 days after planting) until harvest, economic yield (panicle) was separated from the rest of the destructively sampled shoot. At each sampling date, plant samples were dried in an oven at 80°C for 72 hours before determining dry mass. Harvest index was defined as economic yield per total above–ground biomass and calculated using equation 3.4 (Steduto et al., 2009):

$$\boldsymbol{HI = B/Y} \qquad \textbf{Equation 3.4}$$

where; HI = Harvest index

Y = Economic yield

B = Total above–ground biomass.

### *3.4.1.3 Phenology*

Crop establishment and flowering were recorded as explained above (section 3.3.4 and 3.3.5). End of juvenile was defined as hen all of the treatment population exhibited flag leaf. Floral initiation was defined as the period when half of the treatment population exhibited inflorescence (when the flowering has progressed half-way down the head). Anthesis was defined as when half of treatment population exhibits a flower which is fully open. The duration of flowering was from floral initiation until anthesis. Grain filling was observed when half the treatment population exhibited grain formation. Physiological maturity was defined as when grains of half the treatment population exhibited dark colouring at the base of the grain, when grains could not be crushed between fingers.

## 3.6 Determination of Crop Water Productivity (WP)

Water productivity was calculated using equation 3.5 (Steduto et al., 2009):

$$\boldsymbol{WP = B / \sum T} \qquad \textbf{Equation 3.5}$$

where; WP = water productivity (g m$^{-3}$), B = total above ground biomass (g), and

$\sum T$ = cumulative transpiration ($m^3$).

### 3.7 Crop Stress Factors

At harvest the following yield parameters such as panicle and seed mass were recorder for all the treatments. The total above ground biomass was taken as plants that are cut from just above the soil surface thereafter the panicle were cut to measure the panicle mass. The fresh mass was recorded after harvested and the plants were air dried then the dry mass was recorded, both fresh and dry mass was recorded in grams. These yield parameters and transpiration data were further used to calculate stress factors using the following equation 3.6 (Steduto et al., 2009)

$$\left(\frac{\mathrm{Yx} - \mathrm{Ya}}{\mathrm{Yx}}\right) = \mathrm{Ky}\left(\frac{\mathrm{ETx} - \mathrm{ETa}}{\mathrm{ETx}}\right) \qquad \textbf{Equation 3. 6}$$

where: Yx = maximum yield

Ya = actual yield

ETx = maximum evapotranspiration

ETa = actual evapotranspiration, and

Ky = proportionality factor between relative yield loss and relative reduction in evapotranspiration.

The maximum yield was defined as the panicle mass for the no stressed plants (grown under optimal conditions). Actual yield was defined as the panicle mass for the plants that were stressed at different stages of growth. Maximum transpiration was defined as the transpiration that occurred under optimal conditions. Actual transpiration was defined as transpiration that occurred under different water stress treatment.

### 3.8 Agronomic Practices

Soil used in the study was collected from Ukulinga Research Farm and submitted for soil analyses at the KwaZulu–Natal Department of Agriculture and Environmental Affairs soil analyses laboratory. Based on results of the soil fertility analyses, an organic fertilizer, Gromor® (30 g $kg^{-1}$ N, 15 g $kg^{-1}$ P and 15 g $kg^{-1}$ K), was applied at a rate of 410 g per plant. Fertilizer was applied in the early stages of plant growth. Weeding of the pots was conducted weekly. Malathion®, an insecticide, was sprayed at recommended rates (1 mL $L^{-1}$) to control insects fifty-six days after planting.

**Table 3.1:** Physical and chemical characteristics of soil used during seedling establishment.

| P | K | Ca | Mg | Zn | Mn | Cu |
|---|---|---|---|---|---|---|
| | | | (mg $Kg^{-1}$) | | | |
| 116 | 447 | 2 129 | 201 | 32 | 14 | 4.52 |

### 3.9 Germination test

Harvested sorghum seeds were subjected to a standard germination test using three replicates of ten seeds from each variety (Ujiba, Macia and PAN8816) according to their respective treatments. Petri dishes were lined with moistened Whatman® filter paper and incubated in a germination chamber set at alternating temperatures 20/30°C day/night, (16 hr day/8 hr night) for 10 days. The filter paper was re–wetted on a daily basis to maintain adequate moisture levels. Daily germination counts were taken based on radicle protrusion of 2 mm or more. On day ten, final germination percentage was calculated according to ISTA (2011) guidelines. This was followed by measuring root and shoots lengths, root: shoot ratio .Additionally, the following were calculated:

Germination velocity index (GVI), was calculated according to Maguire's (1962) formulae:

$$\mathrm{GVI} = \mathrm{G1/N1} + \mathrm{G2/N2} + \cdots + \mathrm{Gn/Nn} \qquad \textbf{Equation 3.7}$$

where: GVI = germination velocity index, G1, G2…Gn = number of germinated seeds in first, second… last count, and

N1, N2…Nn = number of sowing days at the first, second… last count.

The mean germination time (MGT) was calculated according to the formulae by Ellis and Roberts (1981):

$$\boldsymbol{MGT}=\frac{\Sigma \mathrm{Dn}}{\Sigma \mathrm{n}}$$ **Equation 3.8**

where: MGT= mean germination time,

n = the number of seed which were germinated on day D, and

D = number of days counted from the beginning of germination.

## 3.10 Statistical Analyses

Recorded crop parameters were subjected to statistical analysis using GenStat® 16th edition (VSN International, UK). Data were analysed using a factorial analysis of variance (ANOVA) algorithm in GenStat® at the 5% level of significance. For results of parameters measured from the water productivity experiment, a simple one–way ANOVA was used. Thereafter, means were separated using least significant differences (LSD) at a probability level of 5%. Details of the statistical analyses are shown in the appendices section.

# CHAPTER 4

# GROWTH, DEVELOPMENT AND YIELD RESPONSES OF SORGHUM TO WATER STRESS IMPOSED AT DIFFERENT GROWTH STAGES UNDER CONTROLLED ENVIRONMENT CONDITIONS

## 4.1 Introduction

South Africa stands out as one of the most water-scarce countries (Blignaut and Heerden, 2009; Moeletsi and Walker, 2012). The country is also characterized by extremely variable rainfall, both geographically and over time (Schulze, 2000). Only 12% of the country is suitable for the production of rain-fed crops although the majority of farmers practice farming under rainfed conditions (du Plesis, 2008). It is for this reason that crop water stress is a major concern in crop production since most farming is practiced under rainfed agriculture. In areas where there is generally low rainfall and its distribution is erratic (Ejeta at al., 1999) severe yield losses are likely to occur due to water stress (Karunaratne et al., 2011). Water stress has emerged as one of the most severe stresses threatening sustainable crop production (Tahir and Mehdi, 2001). Therefore, farmers need to be able to make informed decisions with regards to variety selection.

Sorghum remains a basic staple food for many rural communities. This is true especially in the more drought prone areas of South Africa where this hardy crop provides better household food security than maize. It is because of sorghum drought tolerance that it is produced on a wide range of soils and under fluctuating rainfall conditions of approximately 400 mm in the drier western parts to about 800 mm in the wetter eastern parts of South Africa (Saxena et al., 2002; du Plessis, 2008; Okiyo et al., 2010). Under these conditions, water stress can occur at any period during crop growth and this often results in yield losses and crop failure in the most extreme of events (Mabhaudhi, 2012). Even though the importance of water has been quantified for many crops (Karunaratne et al., 2011), there is still limited information in terms of the response of sorghum to water stress at different growth stages. Furthermore there is lack of information in terms of the response to water stress of local varieties especially landraces. Understanding of the effects of drought on between these local varieties important for improving agricultural systems and enhance food security (Chaves et al., 2003).

The first objective of this study was to evaluate crop growth and development of three different sorghum varieties (Ujiba, Macia and PAN8816) under varying water stress treatments. The second objective was to determine effect of water stress at specific growth stages (vegetative stage, reproductive stage and yield formation).

## 4.2 Results

### *4.2.1 Soil water content*

Results of soil water content showed that there were no significant differences ($P = 0.098$) between the four water regimes (Figure 4.1). Despite the lack of statistical significance, the trend of results showed that soil water content was, based on mean values of water regimes, higher for the NS water regime relative to the other three water regimes; the YS water regime had the lowest average soil water content. There were also no significant differences ($P = 0.093$) between three sorghum varieties (PAN8816, Ujiba and Macia) with respect to soil water content. Throughout the crops' growing period the soil water content was fluctuating.

### *4.2.2 Transpiration*

There were significant differences ($P < 0.001$) among the different water stress treatments with respect to measured crop transpiration (Figure 4.2). During the periods where stress was imposed for each growth stage the water transpired also showed a decrease. There were no significant differences between the transpiration of the varieties (PAN8816, Ujiba and Macia) ($P = 0.085$). Throughout the crops' growing period the crop transpiration was fluctuating, this was the same for all the varieties. The interaction between the cultivar and water stress treatment of water transpired was not significant ($P = 0.141$).

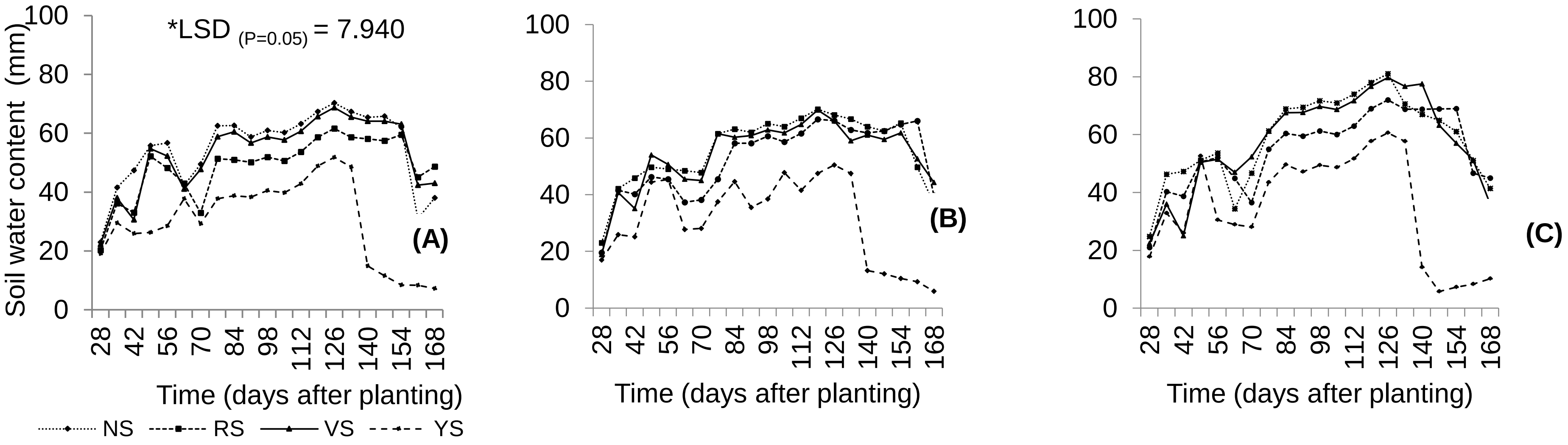

**Figure 4.1:** The weekly soil water content in response to varying water stress treatments (NS, VS, RS and YS) of Macia (A), PAN8816 (B) and Ujiba (C) sorghum varieties. NS = No stress; VS = Vegetative stress; RS = Reproductive stress and YS = Yield formation. *LSD (least significant difference) corresponds to the water regime *x* variety *x* time interaction.

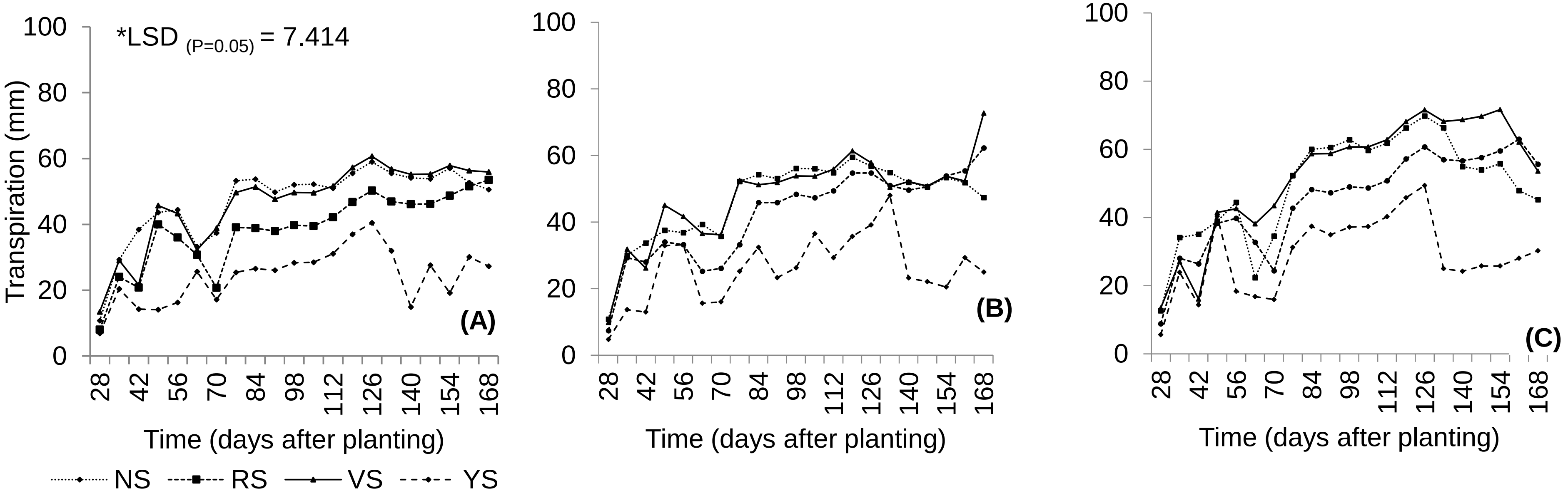

**Figure 4.2:** The weekly transpiration in response to varying water stress treatments (NS, VS, RS and YS) of Macia (A), PAN8816 (B) and Ujiba (C) sorghum varieties. NS = No stress; VS = Vegetative stress; RS = Reproductive stress and YS = Yield formation. *LSD (least significant difference) corresponds to the water regime *x* variety *x* time interaction.

### *4.2.3 Crop growth*

#### *4.2.3.1 Leaf number*

There were highly significant differences ($P < 0.001$) between the different water stress treatments (NS, VS, RS and YS) with respect to leaf number per plant (Figure 4.3). A significant ($P < 0.001$) reduction in leaf number was observed when water stress was imposed at different growth stages. Under optimal conditions (NS), for all the varieties, leaf number was higher compared to the other water stress treatments. The Macia and Ujiba varieties, respectively, had longer canopy duration under optimum conditions (NS) as evidenced by their ability to maintain leaf number longer than the PAN8816 (Figure 4.3A and B). Imposing water stress during the yield formation stage (YS) resulted in leaf abscission. However, the YS water regime remained the most sensitive stage in terms of leaf number hence the rapid leaf loss.

The results showed that there were significant differences ($P < 0.001$) in leaf number of the different sorghum varieties (PAN8816, Ujiba and Macia). PAN8816 had the least number of leaves (7 leaves) at all growth stages (Figure 4.3B) compared to Ujiba and Macia varieties (8 leaves), (Figure 4.3A and B). For all the three varieties, an increase in leaf number was observed from day 28 until day 84 when there was a decrease in leaf number.

The interaction between variety and water stress treatment of leaf number was highly significant ($P < 0.001$). The sorghum varieties responded differently to the different water regimes. The highest leaf number was Ujiba variety at NS water regime (8 leaves) followed by Macia RS water regime (6 leaves), (Figure 4.3). For all varieties and water regimes there was a decline in leaf number after day 126 for Macia and Ujiba but for PAN8816 it was day 140. The most sensitive stage to leaf abscission was the YS water regime specifically Macia (Figure 4.3A). Ujiba and PAN8816 were able to maintain leaves up until day 154 (Figure 4.3B and C).

#### *4.2.3.2 Plant height*

A significant ($P < 0.001$) reduction in plant height was observed when water was withheld at different growth stages, (Figure 4.4). Imposing water stress at the vegetative (VS), reproductive (RS) and yield formation (YS) resulted in shorter plants relative to plants that were not subjected to water stress (NS). The trend in plant height was such that NS (126 cm) > VS (118 cm) > RS (110 cm) > YS (103 cm), (Figure 4.4). These results were consistent with results of leaf number which also showed that the imposing water stress during yield formation (YS) resulted in limitations to plant growth.

There were highly significant differences ($P < 0.001$) between the plant height of different sorghum varieties (PAN8816, Ujiba and Macia). The Ujiba landrace had the tallest plants with mean height of 151 cm (Figure 4C) compared to PAN8816 (128 cm) and Macia (104 cm) varieties (Figure 4.4A and B).

The interaction between variety and water stress treatment of plant height was highly significant ($P < 0.001$). The tallest plants were observed for the Ujiba landrace (151 cm) under optimum conditions (NS) while the Macia had the shortest plants (86 cm) under the YS water regime (Figure 4.4). Imposing water stress during the vegetative stage (VS) led to shorter plants for Macia (104 cm), PAN8816 (109 cm) and Ujiba (142 cm) relative to the NS water regime. A similar trend was observed when water stress was imposed during the reproductive (RS) and yield formation stages.

#### *4.2.3.3 Chlorophyll content index (CCI)*

There were highly significant differences ($P < 0.001$) between different water regimes (NS, VS, RS and YS) with respect to chlorophyll content index (CCI). The CCI for all the varieties was shown to decline in response to water stress imposed at the yield formation stage (YS) (Figure 4.5A, B and C). The decline in CCI was possibly due to enhanced leaf senescence observed when water stress was imposed at the yield formation stage. The VS water regime maintained a relatively higher CCI for Macia (35) and Ujiba (30) (Figure 4.5). Consistent with results of leaf number and plant height, plants were shown to be more sensitive to water stress imposed at the yield formation stage (YS) than the vegetative (VS) and reproductive (RS) growth stages.

There were highly significant differences ($P < 0.001$) between the different sorghum varieties (PAN8816, Ujiba and Macia) with respect to leaf chlorophyll content index (CCI). On day 42 all the varieties showed an increase in CCI; the Macia variety (56) had the highest CCI compared to PAN8816 (49) and Ujiba (47). Macia variety maintained a constant trend throughout the growing period (Figure 4.5A). On the other hand, PAN8816 and Ujiba showed fluctuating trend throughout the growing period (Figure 4.5B).

The PAN8816 variety had the highest CCI (35) for the VS water regime, followed by YS (32) and RS (32) water regimes, respectively. Macia had the highest CCI (37) for YS, followed by RS (34) and VS (32) water regimes, respectively. The Ujiba landrace had the highest CC at RS (34), followed by VS (30) and YS (25) water regimes, respectively.

### *4.2.4 Crop phenology*

For emergence, only results of differences among varieties are reported since all treatments were established at the same water level to 80% field capacity. There were significant differences (P = 0.010) between the time to emergence across the varieties. The time to crop establishment (90% emergence) was 7 – 8 days after planting, on average, for all the varieties.

There were no significant differences (P = 0.949) between the water regimes with respect to the time it took to reach vegetative stage (Table 4.1). Sorghum plants in the NS, RS, VS and YS water regimes took 30 days after planting, on average, to reach the vegetative stage. There were no significant differences (P = 0.925) between water regimes with respect to the time to the juvenile phase to end. With respect to time to floral initiation, there were highly significant differences (P < 0.001) were observed between the water regimes. Sorghum varieties planted in the NS water regime were faster (P < 0.001) to reach floral initiation relative to the other water regimes. Sorghum plants subjected to water stress during the reproductive stage took on average 65 days after planting to reach floral initiation. Imposing water stress during the vegetative stage (VS) resulted in enhanced floral initiation with sorghum plants reaching floral initiation at 45 days after planting (Table 4.1).

Highly significant differences (P < 0.001) were observed between the water regimes with respect to time to anthesis, flowering, yield formation and physiological maturity. The trend in time to anthesis was such that YS (68 DAP) < VS (71 DAP) < RS (76 DAP) (Table 4.1). A similar trend was observed with respect to time taken to reach flowering where YS (78 DAP) < VS (87 DAP) < RS (87 DAP). This trend was consistent from time to anthesis until physiological maturity. Plants in the YS water regime reach yield formation earlier (112 DAP) than plants in the VS (128 DAP) and RS (129 DAP) water regimes (Table 4.1). With respect to time taken to reach physiological maturity, plants in the YS water regime was took matured earlier (145 DAP) relative to plants in the VS (155 DAP) and RS (159 DAP) water regimes (Table 4.1).

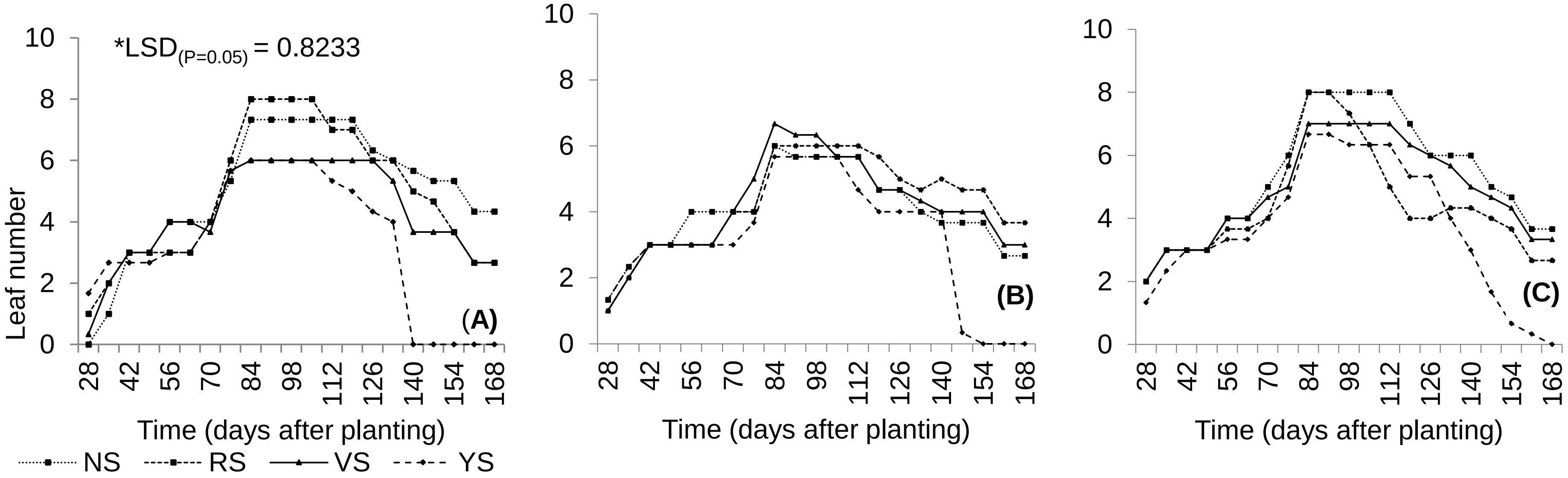

**Figure 4.3:** The weekly leaf number in response to varying water stress treatments (NS, VS, RS and YS) of Macia (A), PAN8816 (B) and Ujiba (C) sorghum varieties. NS = No stress; VS = Vegetative stress; RS = Reproductive stress and YS = Yield formation. *LSD (least significant difference) corresponds to the water regime *x* variety *x* time interaction.

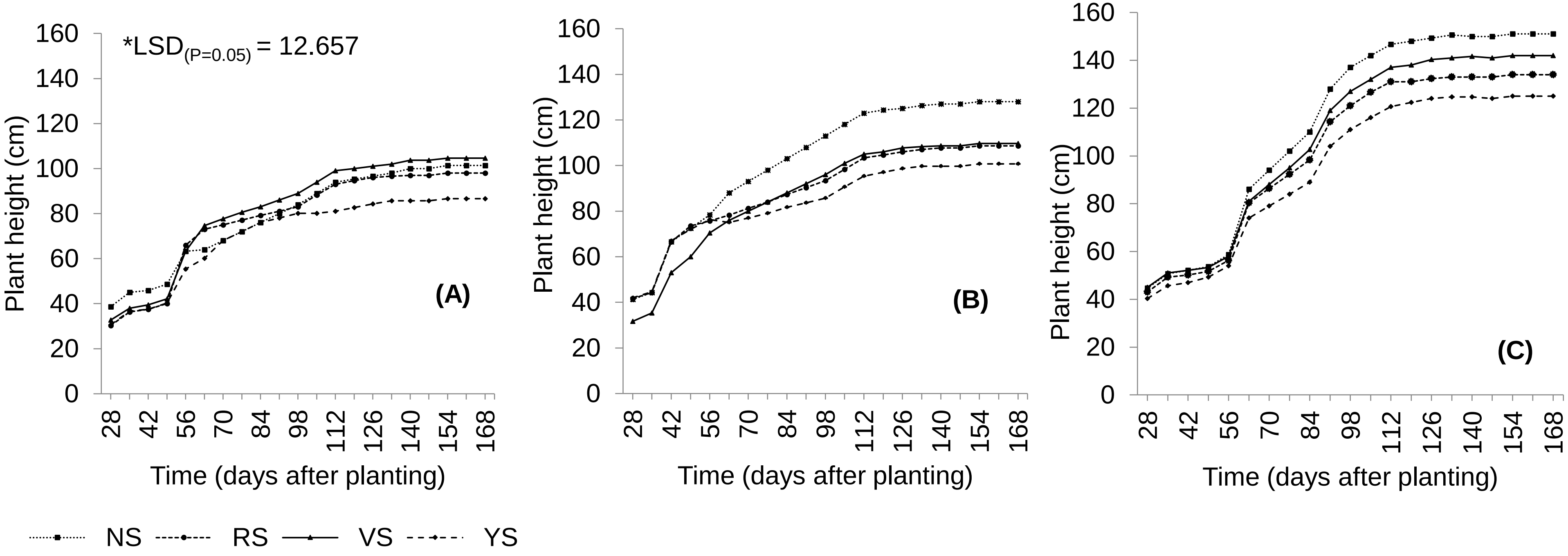

**Figure 4.4:** The weekly plant height in response to varying water stress treatments (NS, VS, RS and YS) of Macia (A), PAN8816 (B) and Ujiba (C) sorghum varieties. NS = No stress; VS = Vegetative stress; RS = Reproductive stress and YS = Yield formation. *LSD (least significant difference) corresponds to the water regime *x* variety *x* time interaction.

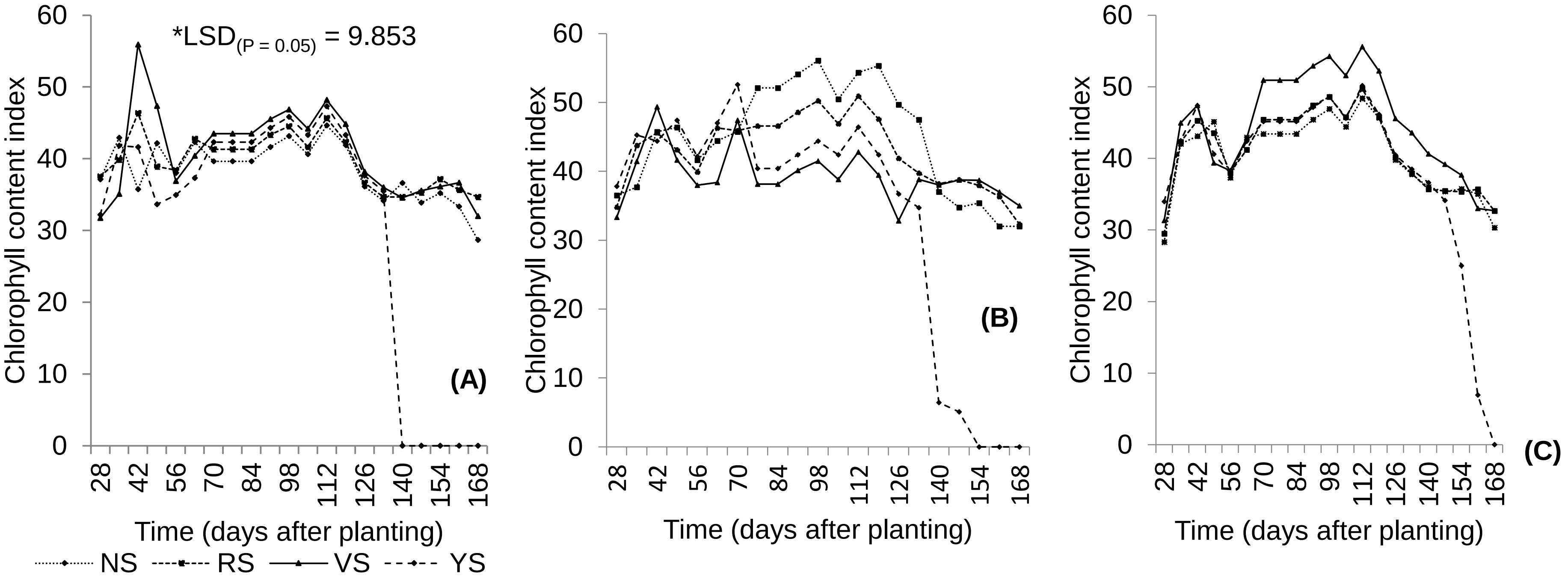

**Figure 4.5:** The weekly chlorophyll content in response to varying water stress treatments (NS, VS, RS and YS) of Macia (A), PAN8816 (B) and Ujiba (C) sorghum varieties. NS = No stress; VS = Vegetative stress; RS = Reproductive stress and YS = Yield formation. *LSD (least significant difference) corresponds to the water regime *x* variety *x* time interaction.

There were no significant differences between the varieties with respect to time taken to reach the vegetative stage (P = 0.458) and time taken to reach end of juvenile stage (P = 0.618) (Table 4.1). Based on mean values of varieties across water regimes, Macia took the least time to reach the vegetative stage (28 DAP) followed by Ujiba and PAN8816, which both took 30 DAP. This trend was also the same with respect to time taken to reach the end of juvenile stage. Macia was took the least time to reach end of juvenile stage (50 DAP) followed by Ujiba (53 DAP) and PAN8816 (52 DAP), respectively. There were significant differences (P = 0.030) between varieties with respect to the time taken to floral initiation and anthesis. Macia took the least time (69 DAP) to reach anthesis compared to PAN8816 (75 DAP) and Ujiba (76 DAP). There were no significant differences (P = 0.119) between varieties with respect to time taken to reach flowering. PAN8816 took 90 DAP relative to Ujiba (80 DAP) and Macia (86 DAP), respectively, to flower. Similar trends were observed for time to yield formation and physiological maturity were there were no significant differences between varieties.

### *4.2.4 Stress factors and yield parameters*

#### *4.2.4.1 Stress factors*

The results of the water stress factor (Ky) showed that, for varieties, the reproductive stage was the most sensitive to the water stress as indicated by Ky > 1(Figure 4.6). However, Ujiba and Macia are more sensitive compared to PAN8816. For all varieties, Ky was less than 1 indicating that the vegetative stage was the least sensitive to water stress. The Ujiba landrace (Ky = 1.2) was less sensitive to water stress imposed at the yield formation stage (YS) than PAN8816 and Macia (Ky = 0.7).

#### *4.2.4.2 Yield parameters*

There were significant differences (P = 0.044) with respect to total above ground biomass across the water regimes. Plants grown in the NS water regime had, on average, higher above ground biomass (126 g) relative to plants grown in the water regimes. Water stress imposed at RS (86 g) and YS (97 g) had a greater effect on above ground biomass compared to VS (120 g), (Table 4.2). There were also significant differences (P < 0.001) with respect to panicle mass across the water regimes. The YS water regime that low panicle mass relative to the other water regimes. The trend in panicle mass was such that NS (31 g) > VS (27 g) > RS (22 g) > YS (18 g) (Table 4.2). There were significant differences (P = 0.027) between varieties with respect to panicle mass. Although Macia had the least biomass, but had larger panicles (30 g) compared to Ujiba (27 g) and PAN8816 (26 g), respectively (Table 4.2). There were no significant differences between varieties for measured seed mass (P = 0.948) and 100 grain seed mass (P = 0.461) (Table 4.2). There were significant difference (P = 0.035) across the water regimes for harvest index.

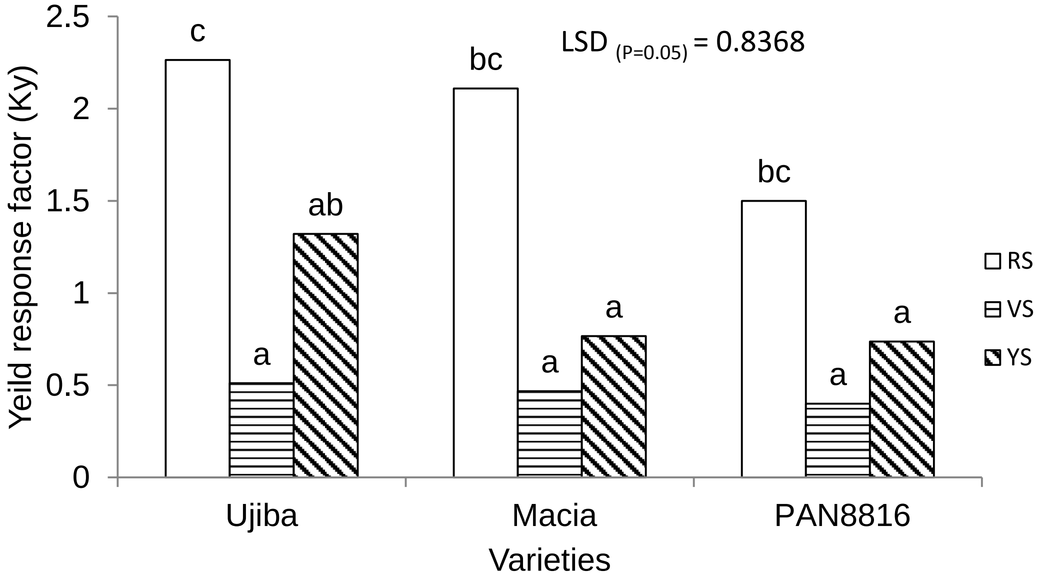

**Figure 4.6:** Yield response factors of Ujiba, Macia and PAN8816 sorghum varieties in response to varying water stress treatments. Reproductive stress (RS), vegetative stress (VS) and yield formation (YS). LSD (least significant difference) corresponds to the water regime *x* variety *x* time interaction.

**Table 4.1:** Time it takes for three sorghum varieties in response to varying water stress treatments of three sorghum varieties to reach phenological stages.

| Water | Variety | Time to establishment (days) | Time to vegetative stage (days) | Time to end of juvenile phase (days) | Time to floral initiation (days) | Time to anthesis (days) | Time to flowering (days) | Time to yield formation (days) | Time to physiological maturity (days) |
|---|---|---|---|---|---|---|---|---|---|
| **NS** | Ujiba | 7.00a | 31.00ab | 53.00ab | 66.00b | 75.00b | 90.00f | 132.00d | 156.70bc |
| | Macia | 8.67bc | 28.00a | 50.00a | 65.55a | 75.00b | 86.33de | 129.30d | 158.00bc |
| | PAN8816 | 8.66bc | 32.67ab | 56.33ab | 62.00b | 75.00b | 82.33bc | 123.30bcd | 160.00c |
| **VS** | Ujiba | 8.00abc | 33.00ab | 52.33ab | 57.00a | 76.00b | 86.00de | 128.70cd | 154.80bc |
| | Macia | 8.67bc | 28.33a | 50.33a | 55.00a | 69.00a | 86.67def | 129.00cd | 156.00bc |
| | PAN8816 | 8abc | 30.67ab | 50.66a | 57.25a | 69.67a | 85.00cd | 127.30cd | 155.00bc |
| **RS** | Ujiba | 8.67bc | 30.33ab | 52.33ab | 67.00b | 76.00b | 86.00de | 128.70cd | 165.20cd |
| | Macia | 8.67bc | 28.67a | 50.67ab | 62.00a | 76.33b | 88.00def | 123.70bcd | 160.50c |
| | PAN8816 | 7.66ab | 35.00b | 57.00b | 66.00b | 76.33b | 89.33ef | 133.70d | 152.00abc |
| **YS** | Ujiba | 8.00abc | 30.33ab | 50.33ab | 60.22a | 67.67a | 81.33b | 107.30a | 145.00ab |
| | Macia | 8.00abc | 30.00ab | 50.10ab | 58.20a | 69.00a | 81.33b | 113.30ab | 139.30a |
| | PAN8816 | 7.66ab | 30.67ab | 51.60ab | 59.33a | 68.67a | 73.67a | 118.00bc | 152.50abc |
| LSD$_{(P=0.05)}$ Var | | 0.53 | 3.05 | 3.21 | 1.18 | 2.34 | 2.45 | 5.68 | 7.44 |
| LSD$_{(P=0.05)}$ Water | | 0.46 | 2.64 | 2.78 | 1.02 | 2.03 | 2.12 | 4.92 | 6.44 |
| LSD$_{(P=0.05)}$ Var*Water | | 0.92 | 5.28 | 5.55 | 2.05 | 4.05 | 4.25 | 9.84 | 12.89 |

Note that values sharing the same letter within the same column are statistically similar at LSD (P= 0.05) for the water regime *x* variety *x* time interaction. Var = Variety; Water = Water stress treatment.

**Table 4.2:** The head dry mass, total above ground biomass, seed mass and harvest index of three sorghum (Ujiba, Macia and PAN8816) varieties in response to varying water stress treatments. NS= No stress; VS= Vegetative stress; RS= Reproductive stress and YS= Yield formation.

| Water regime | Variety | Total above ground biomass (g) | Biomass yield (g/ha) | Panicle mass (g) | Seed mass plant$^{-1}$ (g) | 100 grain mass (g) | Harvest index (%) |
|---|---|---|---|---|---|---|---|
| NS | Ujiba | 121.30bc | 209.90bc | 37.70bc | 32.93cd | 4.00a | 30.16cde |
| | Macia | 132.00bcd | 228.50bcd | 45.30c | 20.23b | 3.84a | 18.64abc |
| | PAN8816 | 131.50bcd | 227.50bcd | 37.40bc | 35.64d | 4.24a | 34.22de |
| VS | Ujiba | 186.60d | 322.90d | 23.49ab | 27.74c | 4.13a | 15.50abc |
| | Macia | 82.30ab | 142.50ab | 30.79abc | 20.19b | 4.15a | 15.50abc |
| | PAN8816 | 93.50abc | 161.70ab | 24.77ab | 37.70d | 3.59a | 40.52e |
| RS | Ujiba | 71.10ab | 123.10ab | 17.77a | 12.13a | 3.73a | 17.50abc |
| | Macia | 43.10a | 74.50a | 26.11abc | 11.62a | 3.53a | 27.67bcde |
| | PAN8816 | 146.40cd | 253.30cd | 24.80abc | 19.68b | 4.08a | 13.50ab |
| YS | Ujiba | 79.80ab | 138.00ab | 16.40a | 18.94b | 3.31a | 23.77abcd |
| | Macia | 115.70bc | 200.30bc | 19.26a | 12.54a | 3.51a | 10.80a |
| | PAN8816 | 96.70abc | 167.30abc | 21.28ab | 19.62b | 3.39a | 20.38abcd |
| LSD$_{(P=0.05)}$ | | 55.32 | 95.30 | 15.60 | 5.74 | 0.811 | 13.46 |

Note that values sharing the same letter within the same column are statistically similar at LSD (P= 0.05) for the water regime *x* variety *x* time interaction. Var = Variety; Water = Water stress treatment.

## 4.3 Discussion

Plant water stress is generally defined as the condition where a plant's water potential and turgor are decreased sufficiently to inhibit normal plant function (Hsiao 1973). The effects of water stress depend on the severity and duration of the stress, the growth stage at which stress is imposed and the genotype of the plant (Kramer, 1983).

Results showed that water stress had an effect on plant growth since reduction in leaf number and plant height were observed when water stress was imposed. This was in agreement with studies done by Gudu et al. (2007) that showed that a reduction in leaf number and plant height of sorghum subjected to moisture stress. The reduction in these parameters could be attributed to low growth due to reduced photosynthetic ability. This was expected because dry matter production and accumulation in plant is mainly as a result of photosynthesis requires water. Any stress that reduces photosynthetic efficiency will reduce plant performance. The physiological responses of plants to a deficit of water include leaf rolling hence, a reduction in leaf area, stomata closure which directly interferes with carbon dioxide ($CO_2$) uptake for photosynthesis (Sanchez et al., 2002). Soil water deficit will therefore reduce overall plant growth.

According to Nayyar and Gupta (2006) water stress is can also cause changes in chlorophyll content. Chlorophyll content is an indicator of photosynthetic capacity of plant tissue. Cate and Perkins (2003) reported that CCI values were strongly correlated with chlorophyll concentration as determined by absorbance of extracted pigments. Hayatu and Mukhtar (2010) suggested that both moderate and severe water stress caused a reduction in the chlorophyll content. The result obtained in the current study were in agreement with reports by Hayatu and Mukhtar (2010).

The time to reach floral initiation, anthesis, yield formation and physiological maturity was affected by water stress. Imposing water stress at RS and YS significantly delayed the time to reach each growth stage. Furthermore, imposing water stress at RS and YS could result in yield reduction since both total biomass and panicle mass would be negatively affected. According to Narayanan (2007), if water deficit occurs at the vegetative stage (prior to booting) sorghum can become physiologically dormant without much reduction in yield. Water stress during the pre-flowering period in grain sorghum reduces grain yield significantly more than any other growth stage (Krieg, 1983). Post flowering water stress decreases seed filling duration, seed size and seed number leading to reduction in grain yield or even total crop loss (Mkhabela, 1995).

# CHAPTER 5

# SORGHUM SEED QUALITY IN RESPONSE TO DIFFERENT PREHARVEST WATER REGIMES

## 5.1 Introduction

Seed quality is critical to agricultural production; poor seed limits the potential yield and reduces productivity. Quality seed is defined as varietally pure with a high germination percentage, free from disease and disease organisms, and with proper moisture content and mass (Santos, 2010). Most subsistence farmers rely on local varieties for production of seed. Due to changing weather patterns, in South Africa most farmers have shifted from cultivating maize to more drought tolerant crops such as sorghum since there is reduction in maize yields under these periodic water stress (Africa Green Media, 2013). The crop is a self–pollinating plant and its drought tolerance is higher than that of maize (Fetene et al., 2011). Sorghum is reported to be the most important cereal for human consumption surpassed only by maize, wheat, rice and barley (Dicko et al., 2006). It is also reported to be one of the main staple food crops for the poorest and food insecure people (Timu et al., 2012). The crop is a cultivated cereal unique due to its tolerance to drought, water logging and saline-alkali infertile soils and high temperature (Taylor and Robbins, 1993). For a long time been it has been considered as a crop of the resource–poor small-scale farmers especially in South Africa (USAID, 2010). Generally, small-scale farmers practice rainfed agriculture therefore knowledge on the seed quality of seeds that are harvested from plants that were stressed at different growth stages will give valuable information. Furthermore, this will enable the farmers to be aware of the critical stages to water stress that will cause significant reduction in seed quality. In this study, the problem is that there is limited information in literature on the seed quality of local sorghum varieties such as PAN8816, Macia and Ujiba (local landrace).

According to Guei et al. (2013) smallholder farmers face several problems when the time comes to establish new crops. These challenges include a limited access to quality seeds. Most smallholder farmers living in drought prone regions continue to rely on drought relief and informal farmer-to-farmer exchange to obtain improved seed varieties. Smallholder farmers tend to prefer open–pollinated varieties and landraces compared to hybrids. Under these conditions, farmers often retain seed from the previous harvest in the next season. Whilst this saves money for the farmer by not purchasing seed yearly, yield losses may also occur if retained seed is of poor quality. Seed quality has been reported to be sensitive to production environment (Odindo, 2007). The fact that most subsistence farmers who cultivate sorghum reside in marginal production areas that are typically dry means that quality of retained seed may be compromised during dry years or if stress occurs at any stage of growth (FAO, 2012).

Good quality seed ensures good germination, rapid emergence and vigorous growth (Santos, 2010). When seed has good physical, physiological, health, and genetic qualities, farmers have greater prospects of producing a good crop (International Seed Testing Association, 1995). High quality seed is a major factor in obtaining a good crop stand and rapid plant development more especially under adverse water and rainfall conditions (FAO, 2006).

Farmers is rural areas who cultivate landraces typically recycle seed from the previous season for planting in the subsequent season. Due to the cost of hybrid seed, farmers often also recycle hybrid seed and in some cases some of these hybrids have been infused into local populations of landraces. The fact that sorghum is being promoted in dry areas suggests that maternal plants may be exposed to water stress during any stage of the crop growth. If such stress were to have a negative effect on subsequent seed quality, this would mean that farmers will be recycling seed of inferior quality hence risking low yields in the long–term. This study aimed to compare the seed quality of landrace (Ujiba), open-pollinated variety (Macia) and hybrid (PAN8816) harvested from plants grown under varying water regimes.

## 5.2 Results

### *5.2.1 Daily germination percentage*

Daily germination percentage showed that there were significant differences (P = 0.008) between the water regimes. The VS and RS water regimes had similar germination percentages (100%) (Figure 5.1). However, progeny form the YS water regime had a germination percentage of 90% and 80% which means imposing water stress at YS reduced the germination percentage (Figure 5.1). The progeny from YS took longer to germinate compared to progeny from the other water regimes. The Ujiba and PAN8816 only took 2 days to germinate. Progeny from the NS, VS and RS water regimes had the highest germination percentage (100%) compared to progeny from the

YS water regime which had the lowest germination percentage (80% and 90%), (Figure 5.1). There were highly significant differences ($P < 0.001$) between the varieties with respect to germination. For PAN8816 and Macia varieties, the time taken to reach final germination percentage was generally 8 days. With respect to the different varieties, the PAN8816 variety had a higher germination percentage (90% – 100%) compared to both Macia and Ujiba (80% – 100%). This trend was visible for all the varieties. The interaction between water regime and varieties was highly significant ($P < 0.001$). The Ujiba and Macia varieties had a germination percentage of 100% for progeny from the NS, VS and RS water regimes and 80% for progeny from the YS water regime (Figure 5.1). PAN8816 variety also had a germination percentage of 100% for progeny from the NS, VS and RS water regimes but had 90% for progeny from the YS water regime (Figure 5.1).

### *5.2.2 Germination vigour characteristics*

There were highly significant differences between the germination velocity index (GVI) amongst water regimes ($P < 0.001$). The GVI was reduced by imposing water stress at VS, RS and YS water regime compared to NS. This trend remained similar for all the varieties except for Ujiba and Macia at RS and VS water regime that were statistically similar. The seeds harvested under NS water regime had the faster germination rate (8) and RS water regimes had the least (5), (Table 5.1). The mean germination time (MGT) was also reduced by imposing water stress VS, RS and YS water regime compared to NS. The MGT maintained a similar trend as GVI for all the varieties. There were highly significant differences between the MGT amongst the water regimes ($P < 0.001$). The NS water regime had a highest MGT (7) and YS water regimes had the least (5) compared to all the other water regimes, (Table 5.1). Seedling length was not affected by different pre–harvest stress treatments ($P = 0.208$). The seeds harvested under NS water regime had longest seedlings (134 mm) and the YS water regime had the shortest seedlings (112 mm), (Table 5.1). The VS, RS and YS water regime showed a reduction in seedling length compared to NS water regime. The NS water regime maintained longer shoots compared to all water regimes followed by RS water regime then YS. The similar trend was observed for root: shoot and root length. There were no significant differences between the water regimes of the root length ($P = 0.535$) and shoot length ($P = 0.147$). Root: shoot ratio had no significant differences between the water regimes ($P = 0.659$). Dry mass of the different water regime was also not significant ($P =$

0.071). The dry mass of the seedling was observed to highest at NS water regime (1 g) and lowest at RS water regime (< 1 g).

There were highly significant differences between the GVI amongst varieties ($P < 0.001$). The PAN8816 variety maintains a highest GVI, followed by Ujiba the lastly Macia variety. GVI PAN8816 variety had the highest GVI on average (8) compared to both Macia (6) and Ujiba (6). Macia variety was observed to have the lowest GVI compared to all the varieties. The similar trend was observed for the MGT of all the varieties. The MGT amongst different varieties was also highly significant ($P < 0.001$). The PAN8816 variety had the highest MGT on average (7) compared to Macia (6) and Ujiba (6), (Table 5.1). Macia variety was observed to have the lowest MGT compared to all the varieties. The seedling length showed no differences between varieties ($P = 0.645$). The PAN8816 maintains highest seedling length compared to both Macia and Ujiba. There was no visible trend for this seedling length across the varieties. There were no significant differences between the varieties root length ($P = 0.757$) and shoot length ($P = 0.007$). Macia had the longer roots (83 mm) compared to PAN8816 (82 mm) and Ujiba (81 mm) (Table 5.1). However, the shoot length was longest for Ujiba (34 mm) compared to Macia (31 mm) and PAN8816 (30 mm). The similar trend was observed for the dry mass of the seedlings where the Ujiba variety had the highest mass (0.81 g) compared to PAN8816 (0.75 g) and Macia (0.79 g).

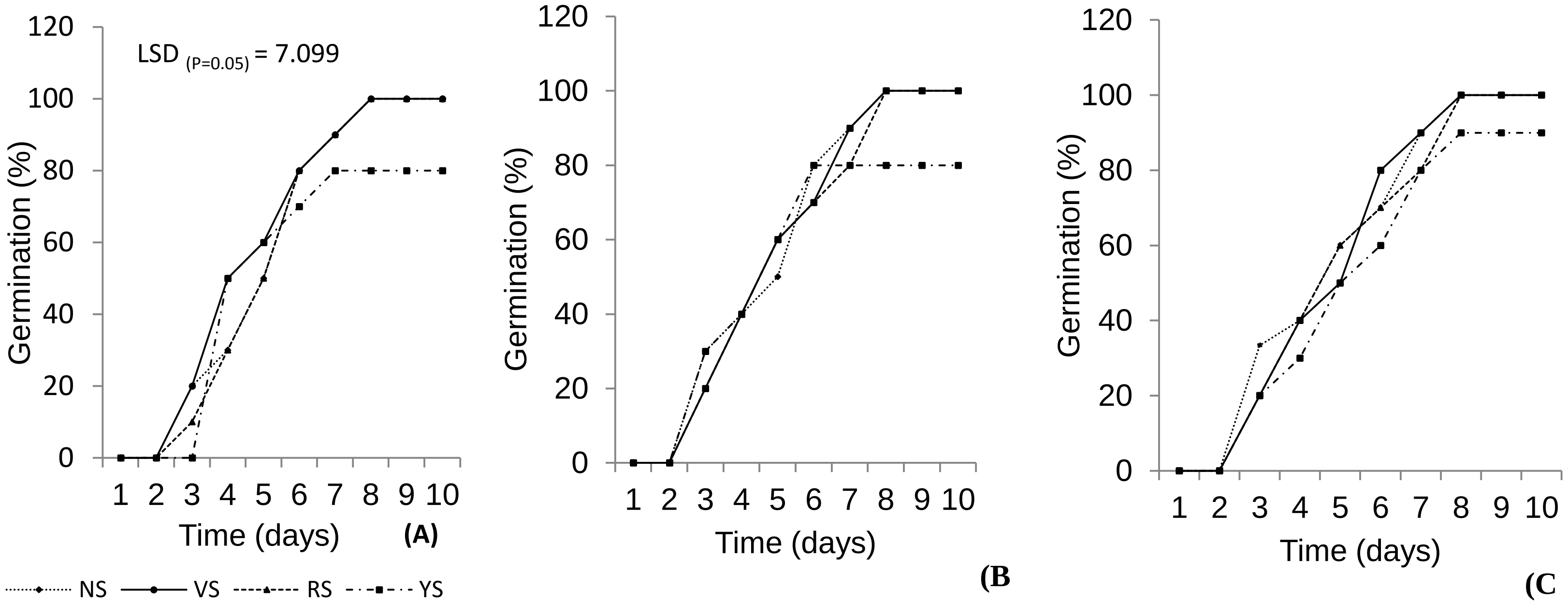

**Figure 5.1:** Daily germination of (A) Macia, (B) Ujiba and (C) PAN8816 with seed harvested from plants that had varying water regimes (NS, VS, RS and YS). NS = No stress; VS = Vegetative stress; RS = Reproductive stress and YS = Yield formation. The LSD value is for the interaction between water regimes *x* varieties *x* time.

**Table 5.1:** Performance of Macia, Ujiba and PAN8816 sorghum seeds harvested from plants subjected to varying water regimes (NS, VS, RS and YS) during a standard germination test.

| Water regime | Variety | Final Germination (%) | GVI | MGT (days) | Seedling length (mm) | Root length (mm) | Shoot length (mm) | Root: Shoot | Dry mass (g) |
|---|---|---|---|---|---|---|---|---|---|
| **NS** | PAN8816 | 100.00b | 9.07f | 7.73e | 120.50c | 85.40ab | 35.08cd | 2.44ab | 0.95a |
| | Macia | 100.00b | 6.96c | 6.749c | 164.40bc | 88.36b | 28.04ab | 3.23d | 1.02a |
| | Ujiba | 100.00b | 8.14d | 7.34de | 1170c | 83.65ab | 33.33bcd | 2.52abc | 1.11a |
| **VS** | PAN8816 | 100.00b | 8.59de | 7.67e | 118.50c | 84.43ab | 34.11cd | 2.48ab | 0.82a |
| | Macia | 100.00b | 6.53bc | 6.46bc | 112.40a | 76.35a | 26.03a | 2.95bcd | 0.91a |
| | Ujiba | 100.00b | 7.20c | 6.90cd | 113.90abc | 82.10ab | 31.78bc | 2.59abc | 0.93a |
| **RS** | PAN8816 | 100.00b | 6.96c | 6.84c | 109.40abc | 78.52ab | 29.55abc | 2.74bcd | 0.59a |
| | Macia | 100.00b | 4.55a | 5.19a | 113.70abc | 81.99ab | 31.67bc | 2.59abc | 0.59a |
| | Ujiba | 100.00b | 4.88a | 5.40a | 116.20bc | 83.26ab | 32.94bcd | 2.53abc | 0.61a |
| **YS** | PAN8816 | 90.00b | 5.95b | 6.09b | 103.40ab | 78.50ab | 24.87a | 3.16cd | 0.64a |
| | Macia | 80.00a | 5.04a | 5.40a | 119.30c | 84.82ab | 34.50cd | 2.47ab | 0.66a |
| | Ujiba | 80.00a | 4.87a | 5.40a | 113.80abc | 75.39a | 38.41d | 1.98aa | 0.61a |
| LSD$_{(P=0.05)}$ Water | | 3.08 | 0.49 | 0.26 | 6.63 | 2.91 | 1.40 | 0.09 | 0.33 |
| LSD$_{(P=0.05)}$ Var | | 2.67 | 0.42 | 0.22 | 5.74 | 2.52 | 1.22 | 0.08 | 0.29 |
| LSD$_{(P=0.05)}$Water*Var | | 5.33 | 0.44 | 0.44 | 11.48 | 5.05 | 2.43 | 0.16 | 0.58 |

**Var** = Varieties; **GVI** = Germination Velocity Index; **MGT** = Mean Germination Time. Mean separation was done using the LSD for the Water*variety interaction.

## 5.4 Discussion

Results obtained from the germination test for this study show that the water stress imposed at NS, VS, RS did not affect the germination percentage for all the varieties however, the stress imposed at YS showed a reduction in germination percentage. This could be because of the water stress that was imposed to the mother plant hence affecting the quality of the seeds. Turk et al. (2004) found that one of the reasons that can reduce, delay, or even prevent germination is water stress. Similarly, Ghassemi-Golezani et al. (1997) reported that water stress has no significant effect on seed quality of maize and sorghum, but it can considerably reduce seed yield. However, Ghassemi-Golezani et al. (1997) did not impose water stress at specific growth stages as was done for the current study; this may explain differences in results. Water stress is reported to decreases germination rate and seedling growth rate (Ahmad et al., 2011).

However, conditions are not always favourable for the seed to germinate. Good seed quality will result in good crop establishment hence high yields, this makes seed quality an essential tool for successful crop production (Mabhaudhi and Modi, 2011). The MGT was also reduced by imposing water stress VS, RS and YS water regime compared to NS. The MGT is the mean time the seedlot requires to initiate and end germination (Mabhaudhi and Modi, 2010). While the GVI is the rate, at which the seeds germinate. These parameters aid the farmer knowledge in terms of to be aware of the planning in terms of when to initiate necessary management practices especially under field conditions where most crops are vulnerable to birds.

Vigour parameters such as shoot length, root length, dry mass and fresh mass were affected by water stress. The seeds harvested under optimal conditions had a good performance in terms of their root and shoot length however, seed harvested under YS water regime have satisfactory performance. Studies by Almaghrabi (2012) were in agreement with results obtained that the reduction in the root length under drought stress may due to an impediment of cell division and elongation. Previous studies suggest that although seed lots may have similar performance under theoretically ideal laboratory conditions, performance may differ in the field under adverse conditions (Mazvimbakupa, 2014). Seed vigour considered as an important aspect in determining the physiological quality of seeds as it provides an indication of seed deterioration. Seed vigour testing does not only measure the percentage of viable seed in a sample, it also reflects the ability of those seeds to produce normal seedlings under less than optimum or adverse growing conditions similar to those which may occur in the field (Mabhaudhi and Modi, 2010). Generally, seeds start to lose vigour before they lose their ability to germinate hence PAN8816 has a good germinability but low vigour and vice versa for the Macia variety. Results indicate that Macia variety is the most vigorous compared to all the varieties. Even though farmers especially subsistence farmers prefer landraces and open pollinated varieties compared to hybrids due to their expense.

# CHAPTER 6

# DETERMINATION OF SORGHUM CROP WATER PRODUCTIVITY UNDER CONTROLLED ENVIRONMENTAL CONDITIONS

## 6.1 Introduction

South Africa is a water scarce country where the demand for water exceeds natural water availability in several river basins. Agriculture consumes 60 – 62% of freshwater resources; this suggests that there is a need to increase crop water productivity in order to increase yields without using more water (Smith, 2000; Geerts et al., 2008). Crop water productivity is defined as the ratio of the physical yield of a crop and the amount of water consumed (Ahmad, 2004). Improvements in crop water productivity are a potential way to achieve this and will be an important strategy for agricultural water management in the future (Kijne et al., 2003). Currently, farmers are experiencing the challenge of having to produce more food using less water. The concept of crop water productivity thus becomes a valuable tool in addressing this problem (Ahmad, 2004). Furthermore, there is limited information reporting the water productivity of South African varieties and how they compare in terms of their water use.

The majority of people living in dry lands, especially in food insecure areas, rely on rainfed agriculture; here drought is one of the major constraints to crop production (ICRISAT, 2007). Sorghum is therefore crucial to household food security as it is uniquely drought and heat tolerant compared to many cereal crops. Sorghum remains one of the cereals that serve as a staple food for people living in poor and food insecure areas (Vilakati, 2009). Crop water productivity addresses the objective of producing more food or gaining more benefits with less water used. Water productivity should be improved to meet the rising demand for food from a growing population. The increasing pressures on water resources, climate change, and increasing demands for food and fibre make it is essential that the world succeeds in producing more food with less water (Vorosmarty, 2010). This could be possibly be accomplished by knowing the crop water productivity of local varieties. The objective of this study was to determine crop water productivity of different sorghum varieties.

## 6.2 Results

### *6.2.1 Crop growth*

#### *6.2.1.1 Leaf area*

Leaf area was shown to vary significantly ($P = 0.041$) among the three varieties (Figure 6.1). PAN8816 had larger leaf area with the maximum leaf area being 3000 $cm^2$ compared to Macia (2500 $cm^2$) and Ujiba (2200 $cm^2$), respectively. Results showed that leaf area, for all varieties, increased up to 63 days after planting (DAP). Thereafter, a sharp decline was observed for PAN8816 and the Ujiba landrace. Although Macia had smaller leaf area than PAN8816 and Ujiba, it was shown to be able to maintain leaf area for longer than the other two varieties. A sharp decline in leaf area of Macia was only observed at 91 DAP relative to 77 DAP observed for PAN8816 and Ujiba (Figure 6.1).

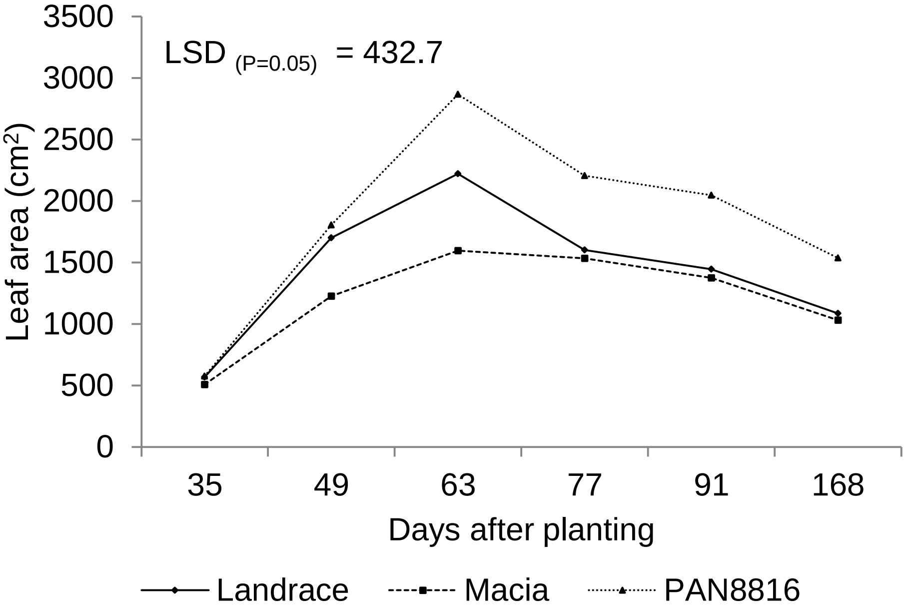

**Figure 6.1:** Leaf area (cm2) of sorghum varieties (PAN8816, Ujiba and Macia) measured at fortnightly intervals up to harvest. The LSD value is for means of varieties.

### *6.2.2 Crop water productivity and transpiration*

#### *6.2.2.1 Transpiration*

There were significant differences ($P < 0.001$) between sorghum varieties with respect to water transpired (Figure 6.2). PAN8816 and Ujiba had an increase in transpiration; however, Macia showed no increase and remained constant (Figure 6.2). At harvest, 168 DAP, for all varieties the transpiration decreased due to reduction in green leaf area due to leaf senescence. The total water use for each variety was PAN8816 (813 mm), Ujiba (803 mm) and Macia (740 mm) (Table 6.1). PAN8816 maintained more leaves, followed by Ujiba and Macia, respectively; the canopy size and duration may explain the differences in levels of measured water use.

#### *6.2.2.2 Biomass*

There were no significant differences ($P = 0.221$) between sorghum varieties for biomass (Figure 6.3). Results showed that, for all varieties, after 42 DAP there was an increase in biomass. Biomass increased over time for all the varieties. At 168 DAP PAN8816 had fresh mass of 220 g, followed by Macia with 210 g and Ujiba 196 g, respectively (Figure 5.3 and Table 5.1). This trend was also observed for dry mass where PAN8816 (152 g) > Macia (146 g) > Ujiba (130 g) (Figure 6.3).

#### *6.2.2.4 Panicle mass*

There were no significant differences ($P = 0.981$) between the panicle fresh mass of PAN8816, Ujiba and Macia varieties (Figure 6.5). However, at 168 DAP, PAN8816 had greater fresh mass (57 g) compared to Ujiba (55 g) and Macia (49 g), respectively (Figure 5.5 and Table 5.1). This was with seed mass hence the more seeds that each panicle comprised the higher the panicle mass. There were also no significant differences ($P = 0.08$) between the panicle dry mass of PAN8816, Ujiba and Macia varieties. At 168 DAP, the Ujiba landrace had greater dry mass (29 g) compared to PAN8816 (28 g) and Macia (26 g), respectively. Both panicle fresh and dry mass increased over time (Figure 6.5).

*6.2.2.5 Seed mass*

There were significant differences ($P < 0.001$) between the seed mass of PAN8816, Ujiba and Macia varieties. The PAN8816 variety had higher seed mass (35 g) compared to Ujiba (14 g) and Macia (15 g), respectively (Figure 6.6).

*6.2.2.3 Water productivity*

There were no significant differences ($P = 0.182$) in water productivity of the three sorghum varieties (PAN8816, Macia and Ujiba). At harvest, the water productivity for PAN8816, Ujiba and Macia were 7891 g $m^{-3}$, 7211 g $m^{-3}$ and 5695 g $m^{-3}$, respectively (Table 6.1). This trend was consistent with the trend in water use (transpiration) whereby PAN8816 used more water compared to Ujiba and Macia, respectively (Table 6.1).

*6.2.2.6 Harvest index*

There were no significant differences ($P = 0.339$) between the sorghum varieties with respect to harvest index the harvest index (HI) (Figure 6.7). PAN8816 had a higher HI (34%) compared to Macia (33%) and Ujiba (27%), respectively.

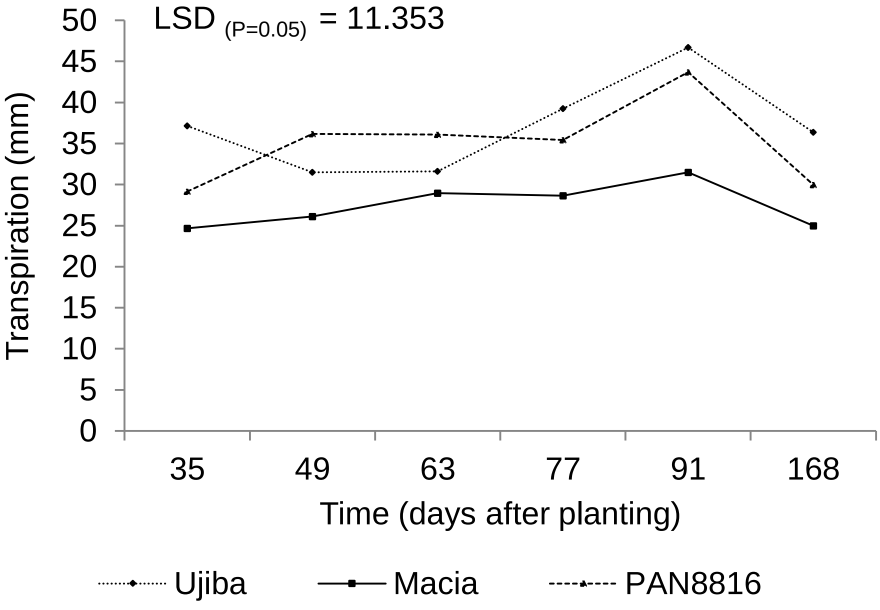

**Figure 6.2:** Crop water use (transpiration) of three sorghum varieties (PAN8816, Macia and Ujiba) measured every fortnight The LSD value is for means of varieties.

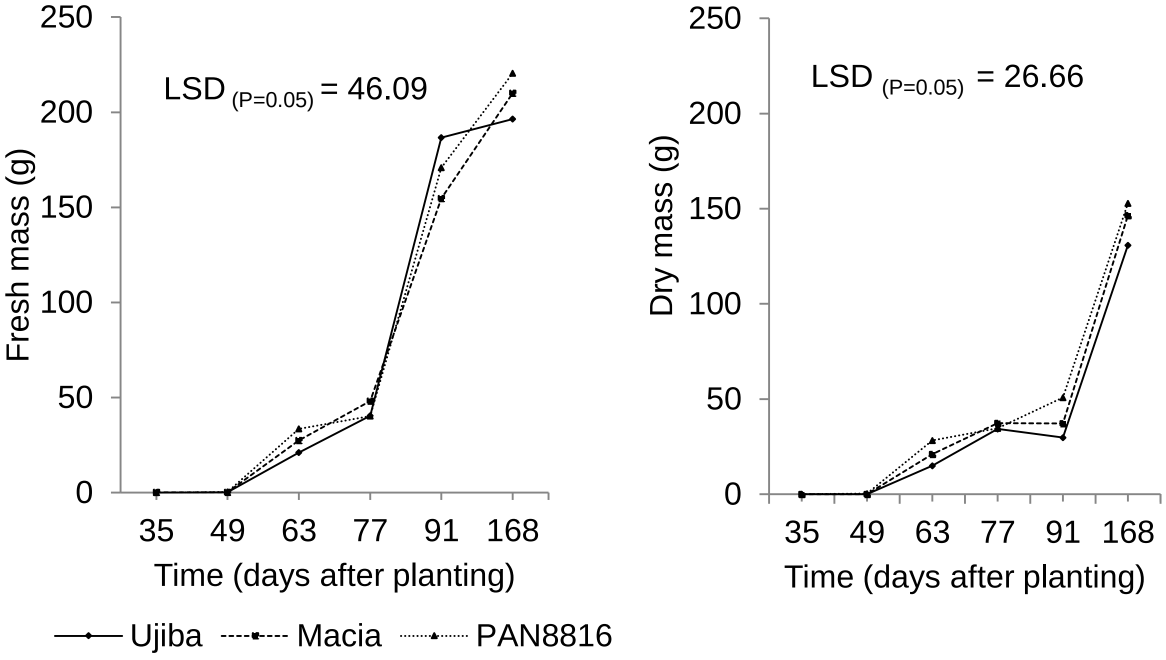

**Figure 6.3:** Fresh and dry mass of three sorghum varieties (PAN8816, Ujiba and Macia) measured every fortnight from destructive sampling. LSD values are for means of varieties.

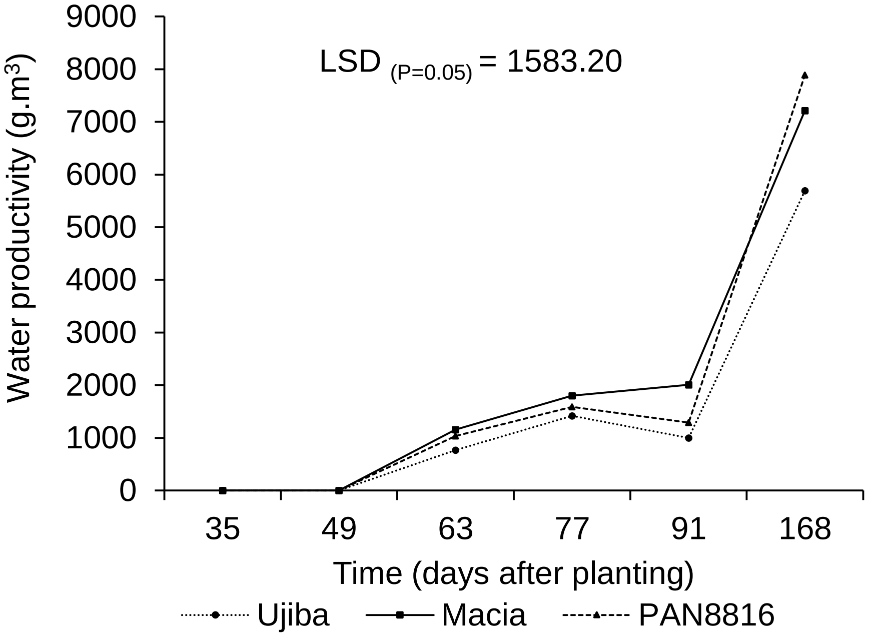

**Figure 6.4:** Crop water productivity of three sorghum varieties (Macia, PAN8816 and Ujiba) measured every fortnight from destructive sampling. LSD values are for means of varieties.

**Table 6.1:** The total above ground biomass, panicle mass and water productivity at harvest of the three sorghum varieties (PAN8816, Macia and Ujiba).

| **Varieties** | **Fresh biomass (g)** | **Dry biomass (g)** | **Water productivity ($g\ m^{-3}$)** | **Water use (mm)** |
|---|---|---|---|---|
| **Ujiba** | 196.40 | 130.90 | 5695.00 | 803.00 |
| **Macia** | 210.40 | 146.40 | 7211.00 | 740.00 |
| **PAN8816** | 220.30 | 152.90 | 7891.00 | 813.00 |
| **LSD$_{(P=0.05)}$** | 46.09 | 26.66 | 1583.20 | 104.90 |

*The LSD value is for means of varieties.

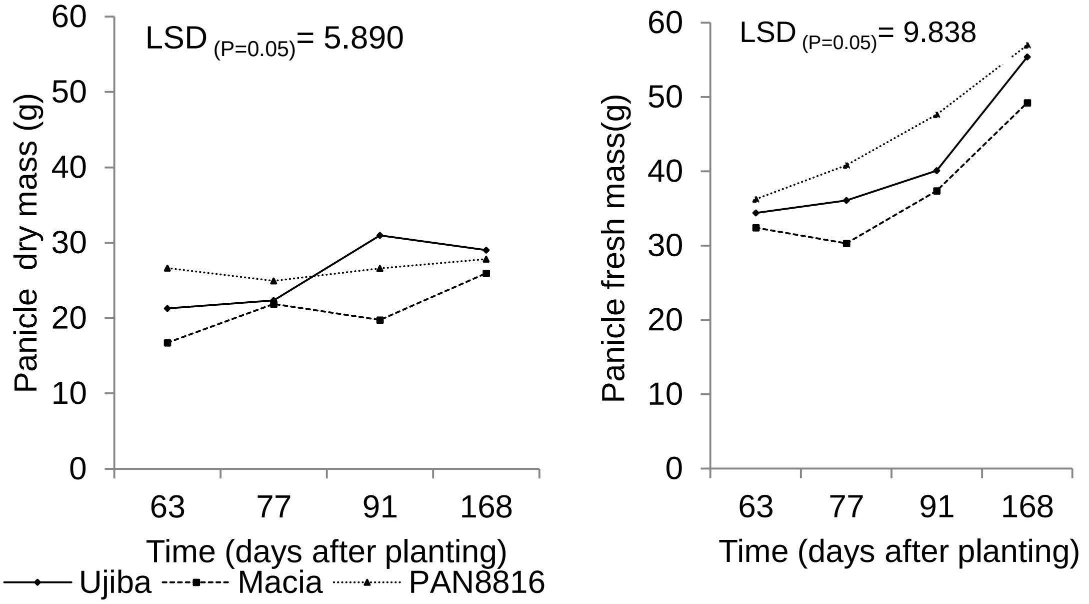

**Figure 6.5:** Fresh and dry panicle mass of three sorghum varieties (PAN8816, Ujiba and Macia) measured every fortnight from destructive sampling. LSD values are for means of varieties.

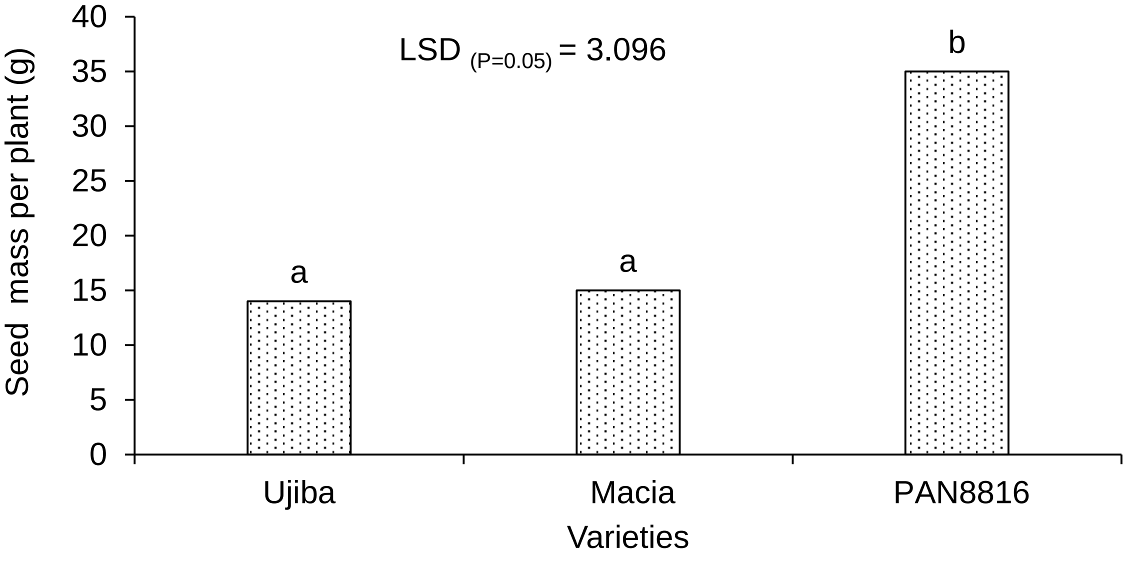

**Figure 6.6:** Seed mass of three sorghum varieties (PAN8816, Ujiba and Macia). LSD values are for means of varieties.

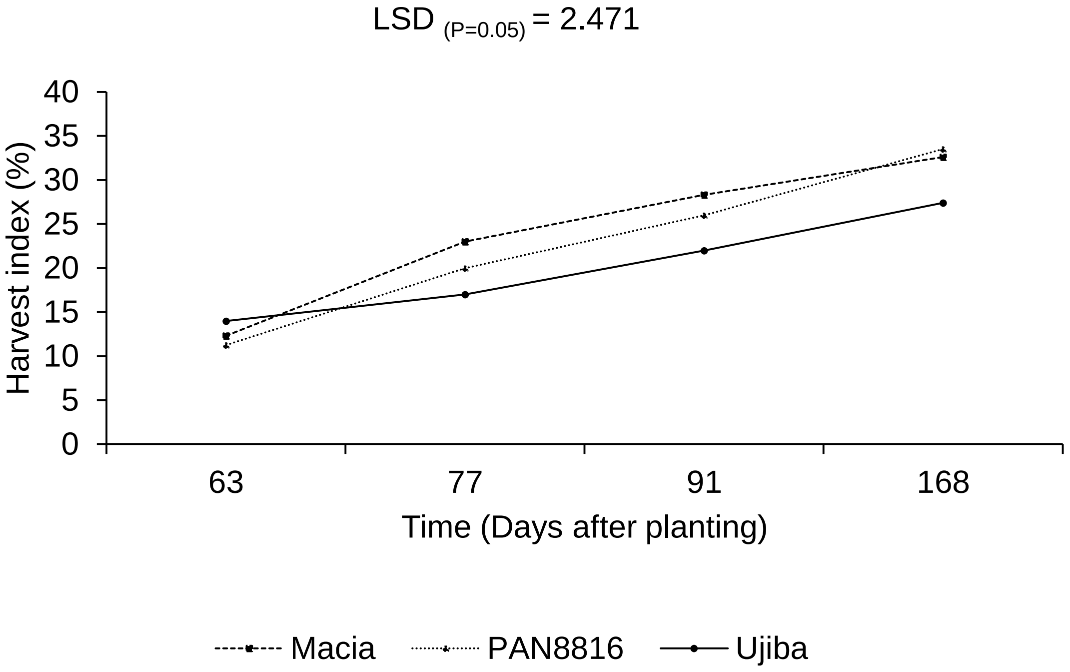

**Figure 6.7:** Harvest index build up and final harvest index of three sorghum varieties (PAN8816, Ujiba and Macia) measured every fortnight from destructive sampling. LSD values are for means of varieties.

## 6.3 Discussion

Crop water productivity depends on the reliability and quality of irrigation water applied in addition to control over water delivery. Improved reliability can ensure better timing of irrigation to ensure crop growth needs (Meinzen-Dick, 1995).

Results of the current study showed that Macia had smaller leaf area than PAN8816 and Ujiba. However, Macia was shown to be able to maintain leaf area for longer than the other two varieties. Tewolde et al. (2005) identified leaf area as the key parameter in the analysis of crop growth and productivity. However, in this study, high leaf did not necessarily result in higher panicle mass. Dry matter production increased with leaf area and reached maximum at optimum leaf area beyond which yield did not increase. This is because net canopy photosynthesis cannot increase indefinitely with leaf area due to mutual shading of leaves within the canopy (Fageria et al., 2006). More leaves can be attributed to bigger surface area and more leaf gas exchange hence more water that is transpired hence PAN8816 which had higher leaf area had correspondingly higher water use.

Results show that there were no difference between the crop water productivity of these for varieties. The water productivity in this study for PAN8816, Ujiba and Macia were 7891 g $m^{-3}$, 7211 g $m^{-3}$ and 5695 g $m^{-3}$ respectively. Studies done by Mengistu et al. (2009) report that the water productivity values for sweet sorghum was 6.20 kg $m^{-3}$ and 9.59 kg $m^{-3}$ for different two seasons which is on similar range with findings in the current study. This could be attributed to the similar conditions in which the crop was grown hence no differences were observed in biomass. Under unlimited water resources the farmer has no incentive to save on irrigation water. In this case full crop water requirement is applied to produce maximum yield with lower water productivity (Owesis, 2000). When water is not enough to provide full irrigation for the whole farm, the farmer has two options: to irrigate part of the farm with full irrigation leaving the other part rainfed or to apply deficit supplemental irrigation to the whole farm (Owesis, 2000). Hence that could help the farmer to productively use the available water.

# CHAPTER 7

# GENERAL DISCUSSION AND CONCLUSION

## 7.1 Introduction

Sorghum remains a basic staple food for many rural communities. This is true especially in the more drought prone areas of South Africa where this hardy crop provides better household food security than maize. Identifying crops that are capable of withstanding periods of erratic rainfall could be a possible solution. Sorghum is reported to be drought tolerant and has the ability to produce reasonable yields under water stress condition. This study focussed on sorghum, not only as a part of the solution to improve water use. It also provides knowledge in terms of the South African varieties' responses to water stress imposed at different growth sages (NS, VS, RS and YS).

## 7.2 Challenges

The following challenges were encountered in this study;

- Plants were attacked by aphids and some were attacked by head smut disease. This was controlled by spraying Malathion®, an insecticide.
- Low temperatures caused the growth period of the crop to be longer than recommended, though the study was conducted in a controlled environment research unit.

## 7.4 Future Teaching, Learning and Research Possibilities

The following recommendations may be made pertaining the observations made during the study;

- The destructive sampling intervals could be done weekly so that harvest index build up could be made for each phenological event.
- Farmers should be encouraged to submit their seeds to registered seed laboratories for quality testing so as to encourage good crop establishment.

- The development of integrated seed systems that support local landraces would lead to the availability of good quality seed and prices affordable to subsistence farmers.

### 7.5 Final comments and summary conclusions

Plant water stress is generally defined as the condition where a plant’s water potential and turgor are decreased sufficiently to inhibit normal plant function. Plant water stress can affect many physiological and morphological plant characteristics and the response of a plant to these is dependent on the intensity, duration and stage of growth to which the water stress is imposed. Results of Chapter 4 showed that water stress had a negative effect on plant growth since a reduction in leaf number and plant height was observed when water stress was imposed. Ujiba, which is a local landrace variety, performed better than the other varieties under water stress. The results also showed that the seed quality of the seeds that imposing water stress during the reproductive and yield formation stages not only lowered yields but also negatively affected subsequent seed quality.

The reproductive and yield formation growth stages were especially sensitive to water stress while the vegetative stage was less sensitive. This concurred with reports in the literature that the literature (Yared et al., 2010). Even the seeds harvested from mother plants that were subjected to water stress at these stages showed a reduction in seed quality parameters.

Chapter 5 focussed on the water productivity of these varieties. Results showed that there were no statistical differences although the PAN8816 hybrid generally had better water productivity that Ujiba and Macia.

Chapter 6 evaluated the effect of water stress on the maternal plant on subsequent seed quality. This study was of interest because farmers often recycle seed due to the unaffordability of hybrid seeds. Results confirmed that water stress imposed at any growth stage could have a negative effect on subsequent seed quality. Water stress imposed at the reproductive and yield formation stages had the greatest effect on subsequent seed quality. This suggests that farmers residing in marginal areas should be discouraged from recycling seeds and that proper seed systems should be established for the supply of good quality landrace seed at affordable prices.

In conclusion, water stress imposed at yield formation and reproductive stage resulted in significant yield reduction for Ujiba, Macia and PAN8816. Under water stress, all sorghum varieties demonstrated phenological plasticity. In terms of overall performance, PAN8816 and Ujiba performed well compared to Macia; this can be attributed to their smaller canopy size and ability to maintain high levels of chlorophyll content. This suggests that Ujiba and PAN8816 may be suitable for farming under resource poor farming systems where these advantages enable them to produce reasonable yields. In addition, this also highlights that local landraces still remain an important germplasm resource that should be used for future crop improvement.

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# APPENDICES

## Appendix 1: Chapter 4 ANOVA’S

***Variate: swc_mm***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 74.20 | 37.10 | 1.51 | |
| Rep.*Units* stratum | | | | | |
| Water_Trt | 3 | 60823.03 | 20274.34 | 827.52 | 0.093 |
| Variety | 2 | 4566.14 | 2283.07 | 93.19 | 0.061 |
| DAP | 20 | 98440.89 | 4922.04 | 200.90 | <.001 |
| Water_Trt.Variety | 6 | 670.77 | 111.79 | 4.56 | <.001 |
| Water_Trt.DAP | 60 | 22076.22 | 367.94 | 15.02 | <.001 |
| Variety. DAP | 40 | 5021.79 | 125.54 | 5.12 | <.001 |
| Water_Trt.Variety. DAP | 120 | 11884.71 | 99.04 | 4.04 | <.001 |
| Residual | 502 | 12299.13 | 24.50 | | |
| Total | 755 | 215856.88 | | | |

***Variate: Transpiration_mm***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 139.57 | 69.79 | 3.27 | |
| Rep.*Units* stratum | | | | | |
| Water_Trt | 3 | 37181.78 | 12393.93 | 580.16 | <.001 |
| Variety | 2 | 3997.14 | 1998.57 | 93.55 | 0.121 |
| DAP | 20 | 112273.77 | 5613.69 | 262.78 | <.001 |
| Water_Trt.Variety | 6 | 548.43 | 91.41 | 4.28 | <.001 |
| Water_Trt.DAP | 60 | 8262.23 | 137.70 | 6.45 | <.001 |
| Variety.DAP | 40 | 3834.64 | 95.87 | 4.49 | <.001 |
| Water_Trt.Variety.DAP | 120 | 5093.42 | 42.45 | 1.99 | 0.141 |
| Residual | 502 | 10724.16 | 21.36 | | |
| Total | 755 | 182055.15 | | | |
| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
| Rep stratum | 2 | 163.25 | 81.63 | 0.95 | |

***Variate: Plant height***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 2762.64 | 1381.32 | 22.19 | |
| Rep.*Units* stratum | | | | | |
| Water_Trt | 3 | 24183.46 | 8061.15 | 129.49 | <.001 |
| Variety | 2 | 100891.58 | 50445.79 | 810.30 | <.001 |
| DAP | 20 | 520312.81 | 26015.64 | 417.89 | <.001 |
| Water_Trt.Variety | 6 | 6503.82 | 1083.97 | 17.41 | <.001 |
| Water_Trt.DAP | 60 | 7310.47 | 121.84 | 1.96 | <.001 |
| Variety.DAP | 40 | 41547.49 | 1038.69 | 16.68 | <.001 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Water_Trt.Variety.DAP | 120 | 2719.55 | 22.66 | 0.36 | 1.000 |
| Residual | 502 | 31252.19 | 62.26 |  |  |
| Total | 755 | 737484.03 |  |  |  |

***Variate: leaf_number***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 13.1032 | 6.5516 | 24.87 |  |
| Rep.*Units* stratum |  |  |  |  |  |
| Water_Trt | 3 | 238.0952 | 79.3651 | 301.30 | <.001 |
| Variety | 2 | 92.0079 | 46.0040 | 174.65 | <.001 |
| DAP | 20 | 2166.5000 | 108.3250 | 411.25 | <.001 |
| Water_Trt.Variety | 6 | 31.7381 | 5.2897 | 20.08 | <.001 |
| Water_Trt.DAP | 60 | 282.7381 | 4.7123 | 17.89 | <.001 |
| Variety.DAP | 40 | 70.9921 | 1.7748 | 6.74 | <.001 |
| Water_Trt.Variety.DAP | 120 | 95.2619 | 0.7938 | 3.01 | <.001 |
| Residual | 502 | 132.2302 | 0.2634 |  |  |
| Total | 755 | 3122.6667 |  |  |  |

***Variate: CCI***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 2052.96 | 1026.48 | 27.21 |  |
| Rep.*Units* stratum |  |  |  |  |  |
| Water_Trt | 3 | 7673.04 | 2557.68 | 67.79 | <.001 |
| Variety | 2 | 1811.63 | 905.81 | 24.01 | <.001 |
| DAP | 20 | 38556.98 | 1927.85 | 51.10 | <.001 |
| Water_Trt.Variety | 6 | 2494.97 | 415.83 | 11.02 | <.001 |
| Water_Trt.DAP | 60 | 20224.83 | 337.08 | 8.93 | <.001 |
| Variety.DAP | 40 | 1698.90 | 42.47 | 1.13 | 0.280 |
| Water_Trt.Variety.DAP | 120 | 6772.59 | 56.44 | 1.50 | 0.002 |
| Residual | 502 | 18939.29 | 37.73 |  |  |
| Total | 755 | 100225.20 |  |  |  |

***Variate: total above ground dry mass***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 3560. | 1780. | 1.67 |  |
| Rep.*Units* stratum |  |  |  |  |  |
| Water_Trt | 3 | 10200. | 3400. | 3.19 | 0.044 |
| Variety | 2 | 4099. | 2050. | 1.92 | 0.170 |
| Water_Trt.Variety | 6 | 34855. | 5809. | 5.44 | 0.001 |
| Residual | 22 | 23480. | 1067. |  |  |
| Total | 35 | 76194. |  |  |  |

***Variate: total above ground fresh mass***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Rep stratum | 2 | 434.7 | 217.4 | 0.28 | |
| Rep.*Units* stratum | | | | | |
| Variety | 2 | 116.4 | 58.2 | 0.08 | 0.927 |
| DAP | 5 | 382064.0 | 76412.8 | 99.03 | <.001 |
| Variety.DAP | 10 | 2910.8 | 291.1 | 0.38 | 0.948 |
| Residual | 34 | 26234.3 | 771.6 | | |
| Total | 53 | 411760.3 | | | |

***Variate: 100_seed_weight***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 0.0618 | 0.0309 | 0.13 | |
| Rep.*Units* stratum | | | | | |
| Water_Trt | 3 | 2.0921 | 0.6974 | 3.04 | 0.051 |
| Variety | 2 | 0.0247 | 0.0124 | 0.05 | 0.948 |
| Water_Trt.Variety | 6 | 1.3513 | 0.2252 | 0.98 | 0.461 |
| Residual | 22 | 5.0497 | 0.2295 | | |
| Total | 35 | 8.5797 | | | |

***Variate: Days_to_Emergence***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 0.2222 | 0.1111 | 0.38 | |
| Rep.*Units* stratum | | | | | |
| Water_trt | 3 | 1.6389 | 0.5463 | 1.86 | 0.165 |
| Variety | 2 | 3.3889 | 1.6944 | 5.78 | 0.010 |
| Water_trt.Variety | 6 | 6.6111 | 1.1019 | 3.76 | 0.010 |
| Residual | 22 | 6.4444 | 0.2929 | | |
| Total | 35 | 18.3056 | | | |

***Variate: Days_to_vegetative_stage***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep stratum | 2 | 8.72 | 4.36 | 0.43 | |
| rep.*Units* stratum | | | | | |
| Water_trt | 3 | 4.75 | 1.58 | 0.16 | 0.925 |
| Variety | 2 | 85.06 | 42.53 | 4.18 | 0.029 |
| Water_trt.Variety | 6 | 54.50 | 9.08 | 0.89 | 0.517 |
| Residual | 22 | 223.94 | 10.18 | | |
| Total | 35 | 376.97 | | | |

***Variate: Days_to_end_of_Juvenile_phase***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 14.22 | 7.11 | 0.66 | |
| Rep.*Units* stratum | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Water_trt | 3 | 2.67 | 0.89 | 0.08 | 0.969 |
| Variety | 2 | 104.22 | 52.11 | 4.85 | 0.068 |
| Water_trt.Variety | 6 | 62.00 | 10.33 | 0.96 | 0.473 |
| Residual | 22 | 236.44 | 10.75 | | |
| Total | 35 | 419.56 | | | |

***Variate: Days_to_floral_intiation***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 4.389 | 2.194 | 0.35 | |
| Rep.*Units* stratum | | | | | |
| Water_trt | 3 | 185.639 | 61.880 | 9.85 | <.001 |
| Variety | 2 | 29.556 | 14.778 | 2.35 | 0.119 |
| Water_trt.Variety | 6 | 74.444 | 12.407 | 1.97 | 0.113 |
| Residual | 22 | 138.278 | 6.285 | | |
| Total | 35 | 432.306 | | | |

***Variate: Days_to_anthesis***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep stratum | 2 | 2.056 | 1.028 | 0.20 | |
| rep.*Units* stratum | | | | | |
| Variety | 2 | 31.722 | 15.861 | 3.04 | 0.068 |
| Water_trt | 3 | 77.111 | 25.704 | 4.93 | 0.009 |
| Variety.Water_trt | 6 | 64.056 | 10.676 | 2.05 | 0.102 |
| Residual | 22 | 114.611 | 5.210 | | |
| Total | 35 | 289.556 | | | |

***Variate: Days_to_flowering***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep stratum | 2 | 4.222 | 2.111 | 0.52 | |
| rep.*Units* stratum | | | | | |
| Water_trt | 3 | 314.972 | 104.991 | 25.73 | <.001 |

```
Variety                      2      12.722      6.361    1.56   0.233
Water_trt.Variety            6     235.278     39.213    9.61   <.001
Residual                    22      89.778      4.081

Total                       35     656.972
```

***Variate: Days_to_yeild_formation***

```
Source of variation       d.f.        s.s.       m.s.    v.r.   F pr.

rep stratum                  2       5.389      2.694    0.28

rep.*Units* stratum
Water_trt                    3     645.861    215.287   22.21   <.001
Variety                      2      52.056     26.028    2.68   0.091
Water_trt.Variety            6     501.056     83.509    8.61   <.001
Residual                    22     213.278      9.694

Total                       35    1417.639
```

***Variate: Physiological maturity***

```
Source of variation       d.f.        s.s.       m.s.    v.r.   F pr.

rep stratum                  2      509.35     254.67    4.40

rep.*Units* stratum
Water_trt                    3     1659.52     553.17    9.55   <.001
Variety                      2      816.76     408.38    7.05   0.004
Water_trt.Variety            6      328.79      54.80    0.95   0.483
Residual                    22     1274.49      57.93

Total                       35     4588.91
```

***Variate: biomassyeild***

```
Source of variation       d.f.        s.s.       m.s.    v.r.   F pr.

Rep stratum                  2      10662.      5331.    1.67

Rep.*Units* stratum
Variety                      2      12276.      6138.    1.92   0.170
Water_Trt                    3      30543.     10181.    3.19   0.044
```

```
Variety.Water_Trt            6      104372.       17395.     5.44   0.001
Residual                    22       70310.        3196.

Total                       35      228162.
```

### *Variate: harvest index*

```
Source of variation       d.f.         s.s.         m.s.     v.r.   F pr.

Rep stratum                  2      0.07201      0.03600     0.77

Rep.*Units* stratum
Water_Trt                    3      0.48274      0.16091     3.42   0.035
Variety                      2      0.63483      0.31741     6.75   0.005
Water_Trt.Variety            6      0.84455      0.14076     2.99   0.027
Residual                    22      1.03438      0.04702

Total                       35      3.06851
```

### *Variate: seed mass*

```
Source of variation       d.f.         s.s.         m.s.     v.r.   F pr.

Rep stratum                  2        39.19        19.59     1.71

Rep.*Units* stratum
Water_Trt                    3      1630.28       543.43    47.36   <.001
Variety                      2       871.04       435.52    37.96   <.001
Water_Trt.Variety            6       211.88        35.31     3.08   0.024
Residual                    22       252.42        11.47

Total                       35      3004.81
```

### *Variate:Total biomass*

```
Source of variation       d.f.         s.s.         m.s.     v.r.   F pr.

Rep stratum                  2       10662.        5331.     1.67
```

```
Rep.*Units* stratum
Variety                      2      12276.       6138.     1.92   0.170
Water_Trt                    3      30543.      10181.     3.19   0.044
Variety.Water_Trt            6     104372.      17395.     5.44   0.001
Residual                    22      70310.       3196.

Total                       35     228162.
```

***Variate: Ky***

```
Source of variation       d.f.        s.s.        m.s.     v.r.   F pr.

REP stratum                  2      1.1721      0.5861     2.51

REP.*Units* stratum
water_treatment              2     13.9775      6.9888    29.90   <.001
Variety                      2      0.4181      0.2090     0.89   0.428
water_treatment.Variety
                             4      0.2906      0.0727     0.31   0.866
Residual                    16      3.7393      0.2337

Total                       26     19.5976
```

## Appendix 2: Chapter 5 ANOVAS

### ***Variate: Germination***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep stratum | 2 | 32.32 | 16.16 | 0.37 | |
| rep.*Units* stratum | | | | | |
| Variety | 2 | 135.35 | 67.68 | 1.55 | 0.219 |
| days | 9 | 140345.96 | 15594.00 | 358.09 | <.001 |
| Variety.days | 18 | 497.98 | 27.67 | 0.64 | 0.859 |
| Residual | 67 | 2917.68 | 43.55 | | |
| Total | 98 | 143929.29 | | | |

### ***Variate: GVI***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep stratum | 2 | 0.3383 | 0.1691 | 0.68 | |
| rep.*Units* stratum | | | | | |
| Water_trt | 3 | 52.3757 | 17.4586 | 70.39 | <.001 |
| Variety | 2 | 22.5579 | 11.2790 | 45.47 | <.001 |
| Water_Trt.Variety | 6 | 3.0477 | 0.5080 | 2.05 | 0.102 |
| Residual | 22 | 5.4566 | 0.2480 | | |
| Total | 35 | 83.7763 | | | |

### ***Variate: MGT***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep stratum | 2 | 0.13776 | 0.06888 | 1.01 | |
| rep.*Units* stratum | | | | | |
| Water_trt | 3 | 18.58941 | 6.19647 | 91.06 | <.001 |
| Variety | 2 | 8.24255 | 4.12128 | 60.56 | <.001 |
| Water_trt.Variety | 6 | 1.29265 | 0.21544 | 3.17 | 0.022 |
| Residual | 22 | 1.49706 | 0.06805 | | |
| Total | 35 | 29.75944 | | | |

### ***Variate: shoot_length***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep stratum | 2 | 16.848 | 8.424 | 0.95 | |
| rep.*Units* stratum | | | | | |
| Water_trt | 3 | 19.915 | 6.638 | 0.75 | 0.535 |
| Variety | 2 | 109.893 | 54.947 | 6.19 | 0.007 |
| Water_trt.Variety | 6 | 383.578 | 63.930 | 7.20 | <.001 |
| Residual | 22 | 195.286 | 8.877 | | |
| Total | 35 | 725.520 | | | |

***Variate: root_length***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep stratum | 2 | 16.848 | 8.424 | 0.95 | |
| rep.*Units* stratum | | | | | |
| Water_trt | 3 | 19.915 | 6.638 | 0.75 | 0.535 |
| Variety | 2 | 109.893 | 54.947 | 6.19 | 0.007 |
| Water_trt.Variety | 6 | 383.578 | 63.930 | 7.20 | <.001 |
| Residual | 22 | 195.286 | 8.877 | | |
| Total | 35 | 725.520 | | | |

***Variate: root to shoot***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep stratum | 2 | 0.014529 | 0.007264 | 0.74 | |
| rep.*Units* stratum | | | | | |
| Water_trt | 3 | 0.013632 | 0.004544 | 0.46 | 0.710 |
| Variety | 2 | 0.119857 | 0.059929 | 6.12 | 0.008 |
| Water_trt.Variety | 6 | 0.426704 | 0.071117 | 7.26 | <.001 |
| Residual | 22 | 0.215360 | 0.009789 | | |
| Total | 35 | 0.790083 | | | |

***Variate: dry_weight***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep stratum | 2 | 0.4876 | 0.2438 | 2.07 | |
| rep.*Units* stratum | | | | | |
| Water_trt | 3 | 0.9485 | 0.3162 | 2.69 | 0.071 |
| Variety | 2 | 0.0214 | 0.0107 | 0.09 | 0.913 |
| Water_trt.Variety | 6 | 0.0439 | 0.0073 | 0.06 | 0.999 |
| Residual | 22 | 2.5856 | 0.1175 | | |
| Total | 35 | 4.0871 | | | |

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## Appendix 3: Chapter 6 ANOVA’S

***Variate: Leaf area***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep Stratum | 2 | 251076. | 125538. | 1.85 | |
| Rep.*Units* Stratum | | | | | |
| Variety | 2 | 3633536. | 1816768. | 26.71 | <.001 |
| DAP | 5 | 14509064. | 2901813. | 42.67 | <.001 |
| Variety. DAP | 10 | 1465038. | 146504. | 2.15 | 0.047 |
| Residual | 34 | 2312392. | 68012. | | |
| Total | 53 | 22171106. | | | |

***Variate: SEED_MASS***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 138.646 | 69.323 | 37.18 | |
| Rep.*Units* stratum | | | | | |
| Variety | 2 | 598.552 | 299.276 | 160.49 | <.001 |
| Residual | 4 | 7.459 | 1.865 | | |
| Total | 8 | 744.658 | | | |

***Variate: transpiration***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 12.23 | 6.12 | 0.13 | |
| Rep.*Units* stratum | | | | | |
| Variety | 2 | 706.98 | 353.49 | 7.55 | 0.008 |
| DAP | 5 | 619.71 | 123.94 | 2.65 | 0.070 |
| Variety.DAP | 10 | 390.12 | 39.01 | 0.83 | 0.600 |
| Residual | 34 | 1591.67 | 46.81 | | |
| Total | 53 | 3320.71 | | | |

***Variate: Panicle Dry mas***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| REP stratum | 2 | 49.65 | 24.83 | 2.05 | |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| REP.*Units* stratum |  |  |  |  |  |
| Variety | 2 | 211.64 | 105.82 | 8.74 | 0.002 |
| DAP | 3 | 198.11 | 66.04 | 5.46 | 0.006 |
| Variety.DAP | 6 | 158.11 | 26.35 | 2.18 | 0.085 |
| Residual | 22 | 266.22 | 12.10 |  |  |
| Total | 35 | 883.73 |  |  |  |

***Variate: Panicle Fresh mass***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep stratum | 2 | 57.69 | 28.84 | 0.85 |  |
| Rep.*units* stratum |  |  |  |  |  |
| Variety | 2 | 391.72 | 195.86 | 5.80 | 0.009 |
| DAP | 3 | 2136.88 | 712.29 | 21.10 | <.001 |
| Variety.DAP | 6 | 65.26 | 10.88 | 0.32 | 0.918 |
| Residual | 22 | 742.67 | 33.76 |  |  |
| Total | 35 | 3394.23 |  |  |  |

***Variate: Water productivity***

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep stratum | 2 | 127611. | 63805. | 0.07 |  |
| Rep.*Units* stratum |  |  |  |  |  |
| Variety | 2 | 3267881. | 1633941. | 1.79 | 0.182 |
| DAP | 5 | 302860333. | 60572067. | 66.53 | <.001 |
| Variety. DAP | 10 | 6394026. | 639403. | 0.70 | 0.716 |
| Residual | 34 | 30953612. | 910400. |  |  |
| Total | 53 | 343603464. |  |  |  |