Sweet sorghum (*Sorghum bicolor* (L.) Moench) response to supplemental irrigation in different growth stages

by

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DECLARATION

I hereby certify that this dissertation is my own original work, except where duly acknowledged. I also certify that no plagiarism was committed in writing this work and that it has not been previously submitted partly or fully for a degree to any other University.

Signed: ______________________________ Date: ______________

Hanson Boy Hlophe

DEDICATION

This work is dedicated to my family, especially my late mother Mrs Maltha J. Hlophe, who struggled and worked tirelessly to see me succeed. The work is also dedicated to my lovely wife Thandazile Z. Hlophe who continuously prayed and supported me throughout my journey to success. The work is also dedicated to my children; Melusi, Calsile and Senabelo.

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ABSTRACT

Sweet sorghum (*Sorghum bicolor* (L.) Moench) is a high biomass and sugar-yielding crop. There is recently an interest in sweet sorghum as feedstock for ethanol production, since it is rich in sugars, and reportedly has low nutrition and water requirements. A field experiment was conducted at Hatfield Experiment farm of the University of Pretoria, South Africa in 2010/11. The aim of the study was to evaluate sweet sorghum performance under different water regimes and determine their effect on biomass and sugar yields. Four water treatments (Control, Supplemental irrigation at early vegetative stage (EVS), Supplemental irrigation at late vegetative stage (LVS) and Dry land. One sweet sorghum variety (Sugar graze) was used in the experiment. Plant height, leaf area index (LAI) and dry matter accumulation were measured periodically through growth analysis. This data was used to calibrate the Soil Water Balance (SWB) crop model for sweet sorghum. Brix and quality analysis were carried out by the ACCI laboratory at the University of KwaZulu Natal at final harvest. Total fresh biomass production (t ha^{-1}) of sweet sorghum was significantly improved by full irrigation (Control) and supplemental irrigation at either the early vegetative stage (EVS) or late vegetative stage (LVS), compared to the Dry land treatment. This shows that with supplemental irrigation higher fresh biomass production can be attained. The Control and Supplemental irrigation at early vegetative stage (EVS) treatments gave the highest fresh stalk yield (16.6 ton ha^{-1} and 17.1ton ha^{-1} respectively) at harvest, followed by the Dry land and Supplemental irrigation at late vegetative stage (LVS) treatments. However, the three irrigated treatments did not differ significantly from each other with regard to total biomass production. It should be noted that the experiment was conducted during a wet season (total rainfall of 757mm during the growing period), which may have contributed to the limited response of the crop to applied water treatments. Water treatments had

no significant effect on total dry matter yield. Although the differences among the water treatments were not significant, a slightly higher dry matter yield was obtained for EVS. Similarly, total sugar yield (t ha^{-1}) and theoretical ethanol yield (L ha^{-1}) were not significantly influenced by water treatments. Sugar yields ranged between 1.64 and 2.77 t ha^{-1} and ethanol yields between 1763 and 2984 L ha^{-1}. The results also showed that treatments that were irrigated until late in the season (Control and LVS) had lower stalk dry matter contents (% DM) than both EVS and Dry land treatments. This probably resulted in lower sugar (t ha^{-1}) and ethanol yields (L ha^{-1}) for these treatments, although high fresh stalk yields were obtained. Brix (t/ha) was greatly influenced by irrigation as there were significant differences between all the water treatments. Based on these results, the main objective was achieved since it was clear that irrigating during the early stages of plant growth ensured optimum results in terms of biomass yield, sugar and ethanol yield. Model simulation results for top and harvestable dry matter and leaf area index of all the irrigation treatments were within reasonable accuracy and statistical parameters were generally acceptable. Soil water deficits were not so well simulated, especially during dry periods when simulated deficits were much higher than measured values. Nonetheless, it can be concluded that the SWB model should be a useful tool for scenario modelling in order to estimate sweet sorghum production and water use under a wide range of conditions.

CHAPTER 1: INTRODUCTION

Sweet sorghum (*Sorghum bicolor* (L.) Moench), also known as sugar sorghum, belongs to the same species as grain sorghum, fibre sorghum, grass sorghum and broom sorghum. Sorghum is the fifth most important cereal crop in production worldwide after maize, rice, wheat and barley (FAOSTAT, 2011). According to Ratnavathi *et al*. (2010), sweet sorghum differs from grain sorghums by only a few genes that control height, the presence of juice in stems, and the presence of sugar in the juice.

Sweet sorghum represents an analogous crop to sugarcane with similar accumulation of sucrose but with a higher agronomic stability to temperature fluctuations; lower water requirements and better tolerance to salinity, alkalinity and drought (Davila-Gomez *et al*., 2011). Sweet sorghum, compared to other crops is more environmentally friendly from an agronomic point of view (Sakellariou-Makrantonaki *et al*., 2007), particularly because of its relatively low nitrogen needs and water requirements. The adaptation of sweet sorghum to drought (Lizarazu *et al*., 2011) is explained by its increased water use efficiency, sustained physiological activity and enlarged root system.

Recently sweet sorghum has been considered as feedstock for ethanol production, since it is very rich in sugars, and has low nitrogen and water demands compared to maize. Sweet sorghum has a high concentration of fermentable sugars in the stem juice (Wu *et al*., 2010; Lizarazu *et al*., 2011), mainly sucrose, fructose and glucose (Sakellariou-Makrantonaki *et al*., 2007). This can be more easily be converted to produce alcohol fuel (biofuel) than maize starch and cellulose rich stover. The biofuel (ethanol) is used as transport fuel in vehicles. Biofuel as defined by Rocateli *et al*. (2010), is a liquid or gaseous fuel that is predominantly produced from biomass. The sucrose content in the sweet sorghum stalk juice is dominant and it remains stable throughout sorghums' growth stages, in contrast to the glucose and fructose contents which were found by Sakellariou-Makrantonaki *et al*. (2007) to be higher or lower depending mainly on the harvest time.

Sugar stalk crops such as sugarcane and sweet sorghum offer more advantages than other seed crops as they produce a solid residue (bagasse) which can also be used as fuel to produce energy. They can also be used as animal feed or as soil amendment after composting with other wastes. The most promising future utilization of bagasse is cellulose-based ethanol production, while the residual solids (mainly lignin) can be burnt to produce heat and power. Bagasse can also be used as a raw material for pulp, paper and boards, or as a feedstock for chemicals and fuels such as lignocellulosic ethanol (Guigou *et.al*. 2011, Rohowsky *et al*., 2012). In addition to this, the panicles of sweet sorghum have grains that can be used either as food or feed. It is the only crop that provides grains and stalks that can be used for sugar, alcohol, syrup, jaggery, fodder, fuel, bedding, roofing, fencing, paper and can be chewed whilst still fresh.

Despite all the advantages of sweet sorghum, Wu *et al.* (2011) and Shen *et al.* (2011) observed a few disadvantages of the crop. The main disadvantages are the seasonal availability and short storage duration of the stalk. Consequently, there is high cost associated with long-term storage and seasonal labour requirements (Bennett and Anex, 2009). It was observed that storage must be initiated immediately after harvest, because the stalk/juice is rich in soluble sugars and can be easily deteriorated in natural conditions. Previous processing methods mainly focused on the stalk juice storage, such as condensation for syrup (>40 ^{o}C), sterilization by high temperature, storage in low temperature (<−20 ^{o}C), and the addition of preservatives.

The adaptation and productivity of sweet sorghum have been extensively studied in many European countries under different environmental conditions (Curt *et al*., 1995), where the high yield potential of the crop, at least in non-limiting water conditions, has been confirmed. The constraint to the cultivation of sweet sorghum is the high temperature that is required for seed germination. The adoption of sweet sorghum as a biofuel crop in semi-arid regions depends on the possibility to cultivate it under limited soil water availability, or on the use of drought tolerant genotypes capable to produce high biomass yields under these soil water deficit conditions (Cosentino *et al*., 2012). In particular, stay-green, tall plant height and medium to long growing season have been proved to be useful, indirect sorghum selection criteria for improving dry matter yield under soil water scarce conditions (Habyarimana *et al*., 2004).

Water is the principal limiting factor of crop production in many areas of the world. It is a scarce resource, especially in Southern Africa where conditions are relatively dry. In dry areas, irrigation is needed to obtain maximum yield because decreasing the water supply by irrigation causes a significant reduction in seasonal evapotranspiration, aerial sweet sorghum dry matter and grain yield (Berenguer and Faci, 2001). In addition to being highly productive in terms of biomass, sweet sorghum is also known to show high drought, water logging resistance and salinity tolerance (Manstrorilli *et al*., 1999; Berenguer and Faci, 2001; Dercas and Liakatas, 2007). Sweet sorghum has also been reported to have higher water-use efficiency than other summer crops under both well-watered and water-stressed conditions (Vasilakoglou *et al.,* 2010). The adaptability, performance and response of sweet sorghum to water stress have not been studied in the semi-arid regions of Southern Africa.

The growth and production of most crops are greatly influenced by water stress. Previous work was done to assess the potential productivity and water requirements of sweet sorghum but there is still no agreement about the most sensitive stages to water stress. Also, there is no proposed water regime to optimize yield and water use efficiency of this crop under local conditions. No local work was done before and therefore necessitates a study to investigate the effect of water stress imposed during different stages on the growth and production of sweet sorghum.

The Soil Water Balance model (SWB) is a mechanistic, real-time, generic crop, soil water balance, irrigation scheduling model. It is based on the improved generic crop version of the New Soil Water Balance (NEWSWB) model (Annandale *et al*., 2000) and it gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop management data (Jovanovic *et al*., 2000). Simulations from SWB are helpful in managing irrigation scheduling, predicting yields and irrigation water requirements of crops in different regions.

However, since SWB is a generic crop-growth model, parameters specific for each crop have to be determined to enable simulations. According to Jovanovic *et al*. (2000), the crop database includes several crop specific growth parameters: vapour pressure deficit-corrected dry matter/water ratio, radiation conversion efficiency, specific leaf area, stem-leaf dry matter partitioning parameter, canopy extinction coefficient for solar radiation, maximum root depth, maximum crop height, cardinal temperatures and growing day degrees for the completion of phenological stages. Crop parameters for sweet sorghum were not previously available and were therefore determined as part of the present study. Once calibrated with the new parameters, growth and productivity response of sweet sorghum to water supply can be simulated for different scenarios. This will help us to model the yields that can be expected for different regions of South Africa, depending on the climatic (temperature, rainfall etc.) and soil conditions.

In this study it was hypothesized that early water stress will have the most severe negative effect on biomass, sugar and bio-ethanol yield of sweet sorghum. It was also hypothesized that a simple generic crop growth model such as SWB can successfully be parameterized to predict sweet sorghum water use and yield for different water supply scenarios in different environments. Therefore, the main purpose of the study was to evaluate sweet sorghum performance under different water regimes and determine their effect on biomass and sugar yield.

Specific objectives of the study:

i. To determine the sweet sorghum stage that is most sensitive to water stress.

ii. To provide estimates of the water use of sweet sorghum under local conditions.

iii. To develop model parameters in order to calibrate and validate the SWB model for sweet sorghum.

CHAPTER 2: LITERATURE REVIEW

2.1 Description of the crop

Sweet sorghum (*Sorghum bicolor* (L.) Moench), also known as sugar sorghum belongs to the same species as grain sorghum, fibre sorghum, grass sorghum and broom sorghum. It is a fast growing C_4 plant, native to tropical zones of Africa, highly productive and can be grown without supplemental irrigation (Lizarazu *et al*., 2011). Sorghum is the fourth most important cereal crop in production worldwide after maize, wheat, rice and barley. According to Ratnavathi *et al*., 2010, sweet sorghum differs from grain sorghums by only a few genes which regulate plant height, amount of juice in stems, and sugar content thereof. Sweet sorghum is characterized by a high photosynthetic efficiency under favourable conditions of light and temperature (Curt *et al*., 1995; Gnansounou *et al*., 2004) and has relatively low input requirements (Bennet and Anex, 2009). In fact, sweet sorghum was found to require 36% less nitrogen than maize to attain a similar ethanol yield (Calvin and Messing, 2012).

Antonopoulou *et al*. (2008) and Ntaikou *et al*. (2008) stated that the stalks of sweet sorghum mainly consist of sucrose (that amounts to 55% of dry matter) and of glucose (3.2% of dry matter). The stalks also consist of cellulose (12.4%) and hemicellulose (10.2%). These were not very different from the findings of Zhao *et al.* (2009) who found that sweet sorghum stalks contain 43.6 – 58.2% soluble sucrose, glucose and fructose and 22.6 – 47.8% insoluble cellulose and lignocellulose. Sweet sorghum has also been found to produce between 1.8 – 5.0 t ha^{-1} of grain yield. It can also produce about 10 -12 tons of bagasse (crushed stalks) that can be converted into cellulosic ethanol to generate about 1500 litres of ethanol (Choudhary *et al*., 2012).

2.2 Soil water requirements of sweet sorghum

Sweet sorghum's nutrient requirements are low when grown as an energy crop. According to Dercas and Liakatas (1999), sweet sorghum uses soil efficiently. Once established, it is tolerant to drought conditions with respect to both survival and sugar production. Sweet sorghum is also able to withstand extended dry periods and recover upon receiving water again. This is as a result of the plant's induced responses to water levels. Transpiration rates of sorghum change based on available water (Dercas and Liakatas, 1999) in a variety-dependent manner. Whitfield *et al*. (2012) demonstrated that osmotic stress in sorghum initiates a complex series of genetic responses including changes in the transcription of proteins controlling water transport, stomatal openings, and plant growth. Studies of sorghum response to water levels generally indicate a positive correlation between water levels and total biomass, but fermentable sugar content on a dry mass basis appears to remain constant above a certain water level (Whitfield *et al*., 2012).

Zhao *et al*. (2009) found that a high sugar-producing sorghum variety, receiving the equivalent of 2.3 mm of rainfall per day, produced approximately 28% more soluble sugars per dry mass than when receiving 1.6 mm while a low sugar content variety was not as strongly affected. Interestingly, total biomass production was similar for the two irrigation levels. Another study in which water levels varied from 5.7 to 17.1 mm per day, increased biomass yields with increasing moisture levels was observed, but no change occurred in the sugar dry mass fraction (Curt *et al*., 1995). Miller and Ottman (2010) compared the effects of irrigation frequency on sweet sorghum biomass and sugars based on allowed depletion of plant available soil water. The levels used (35%, 50%, and 65% depletion) corresponded to approximately 7–10 mm per day. Over this range, although some effects were observed on biomass levels during the growth period, there were no substantial effects observed on either biomass or sugar levels at harvest. It would appear, then, that the mass fraction of sugar in the plant is reduced when moisture levels are below some variety-dependent minimum; above that minimum the sugar fraction remains constant, although total biomass may increase.

According to Choudhary *et al*. (2012), sweet sorghum requires only 25% of the water needed by sugarcane and its cost of production is also one fourth of that of sugarcane. Reddy *et al*. (2007) stated that in its growing period of about 4.5 months, sweet sorghum's water requirement is 8000 m^3 for two crop cycles. This is four times lower than the water requirement of sugarcane (12-16 months duration and 36000 m^3 per crop). As for total water consumption, Manstrorilli *et al*. (1995) reported that sweet sorghum consumed an average of 554 mm water compared to 770 mm of maize. Marsalis *et al*. (2010) also stated that sorghum may deplete less water from the soil than maize and that in general, confirms sweet sorghum's 25% less water requirement compared to maize.

Manstrorilli *et al*., (1995) reported that water use efficiency values for sweet sorghum were almost steady over the years. In comparison to other crops, sweet sorghum requires less water (193 mm kg^{-1}) to produce 1 kg of above-ground dry matter compared to soybean (357 mm), sunflower (278) and grain sorghum (270 mm). These WUE values represent a linear relationship between evapotranspiration and potential dry matter, indicating that sweet sorghum loses water at the same rate from emergence until harvest. Previous studies demonstrated that WUE varied throughout the growing season due to climate, management and crop physiological characteristics (Manstrorilli *et al*., 1995).

2.3 Effect of water stress on growth, development and biomass production of sweet sorghum

Most stresses reduce both the available amount of radiation intercepted by foliage and the accumulation of dry matter, thus reducing canopy expansion. Water stress also results in the reduction of seasonal evapotranspiration, photosynthesis, radiation use efficiency (RUE), total dry matter, grain yield and harvest index (Berenguer and Faci, 2001). Cakir (2004) also stated that irrigation omission during any stage of growth can significantly affect green leaf number, and leaf area index (LAI). In a three year study, Cakir (2004) found out that irrigation applied 36 days after emergence (vegetative stage) increased the LAI value from 1.29 to 4.54 (measurements on day 56), while the value determined for treatments exposed to water stress during this stage was only 3.29. It was then concluded that in general, green leaf area index under adequate and well irrigated conditions increased until 70-80 days after emergence, and then decreased as the older leaves died. This of course is strongly dependant on the type of sweet sorghum variety. LAI of the treatments with imposed water stress during the entire growth season (non-irrigated) or irrigated only during the first and second growth stage and then left to stress during the rest of the season, declined to zero as early as on day 114 after emergence (Cakir, 2004). Such results on leaf area and LAI are in agreement with the view that leaf elongation is among the plant processes that are most sensitive to water shortage.

Habyarimana *et al*. (2004) conducted experiments in four locations in Italy to assess the above ground biomass production in nine sorghum hybrids (H132, H128, Abetone, ABF11, ABF14, ABF18, ABF20, ABF25 and ABF306) at three locations (Catania, Piacenza and Osimo) under variable regimes of water supply. As for water supply, Evapotranspiration (ETc) was 50% at Catania, 100% ETc at Piacenza, and nil at Osimo. At Bari, 50% and 100% ETc were applied in two experiments that were contemporarily conducted side by side. The results showed that irrigation was generally beneficial. Interestingly, dry matter yield as high as 20 Mg ha^{-1} was obtained with some hybrids at Osimo under rain-fed conditions with rainfall amounting to 225 mm per season. Hybrid variability in biomass production performance as statistical main effect was observed throughout the experimental locations. Hybrids ABF25, ABF20, and H132, and Abetone took the lead (mean aboveground biomass yield 23-28 Mg ha^{-1}) over the genotypes when evaluated under wet conditions.

As far as water regime is concerned (Habyarimana *et al.,* 2004), it could be noticed that hybrid H132 was the most susceptible to drought stress, displaying 63% biomass yield reduction, whereas hybrid ABF25, having the least (40%) yield reduction, was accordingly deemed better adapted to soil water deficit conditions. Curt *et al*. (1995) also studied water requirements of sweet sorghum at the lysimeters station the Department of Plant Production: Botany and Plant Protection, of the Universidad Politecnica of Madrid (Spain). They used different water regimes at H1, H2 and H3, corresponding to different irrigation frequencies: 1, 2 and 3 waterings per week, respectively, to look at the productivity and water use efficiency of sweet sorghum in relation to water regime. The application dose used was 40 dm^3 m^{-2} (40 mm per application). The flowering index of the most stressed regime, H1, was lower than the indexes of the other regimes. This suggests that water shortage leads to retarded plant development in sweet sorghum. Regimes H2 and H3 showed no significant differences on the flowering indexes. As for biomass yield, the highest yield was obtained for water regime H3 and the lowest productivity regime was at H1.

2.4 Critical growth stages sensitive to water stress

In many studies that were conducted on several species of plants, it was been found that the critical stages which are sensitive to water stress include flowering stage, fruit setting and assimilate transfer. During these critical stages (Katerji *et al*., 2008), a moderate water deficit can lead to a severe yield reduction. During the vegetative growth of sweet sorghum, two phases can be defined: in the first, leaf growth is predominant; in the second, stem growth is predominant. Manstrorilli *et al*. (1999) evaluated the sensitivity of the two phases (‘leaf’ and ‘stem’) to a temporary soil water stress using as comparison a well-watered crop (never stressed). Manstrorilli *et al*. (1999) observed that the effect of temporary water stress on yield depended on the phenological development stage during which it was applied. In comparison with a crop that was well-watered during the whole cycle, sweet sorghum biomass and stalk production was reduced when water stress was introduced early in the ‘leaf’ predominant stage. Their results showed that sweet sorghum is highly sensitive to water stress during the early vegetative stage. A stress in the ‘leaf’ stage significantly reduced both final biomass and stalk production. Moreover, an early stress provoked an alteration of the water use efficiency, which diminished by 20%.

Manstrorilli *et al*. (1999) found that late vegetative stages were less sensitive to a temporary water stress. It was also observed that a stress period experienced by sweet sorghum at the end of the vegetative stage resulted in only a slight decrease in stalk production, whereas WUE did not differ substantially from regularly irrigated plots. It was then concluded that the best stage for saving irrigation water without losing productivity and lowering the WUE is after the fast growing period – that is the ‘stem’ predominant stage.

In contrast to the two growth phases outlined by Manstrorilli *et al*. (1999) for sweet sorghum, Farah *et al*. (1997) outlined four growth stages. These are the early vegetative stage, late vegetative to boot stage, the boot to bloom stage and the milk to soft dough stage. Farah *et al*. (1997) tested the susceptibility of sorghum to water stress once at each of the four growth stages. They found that grain yields were reduced by 17% at late vegetative to boot stage, 34% at the boot to bloom stage and 10% at the milk to soft dough stage, respectively as a result of water stress. Farah *et al*. (1997), reported that stresses equivalent to a leaf water potential (LWP) of -22.90 MPa, beginning at boot stage for a period of 35 days, reduced yields by 43%, and LWP of -21.70 MPa for 27 days, beginning at early boot or heading stage, reduced yields by 27%, whereas a LWP of -22.70 MPa for the same period, beginning at early grain filling, reduced yields only by 12%. Testing the effects of water stress on forage yield of sorghum at three growth stages 0-30 days DAS (days after sowing), vegetative lag 37-55 DAS and flowering stage 56-75 DAS, it was found that the stage of vegetative lag was the most critical in its demand for assured water supply, whereas the other two stages could tolerate mild stress (Farah *et al*. (1997). Also, Berenguer *et al*. (2001) found that a water stress in sweet sorghum produced a decrease in seasonal evapotranspiration, total dry matter and grain yield.

Manstrorilli *et al*. (1999) concluded that the plant water relationships show that in sweet sorghum, stomata close when the pre-dawn leaf water potential falls to values below -0.4 MPa. This threshold is reached if soil water content passes the wilting point. Such findings led the authors to affirm that irrigation becomes indispensable only when water in the soil drops below wilting point. They also concluded that -0.4 MPa represented a threshold for separating non-stress from stress conditions.

2.5 Water use efficiency and Radiation use efficiency of sweet sorghum

Water use efficiency (WUE) is defined as mm of water evapotranspired (ET) by the crop per kg of above-ground dry biomass (W) produced or the biomass (g) produced per unit of water (kg) consumed (Dercas and Liakatas, 2007; Katerji *et al*., 2008). Under drought stress, water use efficiency is the main concern rather than absolute production. Several studies have demonstrated that the WUE of sweet sorghum is higher than that of maize, grain sorghum, and other C_4 crops and that it changes due to the timing and intensity of the drought stress. Mastrorilli *et al*. (1999) indicated that WUE (stalk DM/mm water) was either maintained or slightly increased when drought stress occurred at later growth stages while with an early stress WUE decreased by about 20%.

According to Katerji *et al*. (2008), two approaches can be used to determine water use efficiency. First, the eco-physiological approach is based on the instantaneous analysis of the relationship between photosynthesis and transpiration per unit leaf area, at the leaf scale, canopy scale and territorial scale. The above approach helps to describe the processes determining water use efficiency through theoretical approaches and to compare leaf photosynthesis and transpiration capacity of a species cultivated under different watering conditions. Secondly, the agronomical approach is based on water consumption and yield concept. Katerji *et al*. (2008) went on to state that the time scale considered is the whole vegetative cycle, which provides essential data to manage the production of irrigated crops and to point out sound management methods allowing the improvement of yield. Studies which use the two approaches have been used in maize and sunflower. Such studies are very helpful since they help us to better understand the potential production or agronomical yield of species studied under contrasting watering conditions.

As for water use efficiency (WUE), sweet sorghum in comparison with other crops, requires less water (193 litres) to produce 1 kg of above ground dry matter (Manstrorilli *et al*., 1995); in fact, soybean requires 357 litres, sunflower 278 litres and grain sorghum 270 litres. Sweet sorghum therefore has a higher WUE than most other crops. Water stress applied during the fast early vegetative stage growth period (Miller and Ottman, 2010) can potentially reduce water use efficiency by 20% but a stress period applied later in the vegetative cycle only slightly decreases stalk production (Manstrorilli *et al*., 1999).

A preliminary study carried out by Steduto *et al*. (1997) on WUE revealed the superior performance of sweet sorghum among various C_4 crops. The 4-year average results that were obtained in independent experiments carried out in Italy, Greece and Spain showed a higher WUE (5.2g of biomass per kg of water) of sweet sorghum compared to other C4 crops. According to Manstrorilli *et al*. (1995), WUE may vary throughout the growing season. Before full ground coverage (leaf area index, LAI<2.5), there is high soil evaporation and as a result, more water is needed to produce 1 kg of above ground biomass, whereas under full expanded canopy conditions the amount of water required decreases to a minimum, remaining constant until harvest.

Wu *et al*., (2010) also stated that sweet sorghum has a high efficiency in water usage (requires one third of water used by sugarcane and half the amount used by maize). The authors concluded that WUE of sweet sorghum is the highest encountered among C_4 crops under both well-watered and water stressed conditions. The same observations were made by Mastrorilli *et al*. (1995). Smith *et al*. (1993) also reported that sweet sorghum has greater WUE than maize, sugarbeet, or fodder beet and required only 36% of the nitrogen fertilizer requirement for maize.

Manstrorilli *et al*. (1995) tried to characterize sweet sorghum productivity, radiation and WUE in an area under non-limiting nutritional and soil water conditions. They did this by comparing sweet sorghum consumptive water use with other crops (soybean, and sunflower) which are traditional in Rutigliano, Bari, Italy. The slopes of the relationship between dry matter versus intercepted photosynthetically active radiation (PAR) for grain sorghum, sunflower and soybean were respectively, 3.39, 2.05 and 1.72 g MJ^{-1}.

Steduto *et al*. (1997) and Dercas and Liakatas (2007) stated that sweet sorghum transforms the intercepted radiation (RUE 3.7 gm^{-2} of dry matter per MJ m^{-1} of absorbed PAR more efficiently than maize and other C_4 crops. Similar findings were reported by Manstrorilli *et al*. (1995), who stated that sweet sorghum radiation use efficiency (RUE) of 3.7 g MJ^{-1} was found to be higher than that of sugarcane (2.7 g MJ^{-1} of intercepted PAR), maize (between 2.1 and 3.2 g MJ^{-1} of intercepted PAR) and pearl millet (3 g MJ^{-1} of intercepted PAR). These findings were not very different from those of Woods (2001), who stated that sweet sorghum has one of the highest RUE's of around 3.6 g dry biomass MJ^{-1} PAR absorbed, compared with approximately 2 g MJ^{-1} PAR for a C3 species of any plant. As might be expected, significant variation was observed in relation to different photosynthetic pathways: sweet and grain sorghum (C_4 species) tended to produce more biomass at the same value of accumulated absorbed PAR. On the contrary, C_3 species with nitrogen fixing nodules, or large proportions of stem, or high concentrations of lipid in their tissues or seeds tend to produce less biomass.

2.6 Effect of planting date on sugar and ethanol yield

The time of planting of sweet sorghum is as crucial as the time to harvest as both have significant effects on sugar and ethanol yield. Studies by Teetor *et al*. (2011) have shown that accumulation of sugars in the stem relates with the developmental stage of the plant. Other authors have confirmed that non-structural carbohydrates increase from pre-boot to anthesis stage. On the other hand, sucrose accumulation in the stems begin at panicle emergence, reaching the highest concentration at the soft dough stage. On the contrary Hoffman-Thoma *et al*., (1996) concluded that the onset of sucrose accumualtion was not necessarily dependant on the inflorescence since it began before the boot stage in some of the varieties that they evaluated. Also, according to Teetor *et al*. (2011), flowering is not necessarily an indicator of maximum sugar content but it is an easily identifiable reproductive stage from which to determine harvest date.

A study by Balole (2001) in Hatfield Experiment Farm, University of Pretoria, South Africa, has shown that late summer plantings of sweet sorghum generally had lower stalk and sugar yields. Early planting was found to produce the highest stem yield, a greater number of tillers, and the greatest stem height. In Arizona and the Lower Rio Grande Valley of south Texas (US), May (early summer) was found to be the ideal month for planting sweet sorghum as it produced the highest sugar since more solar radiation is received between June and August when plants are between the boot and seed stages. Similar results were obtained in Iran where the May (early summer) planting produced the highest stalk yield, Brix and sucrose level as opposed to the July and August (mid summer) plantings which produced unsatisactory growth. A similar trend (Teetor *et al*., 2011) was observed in South Africa where yield was found to decline rapidly as the date of planting was delayed, resulting in a 40% drop in sucrose. Most studies have therefore concluded that early summer planting dates are more desirable the highest biomass yield and sugar concentrations to be obtained.

2.7 Time to harvest sweet sorghum

The right time to harvest sweet sorghum after anthesis is very crucial as it affects all the plant parameters (dry mass of stems, leaves and panicles). According to a study by Zhao *et al*. (2009) stem dry mass (SDM) increased significantly from 5.5–11.5 t ha^{-1} at anthesis to 8.2–16.4 t ha^{-1} at 40 days after anthesis (DAA) in 2006 and from 5.4–18.8 t ha^{-1} to 9.5–23.9 t ha^{-1} for all cultivars during the same period in 2007. Total aboveground dry mass (AGDM) increased from 8.5–17.2 t ha^{-1} at anthesis to13.2–24.5 t ha^{-1} at 40 DAA in 2006 and from 8.8–27.1 t ha^{-1} at anthesis to 14.8–35.2 t ha^{-1} at 40 DAA for the five cultivars in2007. Increases in AGDM and SDM from anthesis to 20 DAA were higher than from 20 DAA to 40 DAA for each cultivar across the two years.

Davila-Gomez *et al*. (2011) discovered that variety or genotype and environmental conditions are the principle factors that influence the optimal maturation time. A continuous evaluation of the maturation progress of sweet sorghum in the field is therefore necessary. Almodares and Hadi (2009) indicated that non-structural carbohydrates of sweet sorghum are also affected by temperature, time of day, maturity, cultivar, spacing and fertilization. These authors, for example found out that in the first week of post-anthesis, ^{o}Brix of all the genotypes evaluated averaged around 8 except for one variety that averaged <6. According to Davila-Gomez *et al*. (2011), Brix is a term that represents an approximation of total solids content. Brix has a positive correlation with total sugar concentration. This positive correlation has been reported in sweet sorghum by many authors like Tsuchihashi and Goto (2004) and Davila-Gomez (2009).

Prasad *et al*. (2007) reported that the sugar concentration in sweet sorghum stems immediately after post anthesis at 12.5 °Brix. All cultivars were found to accumulate 2°Brix per week, with the highest increase from week two to three before arriving at a steady state after the fourth and fifth week. According to Davila-Gomez *et al*., (2011) and Prasad (2007), the optimal harvesting stage is when the juice contains 15.5 – 16.5°Brix. This is one of the most important quality parameters in order to obtain a juice of high fermentable quality and thus maximum ethanol yield per hectare.

The same trend was observed for total soluble sugar content and yield (Zhao *et al*., 2009; 2012) of early and middle maturity cultivars. Total soluble sugar was found to increase with time after anthesis (between 0 – 40 DAA) and then to decrease significantly after that. It was also found that ethanol yield from sugar and starch decreased with time when harvest is delayed, and calculated ethanol yield from cellulosic materials were consistent for most cultivars. Curt *et al*., (1998) on the other hand observed that glucose content was always higher than fructose and both tended to decrease at the end of the growth cycle. The same authors also noted that the sucrose content increased significantly during the last 40 – 50 days of the cycle, reaching 25.6% at harvest (dry stalk basis). Zhao *et al*., (2009) suggested that the right time to harvest sweet sorghum is between 33 and 40 days after anthesis when sugar accumulation is at its maximum. Tsuchihashi *et al*. (2004) and Zhao *et al*. (2011) also stated that sugar and ethanol yields are affected by the time of harvesting. It has also been found that there is a temporary decline of total sugar mass from 12 days after anthesis because of a transition of assimilates from stem to grain.

With delayed harvest after physiological maturity date (Zhao *et al*., 2012), stem moisture content was found to vary between 80.4% and 51.2%, 74.8% and 60.8% respectively in four varieties that were tested. Medium maturing cultivars were also found to accumulate stem biomass between the date of physiological maturity date and frost date and then decrease after the frost date whereas the late cultivars exhibited a slower decline in stem dry mass after the frost date.

CHAPTER 3: MATERIALS AND METHODS

3.1 Site description

The sweet sorghum experiment was planted at the Hatfield Experimental Farm of the University of Pretoria, Pretoria, South Africa (latitude 28°26' S, longitude 25°75' E, altitude 1327 m above sea level) on the 7th December 2010. The area has a mean annual rainfall of 670 mm, mainly concentrated in the months of October to March (Annandale *et al.*, 1999). The lowest monthly mean minimum temperature is 1.5 °C (July) and highest monthly mean maximum temperature is 30 °C (January). The experiment was planted in a sandy clay loam soil with a permanent wilting point of about 130 mm m^{-1} and a field capacity of 260 mm m^{-1}. The chemical properties of the experimental soil are presented in Table 3.1.

Table 3.1: Chemical properties of the soil used in the experiment.

		Chemical Property				
		P	**Ca**	**K**	**Mg**	**Na**
Year	**pH**	**(mg kg^{-1})**	**Mg kg^{-1}**	**Mg kg^{-1}**	**Mg kg^{-1}**	**Mg kg^{-1}**
2010/11	6.1	112.4	610	143	193	50

P – (Bray extraction)

Cations – (NH40Ac)

3.2 Experimental design

Four irrigation treatments and one sweet sorghum variety (Sugar graze) were used. The experiment was laid out in a randomized complete block design (RCBD) with four replications (Fig 3.1). Each plot was 5 m long and 7.2 m wide. Each plot consisted of eight plant rows that were spaced at 0.9 m apart, and with an in-row spacing of 0.1 m between plants resulting in a plant population of approximately 100 000 plants ha^{-1}.

The four water treatments were as follows:

- **Treatment 1:** Control – irrigation was done once a week to refill the soil to field capacity based on neutron probe measurements.
- **Treatment 2:** Dry land – irrigation was done for crop establishment, thereafter the crop depended only on rainfall.
- **Treatment 3:** Supplementary irrigation was only applied during the early vegetative stage (EVS). The regime during this period was the same as for the control.
- **Treatment 4:** Supplementary irrigation was only applied during the late vegetative stage (LVS). The regime during this period was the same as for the control.

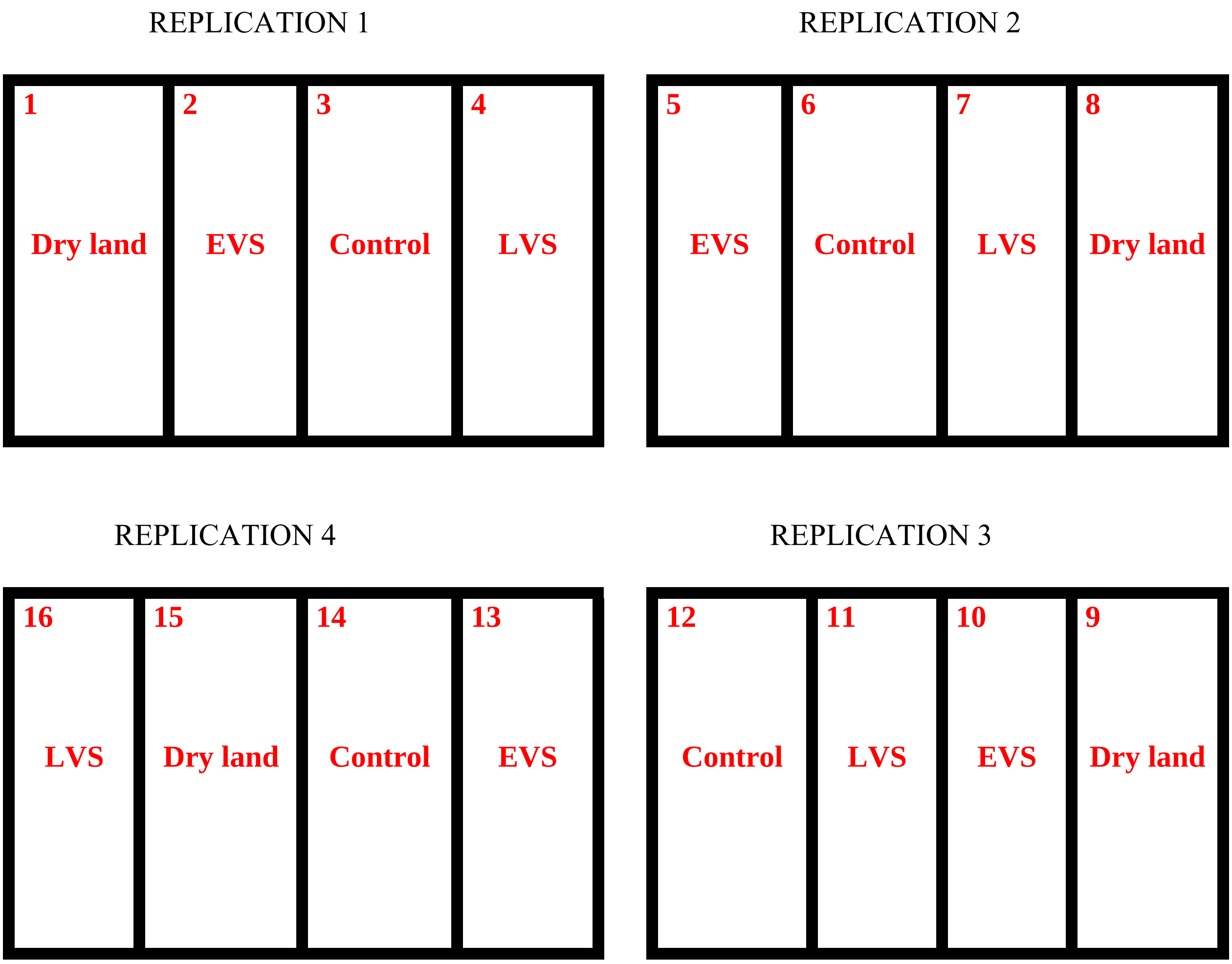

Fig 3.1: Randomized Complete Block Design (RCBD) layout of the sweet sorghum experiment at the University of Pretoria in 2010/11.

3.3 Weather Data Measurements

Daily weather data was measured with an automatic weather station which was located about 200 m from the experiment. The weather data measurements are important driving variables for the SWB crop model. It is worth noting that there was quite a lot of rain during the early stages of the crop. As a result of the wet soil conditions, application of the irrigation treatments was delayed until about six weeks after planting.

3.4 Planting date and planting procedures

The field was ploughed and a rotovator was used to prepare an extremely loose seedbed. Planting was done using a tractor drawn planter on the 7th December 2010. The crop emerged one week after planting and thinning was done to the required spacing at three weeks after planting. Fertilizer was applied at two splits. Prior to sowing, 750 kg ha^{-1} of 2:3:4 (30) was applied, which amounts to 50 kg ha^{-1} N, 75 kg ha^{-1} P and 100 ha^{-1} K at planting. An additional 75 kg ha^{-1} N was side dressed four weeks after planting with LAN (28%), to give a total of 125 kg ha^{-1} N on all plots. A pre-emergence herbicide was applied to the soil early after planting to control broadleaved weeds. Weeds that emerged later were controlled manually. A systemic insecticide (Cypermethrin) was applied twice (before and after panicle formation) to control aphids on the leaves of the crop. The application rate of this insecticide was 300 ml ha^{-1}.

3.5 Irrigation design

Drip irrigation was used to irrigate the sweet sorghum experiment. The drip irrigation system was set up immediately after emergence of the crop. The dripper lines were 0.9 m apart and the individual pressure regulated drippers were spaced 0.3 m apart in the line, delivering 2.4 litres of water hr^{-1}. The dripper lines were running at 150 kPa pressure to ensure that the desired amount of water was applied. A pressure regulating valve was used to monitor the pressure of the drip irrigation system to ensure accurate delivery of irrigation water to the various treatments (Fig 3.2). The total irrigation water amount applied was monitored by water meters that were installed in the system. Since one treatment was Dry land, only three water meters were installed for the irrigated treatments. Water meter readings were taken before and after each irrigation event. Such information is crucial in the calculation of the actual water applied to the crop on a daily basis.

Fig 3.2: Dripper lines layout in the sweet sorghum experiment at Hatfield, Pretoria in 2010/11.

3.6 Observations

3.6.1 Soil water content monitoring

Soil water content was measured twice per week, using a calibrated neutron probe (Fig 3.3). Neutron probe access tubes were installed at the centre of each net plot to a depth of 1.0 m to measure volumetric water content at depth increments of 0.2 m. Readings were taken by lowering the neutron probe sensor through the access tubes in each plot. The access tubes were always covered with a lid when not in use to avoid foreign objects and rain water from falling into them thus minimizing errors when taking readings. The neutron probe was calibrated by regressing volumetric water content against standardized neutron count ratios, using multiple paired measurements when soil was wet and when it was dry. Volumetric soil water content was determined from gravimetric water content and bulk density. Soil water content and water deficit graphs (Figure 4.2 and 4.3) were also plotted using the calculations from the neutron probe.

Fig 3.3: Illustration of drip lines layout and the soil water content measuring instrument (Neutron probe) in the sweet sorghum experiment in 2010/2011.

The measurement of water content was performed according to the protocol of the standard oven method (Shen *et al*., 2011). The water content calculation was based on equation 3.1:

$$M\ (dry\ basis) = \frac{Mw - Md}{Md} \qquad \textbf{(3.1)}$$

Where: M is gravimetric soil water content (dry basis), Mw is the wet mass and Md is the dried mass of the sample.

3.6.2 Growth analysis measurements

Measurements of plant biomass, height, moisture content, interception of photosynthetically active radiation (PAR) and leaf area index (LAI) were taken once every 14 days to monitor plant growth in response to the different irrigation treatments. At harvest: biomass yield, stalk yield, sugar yield, intercepted PAR, height and lodging measurements were carried out. Plant height measurements were also taken fortnightly by measuring two plants per row for the six plant rows in each plot, making a total of twelve sampled plants per treatment. The plants were measured by extending the uppermost fully unfolded leaves. One border row was left on either side of the plots, giving six data rows.

Periodic harvests (destructive sampling) were done every fourteen days for growth analysis starting at 31 days after emergence. This was done by harvesting six plants per plot (1 plant per row from six middle rows) for biomass, leaf area and moisture analysis. The harvested plants were separated into stems, leaves and panicles for biomass estimation. The stems for individual plots were then cut into 20 mm pieces and put into individual paper bags. The same was done for the panicles and leaves. Leaf area of green leaves was determined from the same plants by running the green leaves through an LI 3100 leaf area meter (Li-Cor, Lincoln, Nebraska, USA). Leaf area index (LAI) was then calculated using equation 3.2. Fresh mass was taken for each sample. The samples were then oven dried at 65°C until constant mass was reached to gravimetrically estimate plant dry biomass.

$$LAI = \frac{total\ leaf\ area\ of\ sample}{total\ ground\ sample\ area} \quad (3.2)$$

From plant biomass and leaf area development data, crop growth parameters were calculated. These included leaf area index (LAI) and dry matter accumulation.

3.6.3 Canopy radiation interception

Canopy interception of photosynthetically active radiation (PAR) was measured using a ceptometer (Accupar model LP-80, Decagon Devices). The PAR was measured at two heights, one reference reading above the canopy and several below the canopy on the soil surface, whereafter fractional interception of PAR was calculated using equation 3.3. For the below canopy readings, the ceptometer was positioned diagonally between two plant rows (from the middle of one row to the middle of the next) on the soil surface. The measurements were taken around solar noon on clear days.

$$FI = 1 - \exp(-\mathrm{Kpar\ LAI}) \quad (3.3)$$

3.6.5 Water use and water use efficiency (WUE)

The evaluation of water use efficiency was based on the relationship between water used as evapotranspiration (ET) and dry matter production, using equation 3.4.

$$WUE = \frac{\mathrm{DM\ yield}}{\mathrm{ET}} \quad (3.4)$$

Evapotranspiration (ET) was calculated using the soil water balance equation:

$$\mathrm{ET = DS + P + I - D - R} \quad (3.5)$$

Where: DS = the change in soil water storage (mm)

P = rainfall (mm), I = irrigation (mm), D = drainage below the bottom of the root zone (mm) R = runoff (mm). P was obtained from the rain gauge, I was obtained from water meter readings, and D was estimated using the Soil Water Balance model and R was considered to be zero. DS was the change in soil water storage and was calculated from neutron probe measurements.

The water-use efficiency in terms of total biomass production (WU Ebm) was determined as the ratio of total biomass yield to seasonal evapotranspiration (ET) mm.

$$WUEbm = \frac{\text{Biomass yield}}{\text{ET}} \quad \textbf{(3.6)}$$

In order for the SWB model to be used to predict sweet sorghum yield under supplemental irrigation, some model growth parameters had to be determined from growth analysis data collected in the 2010/2011 season on the Hatfield Experiment Farm of the University of Pretoria. The control water treatment was selected to determine crop-specific growth parameters which were used to calibrate the SWB Model. This treatment had no water limitation (i.e. it received full irrigation throughout). Validation of the model was then done on data collected from the other three treatments (described earlier). Statistical parameters (R^2, D, RMSE and MAE) were used to evaluate the accuracy of simulations against measured values (De Jager, 1994). R^2 is the coefficient of determination, D is the index of agreement of Willmot (1982), RMSE is the root of the mean square error, and MAE is the absolute error expressed as a percentage of the mean of the measured values.

Dry matter ratio (DWR) is a crop specific parameter determining water use efficiency corrected for vapour pressure deficit (VPD). DWR was estimated using the equation according to Tanner and Sinclair (1983):

$$DWR = \frac{(DM * VPD)}{ET} \qquad \textbf{(3.7)}$$

DM (kg m^{-2}) was measured at harvest, whilst VPD represents seasonal average. Both VPD and DWR are in Pa while ET is in mm.

Radiation use efficiency (Ec) is a crop specific parameter used to calculate dry matter production under conditions of radiation limited growth and can be calculated by the equation of Monteith (1977):

$$DM = Ec * (FI_{solar} * RS) \qquad \textbf{(3.8)}$$

DM (kg m^{-2}) is dry matter measured at harvest, while Ec represents the radiation use efficiency in g MJ^{-1}. FI is the fractional interception of solar radiation and RS is solar radiation. FI_{solar} * RS is the product of fractional interception of solar radiation and solar radiation in W m^{-2}. VPD was calculated following the equation in Jovanovic & Annandale (2000):

$$VPD = \left[\frac{esTmax + esTmin}{2}\right] - ea \qquad \textbf{(3.9)}$$

Where, esTmax is the saturated vapour pressure at maximum air temperature (Pa), esTmin is the saturated vapour pressure at minimum air temperature (Pa) and ea actual vapour pressure (Pa). Saturated vapour pressures (es) at maximum (Tmax) and minimum (Tmin) air temperatures were calculated by replacing T with Tmax and Tmin (Tmax and Tmin in ^{o}C) in the following equation (Tetens, 1930 as cited by Jovanovic & Annandale, 2000):

$$es = 0.611 \exp[17.27T/(T + 273.3)] \qquad \textbf{(3.10)}$$

Actual vapour pressure (ea) was calculated as a function of percent relative humidity, as follows:

$$ea = [es(Tmin * \frac{RHmax}{100} + es(Tmax * RHmin/100]/2 \quad (3.11)$$

3.6.6 Sugar analysis (Brix determination)

Stalk samples that were free from stalk borer infestation were sampled at harvest time and sent to ACCI laboratory at the University of KwaZulu Natal (UKZN) for Brix determination. A total of 10 stalk pieces (2 – 3 kg) of 0.2 m long were randomly selected from each of the 16 plots for the quality analysis. The sections were put in labelled polypropylene plastic bags and kept in a cold room (4^{o}C) immediately after cutting to delay sugar deterioration. They were then couriered overnight to UKZN for the analysis of fermentable sugars (sucrose, glucose and fructose).

Total soluble sugar content (%) was calculated from the determined stalk Brix (%). The methodolody was adopted from Liu et al. (2008), who established the following linear relationship between stalk Brix (%) and sugar content.

Soluble sugar content (%) = 0.8111 x Brix (%) – 0.3728 **(3.12)**

The conversion to ton per hectare was done by multiplying of soluble sugar content (%) with the stalk dry matter yield (t ha^{-1}).

The calculation of ethanol yield from dry biomass of sweet sorghum was expressed by Zhao *et al*. (2009) as:

Ethanol yield from sugar (L ha^{-1}) = total sugar content (%) in dry matter

x dry biomass (t ha^{-1}) x 0.51 x 0.85

x(1000/0.79) **(3.13)**

where: 0.51 is the conversion factor of ethanol from sugar

0.85 is the process efficiency of ethanol from sugar

1000 is the conversion factor from t ha^{-1} to L ha^{-1}

0.79 is the specific gravity of ethanol; g ml^{-1}

3.7 Total biomass and stalk yield determination

Harvesting was done by hand using sickles for cutting the stalks about 5 cm above the soil surface, which was as close as practically possible. Of the eight plant rows in a plot, the six middle rows were harvested for final yield determination leaving one border row on either side of each plot. Before harvesting, the stalks were counted to determine plant population in each plot and final plant height was taken from randomly selected plants. Since the length of plots was 5 m, when harvesting 0.25 m was left as border plants on either ends of each row thus harvesting 4.5 m long by 6 rows per plot. Bulk samples were weighed immediately following harvest to get the gross fresh yield. Gross fresh mass consisted of stalks, leaves and panicles. Sub-samples of 2 kg of each were then obtained from each harvested plot. These were then weighed and dried in an oven at 65^{o}C until constant mass to estimate above ground dry matter yields.

The procedure that was followed when harvesting the sweet sorghum experiments can be summarized as follows:

- Final plant height was taken before harvesting, by randomly selecting representative plants in each plot. The average was then taken as the final plant height.
- Plants were harvested at the soft dough stage as outlined by many researchers.
- Since there were eight plant rows in a plot, when harvesting, one border row was left on either sides, leaving a net plot of six rows of 5 m each. In each row, 0.25 m was left on each side, giving a harvested row length of 4.5 m long. This was done to minimize border effects.

- Each plot was harvested by row. Number of plants per row was counted before the plants were cut.
- Each row was harvested and bundled separately to obtain the fresh mass which was then used to estimate the total biomass yield.
- Dry matter yield was estimated by randomly selecting two rows and weighing them separately. Plants of each of the two selected representative rows were separated into leaves, stalks and heads and then weighed to determine the fresh mass of each component. The fresh mass of the different components of the plants was then obtained.
- Sub samples (2 – 3 kg) of stalks, leaves and panicles were then taken from each of two selected rows and oven-dried for 3 days at 65°C to obtain the dry matter mass of each sample components.
- Sub-samples of approximately 2 kg of stripped fresh and healthy stalks that were cut into lengths of 20 cm were then placed in labelled plastic bags and immediately put in a cold room to prevent rapid sugar deterioration. The samples were then sent to ACCI laboratory in KwaZulu Natal by overnight courier for quality analysis.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Weather data

The study area of the experimental field in Hatfield, Pretoria is characterized by a climate with hot and wet summers and cold - dry winters. The air temperature and precipitation (30-day average values) that prevailed at the experimental site during the growing period between December 2010 and May 2011 is schematically presented in Figure 4.1. It can be seen that the monthly mean maximum temperature did not fluctuate much from the 30 ^{o}C that was mentioned as the long term average under site description. The monthly mean minimum temperature was 14.9 ^{o}C and it remained almost constant from November – March. A sudden drop in minimum temperatures was observed between March and May. The total rainfall received during the study period was 757.4 mm with most rain having been received in December, January and March and the minimum was received in May. The mean monthly solar radiation ranged from 20 MJ m^{-2} to 23 MJ m^{-2} from November to March. The lowest mean monthly solar radiation was received in April and May.

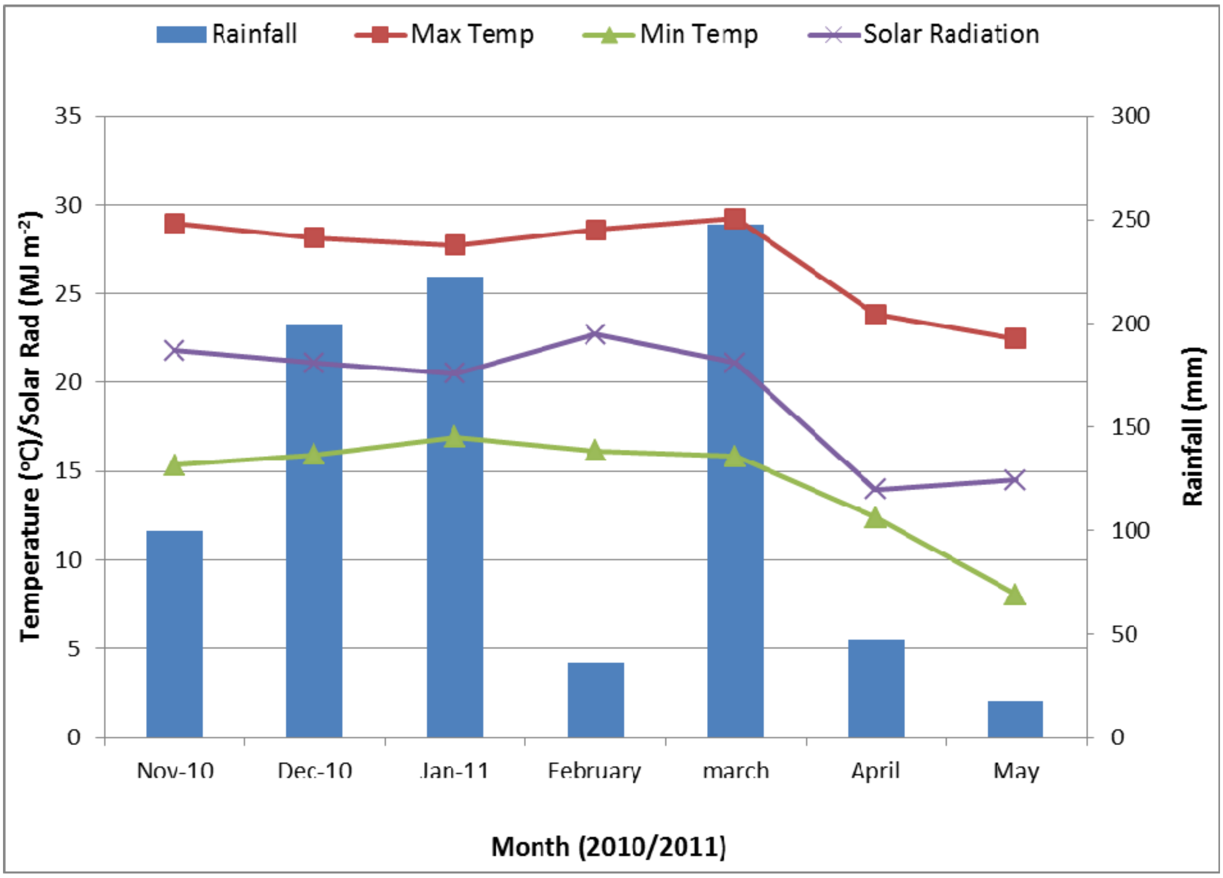

Fig 4.1: Temperature, solar radiation and precipitation (30-day mean values) occurring in the study area during the growing period of sweet sorghum in 2010/2011 growing season.

4.2 Water Content and Water Deficits

The soil water content and soil water deficit graphs were deduced from the neutron probe readings throughout the growth period of the sweet sorghum. The access tubes were installed up to 1m.The periodic soil water content measurements gave an indication of the amount of water that was in the soil. It also gave an estimate of how much water had to be added by irrigation to fill the soil status back to field capacity.

4.2.1 Soil water content

Soil water content was high for the Control and Early Vegetative Stage (EVS) water treatments throughout the growing season (Figure 4.2). More rain was received towards the end of March, which made the soil water contents to go beyond field capacity (260 mm) at times. The Late vegetative stage (LVS) and Dry land treatments had lowest soil water contents and were probably stressed during the early stages. This can be seen from the graph as the soil water content for these treatments were well below field capacity most of the time. This was however reversed when the crop received rains towards the end of March. As more rains were received towards the end of March, soil water deficits were reduced for all the water treatments, reducing the stress even for the Dry land and LVS treatments. Jahanzad *et al*. (2013) stated that when soil water content is not enough to facilitate nutrient uptake by roots, plants face difficulty in absorbing essential elements such as nitrogen and phosphorus for their growth and development, leading to yield reduction. Moreover, reduced transpiration deriving from dry soil might not only disrupt nutrient uptake by roots but also ion transportation from roots to shoots. This may have been a contributing factor to the low total dry matter yield obtained from the Dry land treatment in this experiment.

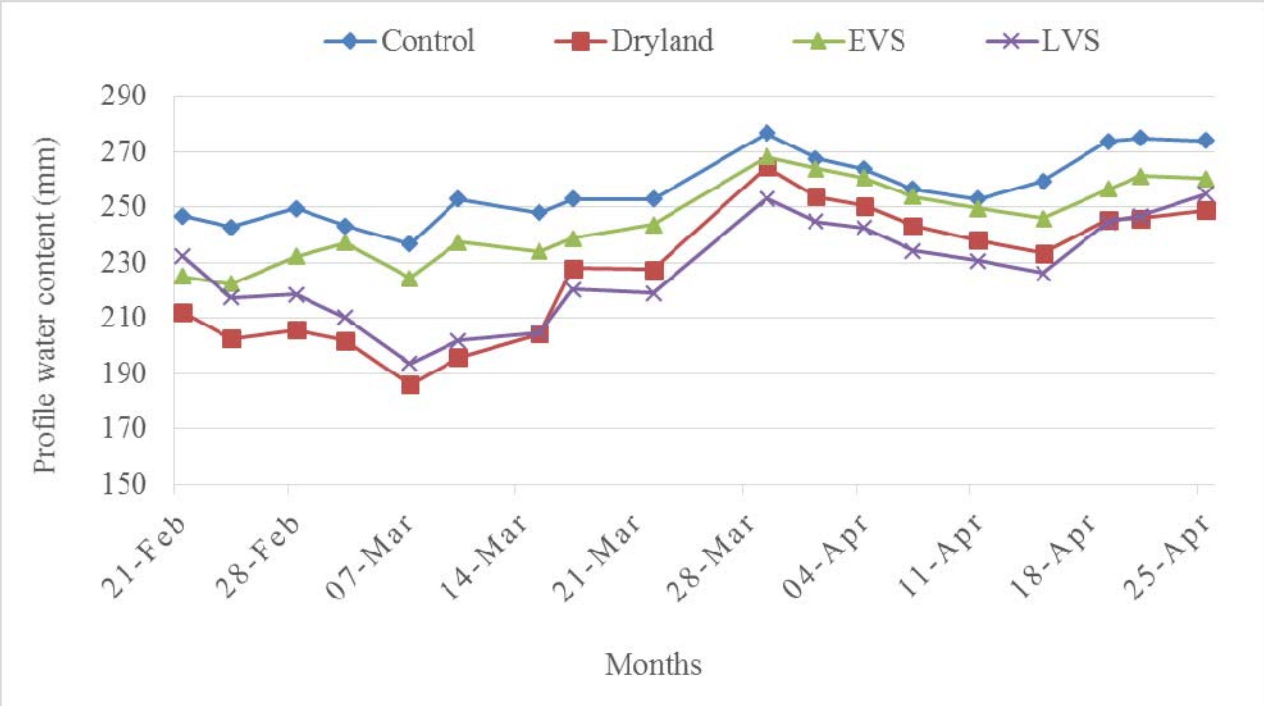

Fig 4.2: **Soil water content measurements per treatment as drawn from soil water meter readings.**

4.2.2 Soil water deficit

Soil water deficit was high for the Dry land treatment which was not irrigated throughout the season, and the late vegetative stage which was stressed early in the season. Figure 4.3 shows that at some point (around the 7th of March 2010), the soil water deficit for Dry land went up to 65 mm while that for LVS went as high as 58 mm. Another rise in soil water deficit (although moderate) was experienced between the 4th and 18th April 2010. The expected trend on the deficit graph was obtained for these treatments. That is, early in the season, the deficits were high as expected, but late in the season deficits for Dry land were quite low due to rain late in March. Deficits for both the control and EVS were low throughout. EVS was not supposed to get irrigation late in the season, and was expected to have higher deficits (and develop stress) late in the season, but that did not really happen due to the late rains which were received in March.

Since both these treatments did not experience any stress, it is expected that they yield higher than the stressed treatments.

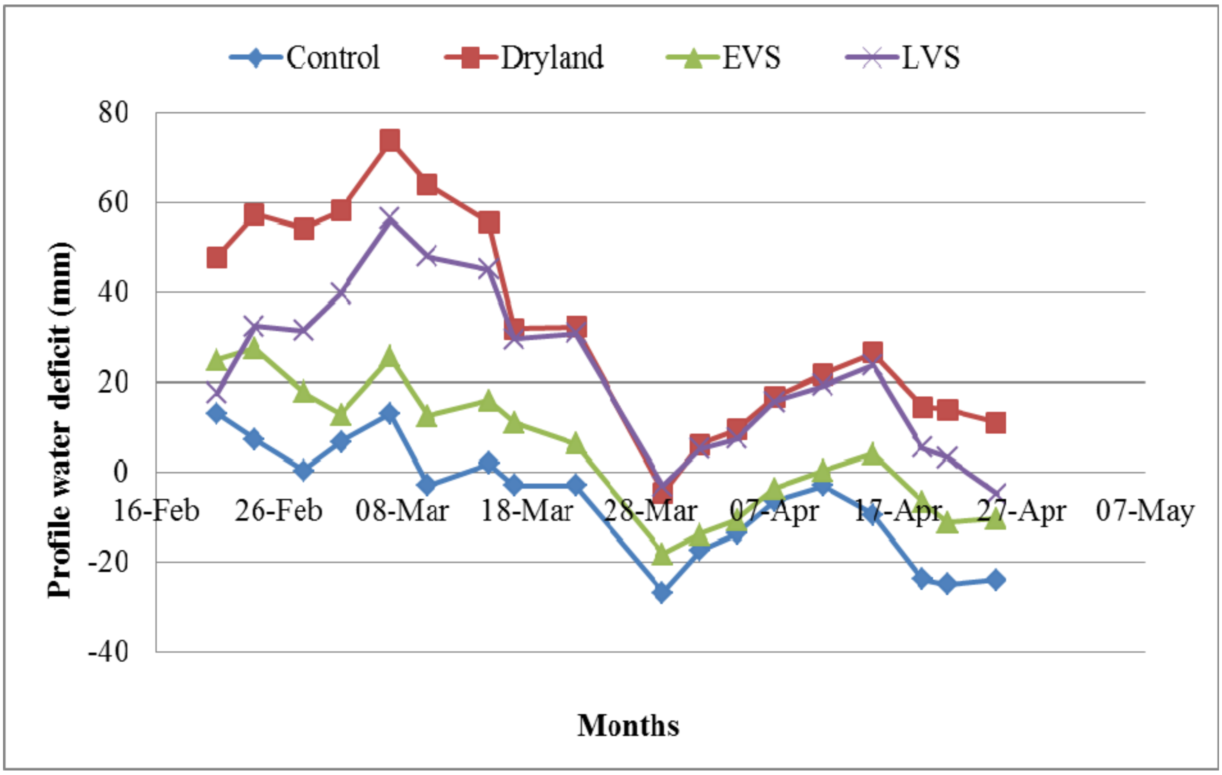

Fig 4.3: Water deficit from the different water treatments as determined from neutron probe readings.

4.3 Water use

As mentioned earlier, a lot of rain was received during the 2010/2011 growing season compared to the long term average. As a result, less irrigation water was supplied to the crop than when it would have been a drier year. A total of 772 mm rain was received for the duration of the crop growth cycle (Table 4.1), resulting in delayed application of the irrigation treatments and less water applied. In all, a total of only 216 mm was applied through irrigation during the study period to the control while EVS and LVS received 63 mm and 120 mm, respectively. The total amount of irrigation and rainfall received by the three irrigation treatments were 988 mm for the control; 835 mm for EVS and 892 mm for LVS. These amounts of water were not all used by the crop as some was lost through drainage.

Table 4. 1: Seasonal soil water balance component data for sweet sorghum in 2010

Treatments	**Soil water balance component data (mm)***					
	Precipitation	Irrigation	Transpiration	Evaporation	ET	Drainage
Control	772	216	446	179	625	269
Dry land	772	0	401	190	591	157
EVS	772	63	458	117	575	160
LVS	772	120	451	176	627	164

* The soil Water Balance Model was used to estimate drainage (D), as well as to separate evaporation (E) and Transpiration (T).

Evapotranspiration (ET) is a term used to describe the water consumed by plants over its growth cycle. Plant water use (ET) considers both transpiration and soil water evaporation. From Table 4.1, it can be seen that water consumption (ET) for the control was 625 mm, while the Dry land, EVS and LVS treatments used 591 mm, 575 and 627 mm, respectively. Calculated evaporation for the Dry land treatment was higher than the rest of the irrigation treatments. This resulted in a faster decline in LAI of Dry land later in the season (Fig. 4.5) probably because of earlier senescence. This also resulted in longer exposure of the soil surface. Oktem (2008) also made the same observation on maize and he stated that low ground cover percentage and LAI in the early growing stages accelerate water evaporation from the soil. In the sweet sorghum experiment, early leaf development was similar due to the wet conditions.

The water use values of this experiment were slightly higher than those reported by Manstrorilli, *et al*. (1999) in Bari, Southern Italy, who obtained an average water consumption of 554 mm for a well-watered crop, 443 mm for sweet sorghum stressed at the leaf stage (where vegetative growth is more predominant) and 455 mm when stress was applied at the late vegetative stage. In a separate study in Central Greece, Dercas and Liakatas (2007) obtained average water use values similar to that obtained in the present study. They reported water use of 656.7 mm for non-stressed sweet sorghum, 493.7 mm for a moderately stressed crop, 420.7 mm for a severely stressed crop and 601 mm when stress was applied after anthesis. In Central Greece, Sakellariou-Makrantonaki et al. (2007) found water consumption use of 777 mm (full irrigation) and 637 mm for supplement irrigation treatments. Transpiration is closely linked to photosynthesis and therefore dry matter production. The amount of water transpired by plants also depends on the amount of water available in the soil. In sweet sorghum, dry matter production is greatly boosted by high transpiration mostly when there is enough water during the early vegetative stages. Transpiration was high for EVS (458 mm) hence the high dry matter production. Although transpiration was also high (451 mm) for LVS, dry matter production was not improved since the crop received supplemental irrigation late in the season. There was also high drainage in the experiment as more rains were received early in the season. Drainage was estimated using the SWB model. The control had the highest drainage (269 mm) and Dry land had the lowest drainage of 161 mm.

4.4 Plant growth as influenced by water regimes

The effects of water stress on sweet sorghum growth and yield do not only depend on the magnitude of the stress, but also on the phonological stage of growth at which stress is applied. According to literature sweet sorghum is sensitive to water stress during the early vegetative stage (when leaf growth is predominant). Literature also has it that stresses at this stage significantly reduce both biomass and stalk production. Also, an early stress provokes an alteration of the water use efficiency and can reduce it by up to 20 percent (Manstrorilli *et al.*, and 1999). The late vegetative stage (when stem growth is predominant) is reported to be less sensitive to water stress and results in only a slight decrease in stalk production (Manstrorilli *et al.*, and 1999). The best stage for saving irrigation water without losing productivity and lowering the water use efficiency is after the vegetative stage (Rocateli *et al.*, 2012; Manstrorilli *et al.*, 1999).

4.4.1 Plant height

Sweet sorghum plant height results recorded for the different water treatments are shown in Figure 4.4. Overall, the highest mean height (3.49 m) was obtained for the control treatment. According to Calvin and Messing (2012), plant height is a relevant trait of plant architecture that is highly correlated with biomass yield. Indeed, some sweet sorghum cultivars are reported to be over three meters tall and are able to produce biomass in the order of 58.3–80.5 tons of fresh stems per hectare in semi-arid zones. Plant height is very important in sweet sorghum since it can give an indication of stalk yield. Qu *et al.* (2014) also stated that the advantage of plant height and leaf number of sweet sorghum is the foundation for high DM yield.

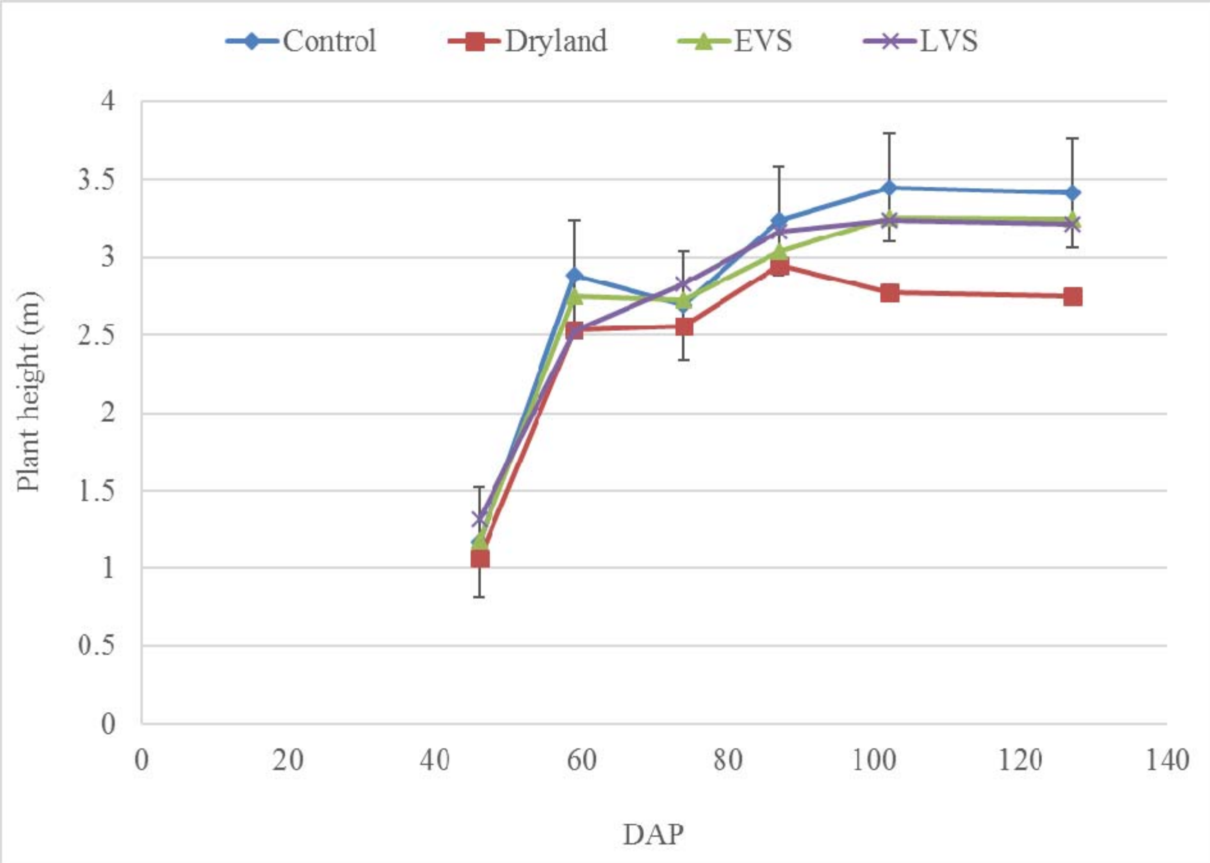

Fig 4.4: Plant height development of sweet sorghum under different irrigation treatments.

From the results of this experiment, there was a faster growth rate in the early weeks of both the control and the early vegetative stage (EVS) treatments, when compared with the Dry land and late vegetative stage (LVS) treatments. This can be explained by the fact that the latter two treatments were probably exposed to early water stress (Figure 4.3), which is known to restrict growth processes (cell division and elongation) responsible for leaf expansion and leaf appearance relatively soon after irrigation is withheld (Inman-Bamber, 2004). Leaf and stalk extension rate are thus a highly sensitive indicator of crop water status. When irrigation water was stopped for the EVS and initiated for the LVS, the plants in the EVS were not much affected and there was a slight pick-up in the height of plants in the LVS treatments but over all there were no significant differences observed in the later stages of the crop growth between the two treatments. Significant rainfall late in the season resulted in the fact that EVS was probably never exposed to serious stress conditions. The shortest plants were observed in the Dry land treatment. Mastrorilli *et al*. (1999) concluded that sorghum plants had highest water demand during the first weeks of growth. Therefore, irrigation should be emphasized in the early stages of growth and at any time soil water content drops below wilting point. In summary, the results presented in Figure 4.4 show that plant height was significantly affected by the different water regimes. Plants in irrigated plots were taller than non-irrigated plants on all the measurement dates and this concurs with the results Sakellariou-Makrantonaki *et al*. (2007).

4.4.2 Leaf area development

Leaf area expansion is of great importance for light interception and photosynthesis. It varies according to the quantity of assimilates allocated to the production of leaves and the ratio of the leaf area produced per unit of leaf dry matter. The leaves from all the treatments expanded almost at the same rate in the early stages until day 63, whereafter slight differences were observed. Differences in LAI (Figure 4.5) obtained from day 77 when the highest LAI was obtained for the control and EVS, which were significantly higher ($P<0.05$) Dry land. The LAI from Dry land continued to drop faster than the other irrigated treatments because Dry land was stressed throughout the experiment. The LAI of EVS dropped at a similar gradient as that of the dry land treatment. Leaf senescence is much faster in stressed plants compared to irrigated plants.

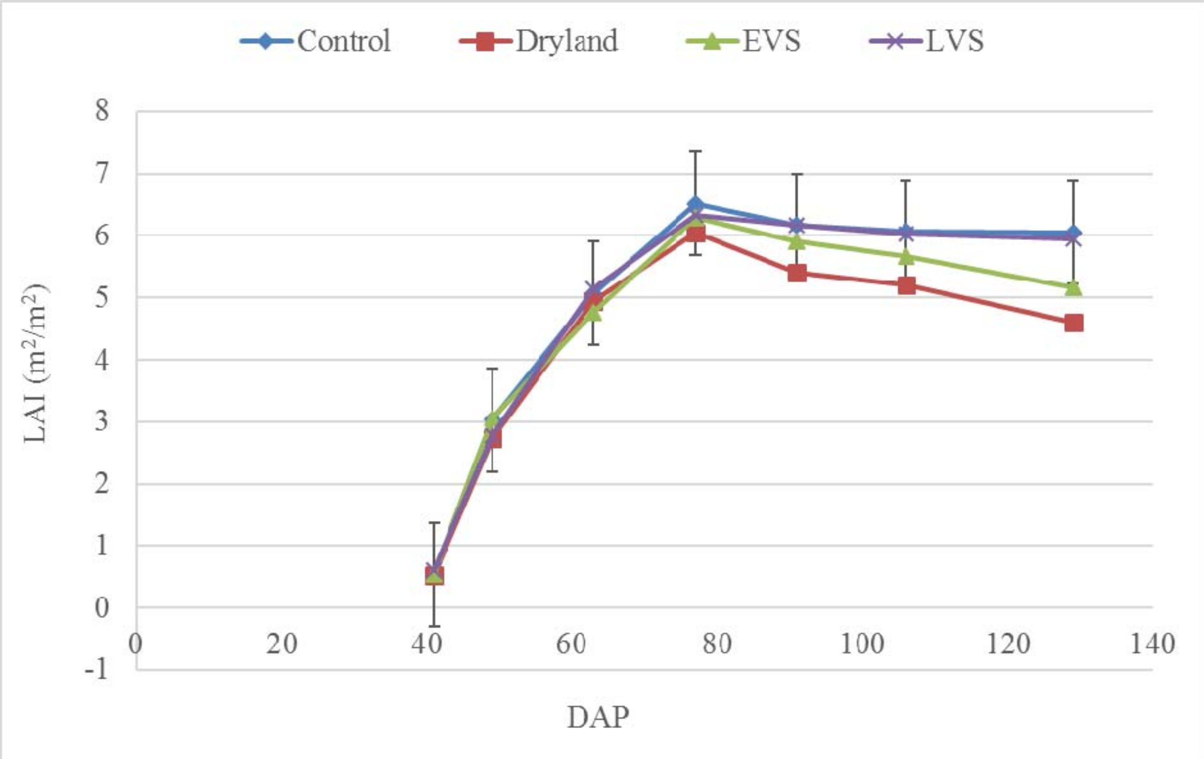

Fig 4.5: The development of leaf area index of sweet sorghum under different irrigation treatments.

The maximum LAI for all the treatments was reached at 80 DAP. LAI at this stage was 6.5 for the control and of 6.05. The lowest LAI was at 40 DAP for all the irrigation treatments. This was in agreement with the observation by Sakellariou-Mankrantonaki *et al*. (2007); Oktem (2008) and Cosentino *et al*. (2012) who obtained maximum LAI of 6 for plants under full irrigation and noted that LAI decreased with increasing water deficits. Water stress during growth is crucial to leaf area development, potential biomass production and subsequent stem yield.

After reaching its maximum value (at around the boot stage of the crop) the LAI slowly started to decrease, being still high at final harvest in the irrigated treatments (Fig. 4.3). Otherwise there were no significant statistical differences between all the water treatments up to day 77. Many studies consider maximum assimilation and complete canopy cover when the leaf area index reaches values above 4–5, whereas values relatively lower than 3 characterize open leaf canopies and considerable loss in photo-synthetically active radiation (Cosentino *et al*., 2012). The present results therefore suggest the possibility that the plant canopies of all four treatments were completely closed from about 77 DAP and there was probably little loss in photosynthetically active radiation.

4.5 Biomass and stalk yield

4.5.1 Leaf dry matter yield

Leaf dry matter accumulation (Figure 4.6) increased at almost the same rate from the first sampling (41 days after planting) to the fourth sampling date (77 days after planting). This was due to the high rainfall that was received by the crop during the early vegetative stages of crop growth. From the fourth sampling date (77 days after planting), differences started to show, which were however not significant ($P<0.05$). Despite the differences not being significant, the Control (3.97 t ha^{-1}) and LVS (4.04 t ha^{-1}) resulted in slightly higher leaf dry mass yields than that of EVS (3.8 t ha^{-1}) and Dry land (3.54 t ha^{-1}). From 77 days after planting until crop maturity, plants of both LVS and the control showed significantly higher leaf mass values ($P<0.05$) than plants of EVS and Dry land which were subjected to stress at the late vegetative stage.

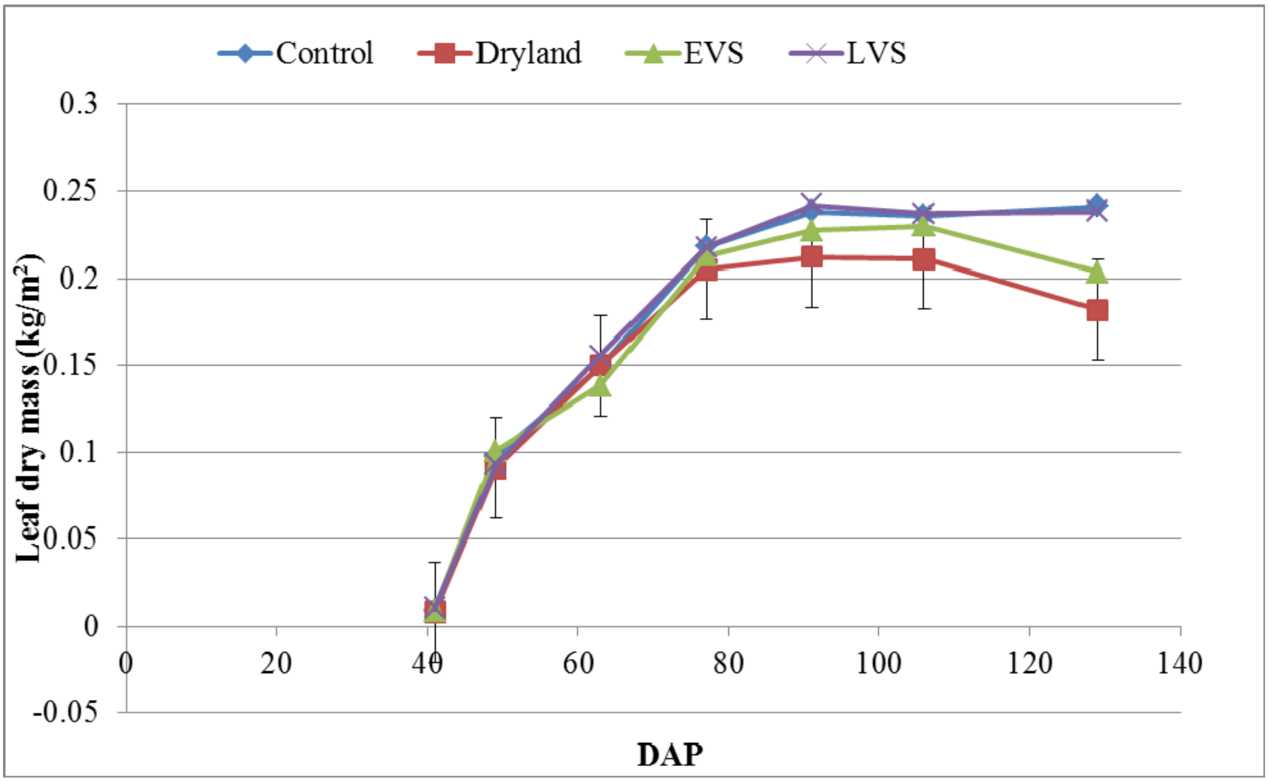

Fig 4.6: Leaf dry mass yield of sweet sorghum under different irrigation treatments.

Yields from 77 DAP onwards were all higher than those that were found by Habyarimana *et al.*, (2004), which ranged between 1.50 t ha^{-1} and 1.67 t ha^{-1}. Although LVS received supplementary irrigation (which should have relieved water stress) at late vegetative stage, there was no response in terms of renewed leaf growth, because leaf growth and initiation had stopped and dry matter accumulation in the stems was more dominant. This fact was also highlighted by Manstrorilli *et al.*, (1999) who stated that sweet sorghum vegetative growth usually follows a pattern of leaf growth first, and then towards the latter part of the vegetative growth period, stems grow and elongate rapidly.

4.5.2 Stalk dry matter yield

Stalk dry matter yield (Figure 4.7) showed significant differences ($P<0.05$) between EVS and Dry land after 80 DAP, but there were no significant differences between EVS and Control. The highest stem dry mass (on 106 DAP) was obtained for EVS (19.0 t ha^{-1}) and the lowest maximum was obtained for Dry land (17.3 t ha^{-1}).

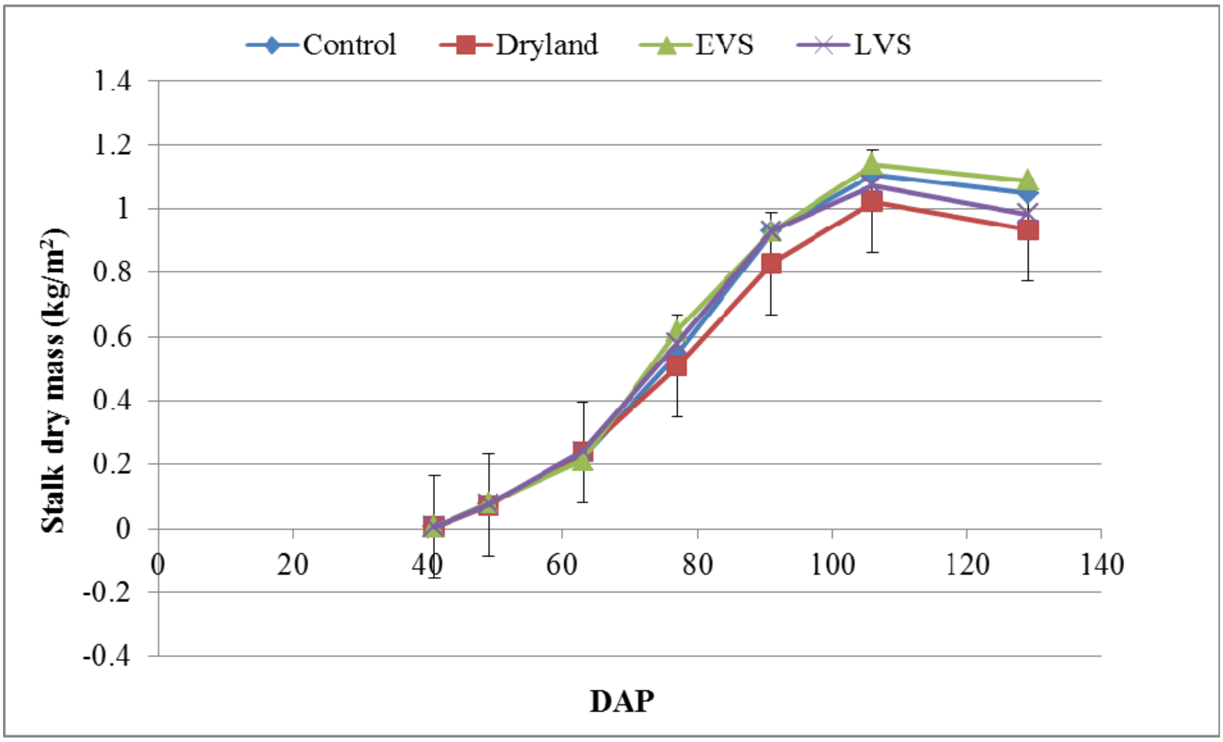

Fig 4.7: Stalk dry matter accumulation of sweet sorghum under different irrigation treatments.

In the initial stages of vegetative growth stem accumulation was increasing at almost the same rate for all the treatments due to the sufficient rainfall that was received by the crop during the early vegetative stages of crop growth. Later in the season treatment differences started to develop. Although EVS did not have the highest leaf area index and leaf dry matter, it had the highest stalk dry matter yield compared to the other treatments. This was probably due to the fact that EVS had the highest harvest index (ratio of stalk mass to total dry matter). These results concur with the findings by Mastrorilli *et al*. (1999), who stated that the best stage for saving irrigation water without losing productivity and lowering the water use efficiency is after the fast growing (leaf) period. The highest stalk yield recorded under well watered conditions were also slightly higher than those reported in literature by Habyarimana *et al*., (2004), which ranged from 17.44 t ha^{-1} to 18.22 t ha^{-1}. However, the results obtained from this experiment were lower than those reported by Curt *et al*. (1998), Dercas and Liakatas (2007) and Mastrorilli *et al*. (1995, 1999) who reported stalk yields of 26.7 t ha^{-1}, 29.8 t ha^{-1} and 22.6–32.5 t ha^{-1}, respectively.

4.5.3 Total dry matter yield

Differences occurred between the four water treatments on day 77 after planting (Figure 4.8). As more leaves were exposed to sunlight, the rate of total dry matter accumulation increased gradually. According to Cakir (2004), total dry matter accumulation accelerated after each water application. High rainfall received at the beginning of the exponential vegetative growth stage accelerated the process of biomass accumulation, resulting in no differences in growth of the crop until day 63 after planting. The adverse effect of water stress on dry matter accumulation, especially for the Dry land treatment, became significant from 77 days after planting onwards.

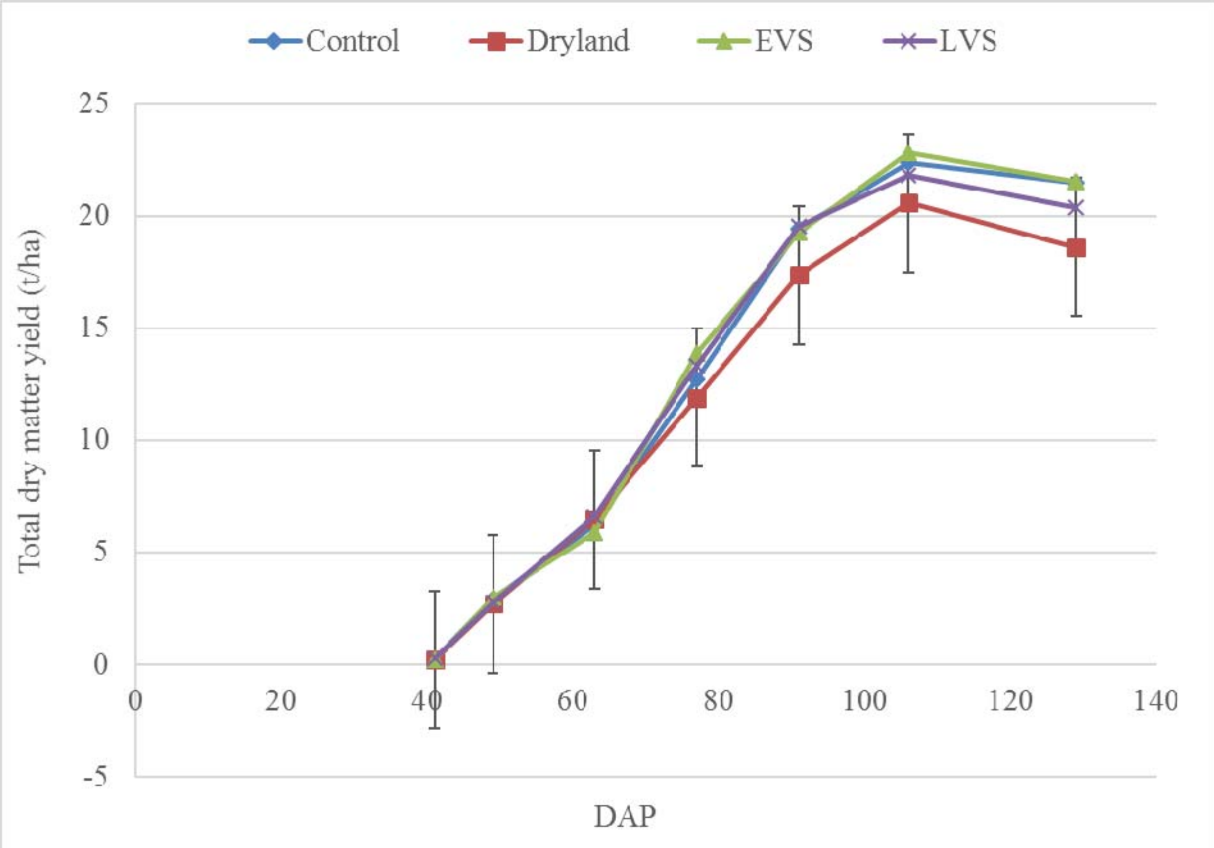

Fig 4.8: Total dry matter accumulation of sweet sorghum under different irrigation treatments**.**

Plants of the EVS (because of the same reason stated above) and control treatment produced the highest total dry matter yields (23.5 t ha^{-1} and 22 t ha^{-1} respectively), which was significantly higher than the Dry land treatment (18 t ha^{-1}). Mastrorilli *et al*. (1999) also found a similar trend and concluded that sorghum plants have a high water demand during the first weeks, and irrigation should be sufficient in the early stages of plant growth. It was also found that the vegetative phase directly influences the later development of the panicle and the final yield Mastrorilli *et al*. (1995). Stalk yield is an important parameter for sweet sorghum and the most important plant component from an economic point of view because it gives an indication of how much sugar and potentially ethanol yield can be expected, although the Brix of course also plays a role (Curt *et al*., 1995; Wu *et al*., 2010 and Zhao *et al*., 2009, 2012).

4.5.4 Total sugar yield and theoretical Ethanol yield

The response of sucrose DM concentration and dry matter content to early water stress contrasts with the response to late water deficits imposed prior to harvest. With late water deficit, sucrose DM concentration and dry matter content can both increase by up to 15%, but usually 8% (Robertson *et al*., 1999). The sucrose concentration is reduced rather than increased by early season water deficits. This can possibly be explained by the greater portion of actively-growing internodes in crops relieved from water deficit earlier in the season. These actively-growing internodes are known to contain lower levels of dry matter and sucrose and higher levels of reducing sugars (Robertson *et al*., 1995). In the case of sugarcane the photosynthesis process is less sensitive to water stress than cell growth. As a result, when the plant is water stressed late in the season it stops growing vegetatively but continue to produce sugars, and therefore accumulates in the stalks. Therefore, farmers follow a period of “drying off” or do “chemical ripening” just before harvesting in order to stop vegetative growth and increase sugar yield. This is the opposite of what happens to well watered plants (Robertson *et al*., 1999; Inman-Bamber, 2004).

Table 4.2: Total sugar yield and ethanol yield of sweet sorghum (var. Sugargraze) under different water treatment methods in Hatfield, Pretoria.

Treatment	Fresh yield (ton ha^{-1})		Dry matter yield (t ha^{-1})		Stalk dry matter content	Brix of stalks		Total Sugar yield	Ethanol yield
	Total	Stalk	Total	Stalk	(%) of fresh mass	DM (%)	t ha^{-1}	(t ha^{-1})	(L ha^{-1})
Control	52.93a	41.04a	16.53	9.36	22.8	44.97	3.24	1.72	1854.3ab
EVS	52.21a	41.27a	17.68	10.37	25.1	56.25	4.75	2.39	2574.9a
LVS	47.79a	34.88b	14.78	8.20	23.5	42.50	2.84	1.44	1551.1bc
Dry land	40.54b	34.21b	15.51b	8.63	25.2	52.90	3.90	1.89	2031.9a
LSD (α = 0.05)	6.47	5.61	NS	NS	-	NS	NS	NS	678.3
CV	23.32	14.39	17.96	26.10	-	15.61	27.17	35.16	27.96

*Values followed by the same letter in a column are not significantly different at p = 0.05

Table 4.2 shows the results for sugar yield (t ha^{-1}) and calculated theoretical ethanol yield (L ha^{-1}) for the different irrigation treatments. The highest sugar yield was obtained with EVS (2.39 t ha^{-1}) and Dry land (1.89 t ha^{-1}). These yields were not significantly different ($P<0.05$) from yields of Control and LVS, which were 1.72 t $ha^{-1}$and 1.44 t ha^{-1} respectively. These findings were in agreement with those of Vasilakoglou *et al*., (2010) who studied the productivity of sweet sorghum under increased salinity and reduced irrigation. Among the varieties they used was Sugar graze, and they found sugar yields ranging from 1.25 – 2.98 t ha^{-1}. Reddy *et al*. (2007) obtained yields ranging from 1.1 - 3.0 t ha^{-1} on seven promising lines of sweet sorghum and this was almost the same as the sugar yields obtained in the present study. These yields were however lower than the mean yields of 3.96 t ha^{-1} which were obtained by Teetor *et al*. (2011). This was probably due to the fact that the panicles were not removed from plants in the present study, which would have led to the diversion of some sugars to the grains during the period of rapid ear mass increase, at the expense of sugar accumulation in stems. Zhao *et al*. (2009) obtained sugar yields ranging from 1.3 – 3.3 tons ha^{-1} at anthesis to 4.1 – 7.4 tons ha^{-1} at 40 days after anthesis in 2006, and from 2.3 – 6.3 tons ha^{-1} at anthesis to 5.1 – 10.5 t ha^{-1} at 40 days after anthesis for five cultivars in 2007. This shows that harvest time after anthesis also has an effect on sugar yield. The sugar yields obtained from the present study were within the range of the findings of the above authors.

Total ethanol yields calculated from sugar yield (Table 4.1) ranged from 1763.1 to 2983.7 L ha^{-1}. Ethanol yields of EVS and the Dry land were not significantly different. The late vegetative stage treatment (LVS) was the only significantly different treatment and had lower ethanol yield than EVS, but not significantly less than the control and dry land. This can probably be explained by the formation of new actively-growing internodes after relieving the plants of water stress, which are known to contain lower levels of sucrose, as was reported by Robertson *et al*. (1999). The ethanol yields in this study were lower than the results of Zhao *et al*., (2009), which ranged from 2967 – 5783 L ha^{-1} at anthesis to 4867 – 9456 L ha^{-1} at 40 days after anthesis. The results that were obtained from this experiment were within the same range as those reported by Vasilakoglou *et al*. (2010) of 1271 – 7620 L ha^{-1}. These variations might have been due to the variety (genotype) and also the environment as most of the results referred to in this document were obtained from experiments conducted in Europe.

CHAPTER 5: SWB MODEL PARAMETERIZATION AND CALIBRATION FOR SWEET SORGHUM

5.1 Introduction

Modelling is an important part of research and used to simulate real-time events which are normally too difficult and expensive to replicate on a large scale or multiple times. Models use empirically, physically, or theoretically based equations to estimate one or more outcomes of an event or multiple outcomes of the same event with variable input scenarios.

In agricultural applications (Perkins, 2012), crop models can be used to support decision-making that will affect the long term health, financial, and/or physical functioning of a farming operation. Models are also useful in estimating long term economic trends, such as quantity supply and demand as was done by Mazraati and Shelbi (2011) projecting the effect of alternative fuels and advanced technology vehicles on oil quantity demanded by the United States up to 2030. The application of modelling in these situations and many others opens the opportunity for application in a variety of other situations, including the development and impact assessment of alternative biofuel feedstocks.

Crop models can assist with the search for regionally appropriate biofuel feed stocks such as sweet sorghum (*Sorghum bicolor* (L.) Moench), which has a good yield potential and the ability to meet international standards. However, few crop models have incorporated specific crop parameters associated with estimating biomass production of sweet sorghum.

Shih *et al*. (1981) developed a model that used leaf area and leaf dry biomass to estimate sweet sorghum total fresh biomass produced during different plant growth stages. No other papers were found in continuation of this research. Ferraris and Vanderlip (1986) compared SORGF/SORG5 models in predicting sweet sorghum biomass and concluded that more detailed physiology of sweet sorghum varieties was needed to improve the accuracy of these models.

The Biosystems and Agricultural Engineering (BAE) Department at Oklahoma State University (OSU) published a report predicting sweet sorghum yields by soil and climate regions using the Soil Water Assessment Tool (SWAT) (BAE-OSU, 2006). Due to the limited availability of actual field scale sweet sorghum biomass data, the report recommended more sweet sorghum data is needed from known soils, either irrigated or Dry land, in order to accurately predict sweet sorghum yields and to calibrate/validate model parameters. This report did not have crop parameters specifically developed for sweet sorghum and as a result parameters from maize, sorghum hay, and sugar cane were combined to make a sweet sorghum crop parameter set, which may not be representative of actual sweet sorghum physiology.

Morris (2008), in an economic study of sweet sorghum as a bio-feedstock in Texas, used a Multi-Variate Empirical (MVE) probability distribution to estimate the annual stochastic yields from sweet sorghum. Sweet sorghum crop parameters did not appear to be used to estimate the MVE parameters; instead sweet sorghum yield data from Texas Agri-Life Research field experiments were used with MVE model parameters derived from maize, grain sorghum, and cotton yields, modelled from 47 years of weather data using output from the CroPMan crop model (Morris, 2008). This economic feasibility study concluded that a facility in Texas designated specifically for sweet sorghum would not be economically viable in 14 regions with a short growing season. The author suggested that sweet sorghum could be a supplement to the industry during part of the year in sugar producing counties. Modelling was not described in detail in this study, and it appeared that biomass yields from sweet sorghum were not directly estimated with the CroPMan model. No published literature was found describing CroPMan parameters or models being used to estimate the biomass accumulation of sweet sorghum.

In the modelling studies described above, a designated model and set of parameters developed from sweet sorghum literature were non-existent or not described in detail. The lack of specific literature-based modelling parameters and available biomass comparison data showed a need for further sweet sorghum model development and viable field experiments for model comparison. The versatility of models such as APSIM, SWAT and the Soil Water Balance (SWB) model, suggests that some of these models may be suitable to estimate sweet sorghum biomass production, provided that model parameters are available, or can be determined for this crop.

5.2 Soil Water Balance Model

The Soil Water Balance (SWB) model is a mechanistic, daily time step, generic crop irrigation model which can be run using two types of models (Annandale *et. al*, 1999):

a. The mechanistic crop growth model, which calculates crop growth and soil water balance components mechanistically.

b. The FAO-type crop factor model, which calculates the soil water balance mechanistically without simulating dry matter production.

SWB is a growth simulator designed as a real time and user-friendly irrigation scheduling tool based on the improved generic crop version of NEWSWB (Benade *et.al*, 1997). According to Jovanovic and Annandale (2000), the SWB model gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop databases.

The crop database that is of importance includes several crop specific growth parameters; vapour pressure deficit corrected dry matter/water ratio, specific leaf area, stem-leaf dry matter partitioning parameter, maximum root depth, maximum crop height, canopy extinction coefficient for solar radiation and growing day degrees necessary for the completion of several phenological stages. In the crop unit, SWB calculates crop dry matter accumulation in direct proportion to transpiration corrected for vapour pressure deficit. It also calculates radiation-limited growth and uses the lower of the two values. This dry matter is partitioned to roots, stems, leaves, grain or fruits, depending on phenology which is calculated with thermal time and modified by water stress.

The weather unit of SWB calculates the Penman-Monteith grass reference daily evapotranspiration according to the recommendations of the Food and Agriculture Organization (FAO). In the soil unit of SWB, potential evapotranspiration is divided into potential evaporation and potential transpiration by calculating canopy radiant interception from simulated leaf area. This represents the upper limits of evaporation and transpiration, which will only proceed at potential rates if atmospheric demand is limiting.

Since SWB is a generic crop model (Annandale *et. al*, 2000), parameters specific for each crop have to be experimentally determined. Currently, there is little or no information available for the sweet sorghum variety (Sugar graze) that was used in this study. The objectives of this part of the study were therefore to:

i. Collect field data to determine crop-specific model parameters for sweet sorghum.
ii. Calibrate and validate the SWB model for this variety of sweet sorghum
iii. Use the calibrated model to simulate potential yields of sweet sorghum under different water treatment scenarios.

5.3 Crop parameter determination

Model growth parameters for sweet sorghum were determined from growth analysis data collected during the 2010/2011 field experiments at the Hatfield Experimental Farm. The parameters needed to run the SWB model include base temperature (^oC), optimum temperature (^oC) and cut off temperature (^oC), which were obtained from literature. Transition day degrees (d ^oC), day degrees for leaf senescence (d ^oC), maximum root depth (m), stem to grain translocation, canopy storage (mm), minimum leaf water potential (kPa), at optimum growth, maximum transpiration (mm day^{-1}), specific leaf area (m^2 kg^{-1}), leaf-stem partitioning parameter (m^2 kg^{-1}), total dry matter (TDM) at emergence (kg m^{-2}), root fraction, root growth rate, maximum crop height (m) and stress index are also needed for running the growth model. These were measured or calculated from measurements, or default values as suggested by Annandale *et al*. (1999) were used and refined through calibration. Extinction coefficient, dry matter to water ratio (Pa), radiation use efficiency (kg MJ^{-1}), emergence day degrees (d ^oC), flowering day degrees (d ^oC) and day degrees to maturity (d ^oC) were also calculated from field measurements.

5.3.1 Weather variables

Weather variables were obtained from an automatic weather station located close to the experimental site. The weather data inputs required by the model included daily maximum and minimum temperatures (^oC), maximum and minimum relative humidity (%), average wind speed ($m\ s^{-1}$), precipitation (mm) and total solar radiation ($MJ\ m^{-2}\ day^{-1}$).

5.3.2 Soil parameters

Soil samples were collected before planting to obtain soil chemical and physical properties. Soil physical analysis results were used for SWB model soil inputs (Table 3.1).

5.3 RESULTS

The crop parameters determined for sweet sorghum together with their respective values, are included in Table 5.1.

Table 5.1: Crop specific growth parameters for sweet sorghum that were determined and included in the SWB database

Crop Parameter	Value	Source
Canopy radiation extinction coefficient	0.58	Data
Corrected dry matter-water ratio (Pa)	6.8	Data
Radiation use efficiency (kg MJ^{-1})	0.0020	Data
Base temperature (°C)	10.0	Literature (Curt *et al*., 1995; Curt *et al*., 1998)
Temperature for optimum growth (°C)	25.0	Literature (FAO database)
Cut-off temperature (°C)	36.0	Literature
Emergence day degrees (d °C)	120	Data
Flowering day degrees (d °C)	850	Data
Day degrees for maturity (d °C)	1600	Data
Transition period day degrees (d °C)	200	Data
Day degrees for leaf senescence (d °C)	1100	Data
Maximum crop height (m)	3.45	Data
Maximum root depth (m)	1.5	Calibration
Fraction of total dry matter translocated to heads	0.005	Literature (FAO Database)
Canopy storage (mm)	2.0	Literature
Leaf water potential at maximum transpiration (kPa)	-1500	Literature (Steduto *et al*., 1997)
Maximum transpiration (mm day^{-1})	10.0	Literature
Specific leaf area (m^2 kg^{-1})	12.0	Data
Leaf stem partition parameter (m^2 kg^{-1})	1.359	Data
Total dry matter at emergence (kg m^{-2})	0.020	Literature (FAO database)
Fraction of total dry matter partitioned to roots	0.15	Calibration
Root growth rate (m^2 $kg^{-0.5}$)	4.0	Literature (FAO database)
Stress index	0.90	Literature

The parameters in Table 5.1 were added to the SWB crop parameter database, whereafter the model was run for the calibration set (Control treatment) Figure 5.1 shows the soil water balance graph that was simulated for the control. It can be seen that according to the simulations this treatment was not stressed as the soil water content was very close to field capacity throughout the growth cycle. It is also clear that 2010/2011 was a very wet season, as a total of 722 mm of rain was received at Hatfield, Pretoria. Model simulations of root depth, LAI, Top and harvestable dry matter, and soil water deficits for the calibration data set are presented in Figure 5.2. The SWB model generally simulated top dry matter, harvestable dry matter, and leaf area index accurately, as there was generally good agreement between the measured and simulated values (Figure 5.2). Most of the statistical parameters (R^2, D, RMSE and MAE) were also within acceptable ranges (Figure 5.2). This means that the SWB model was successfully calibrated and it should be possible to accurately simulate sweet sorghum growth and yield under different water supply conditions. It can also be seen that the soil water deficits were fairly well simulated, although the MAE was greater than the acceptable 20% (De Jager, 1994). It is also worth mentioning that no measured data points were made for root depth in all the water treatments. As a result, only simulated values are shown for root depth. The measured single data point for the HDM graph represents the final yield.

After calibration of the model for the control treatment, the model was then validated on the other treatments. The simulation results for top and harvestable dry matter yield, and leaf area index of all these three treatments were simulated with reasonable accuracy and statistical parameters were generally within acceptable limits (Figure 5.3 to 5.8). Soil water deficits were, however, not so well simulated, especially during dry periods, when simulated deficits were much higher than measured values. This discrepancy can probably be attributed to the fact that soil water content measurements were only taken to a depth of 1.0 m, while the roots of sorghum are known to reach depths of up to 1.8 m. Therefore the total profile deficits measured with the neutron probe during dry periods were probably less than the actual (and simulated) deficits for a deeper profile (up to 1.8 m). A root depth of 1.5 m was used in model simulations. From these results, it is evident that the calibrated SWB model generally performed satisfactory under well watered and reasonably well under Dry land conditions. SWB should therefore be a useful tool for scenario modelling in order to estimate sweet sorghum production and water use under a wide range of conditions.

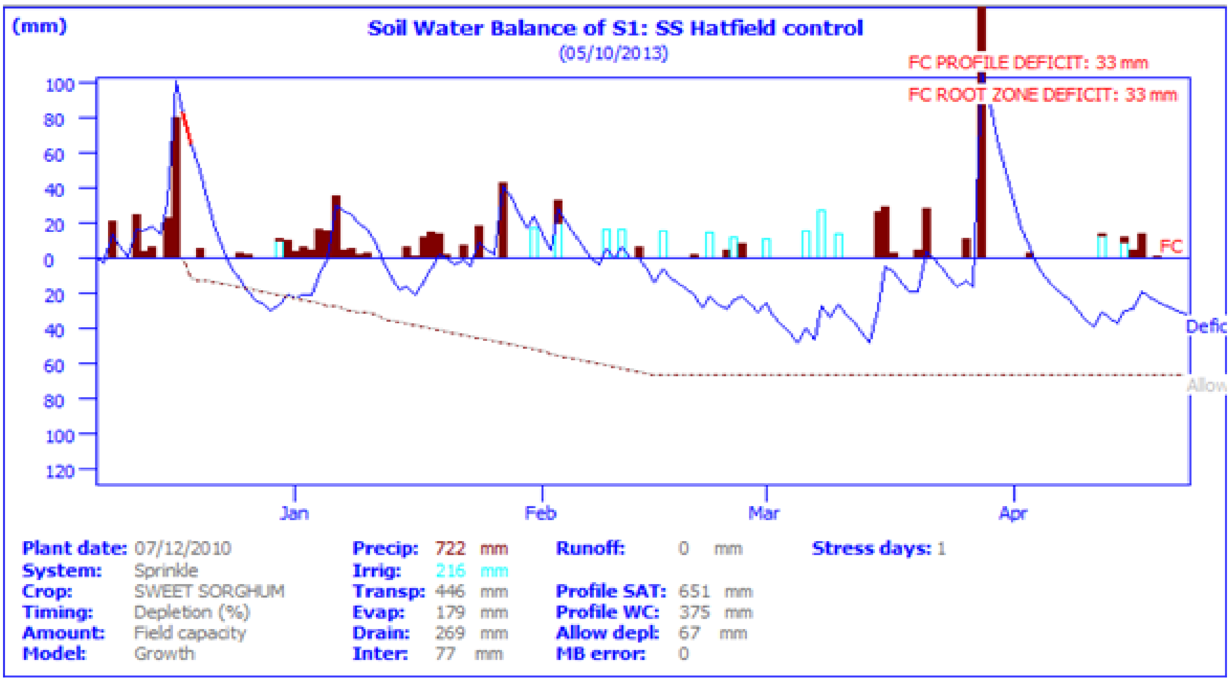

Fig 5.1: Soil water balance simulation results of the Control treatment.

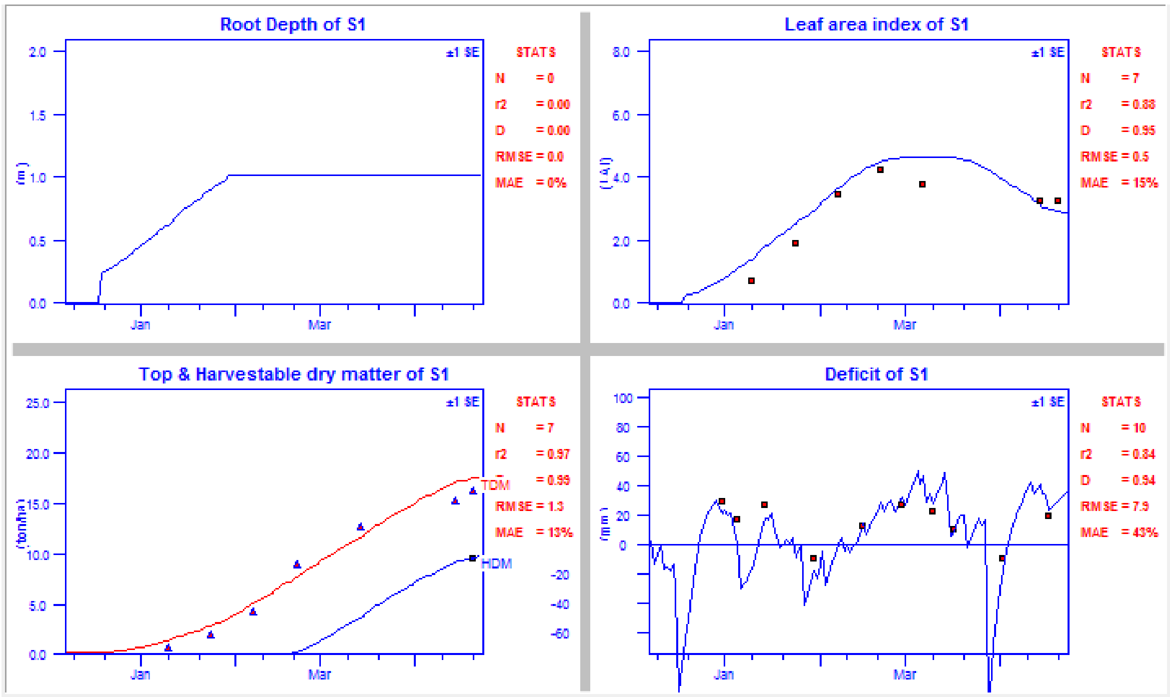

Fig 5.2: Measured and simulated leaf area index, total and harvestable dry matter yields, and soil water deficits for the Control treatment.

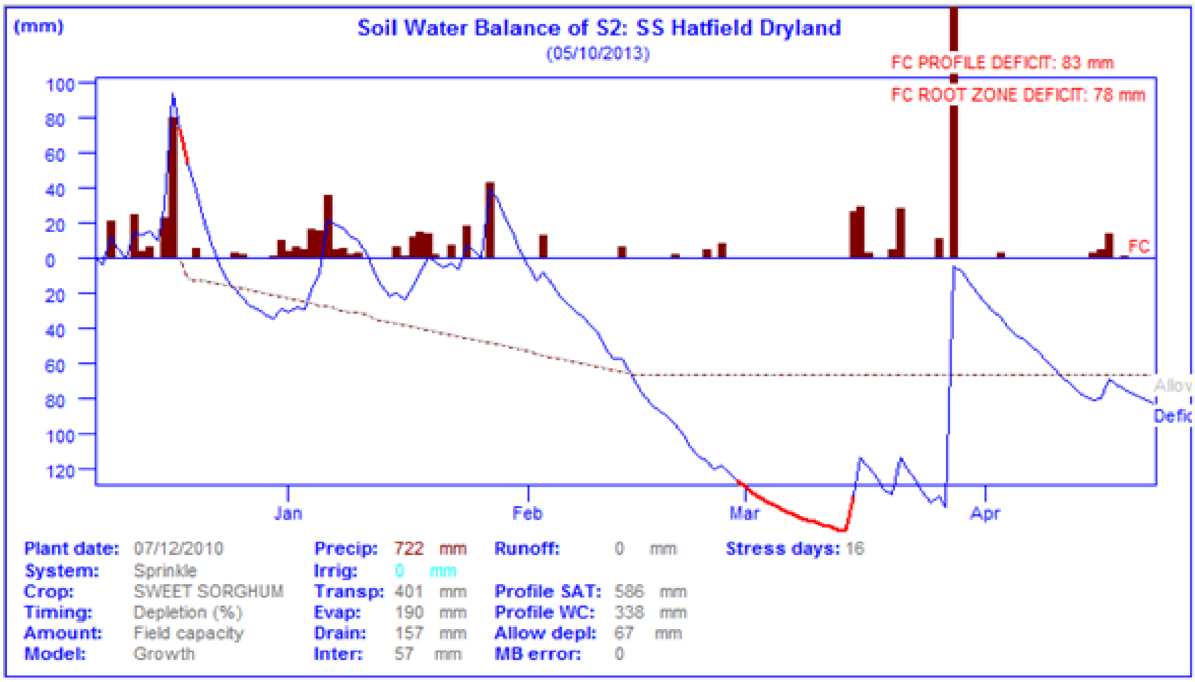

Fig 5.3: Soil water balance simulation results of sweet sorghum (Dry land) at Hatfield, Pretoria in the 2010/11 season. Red colouring of the deficit line indicates water stress.

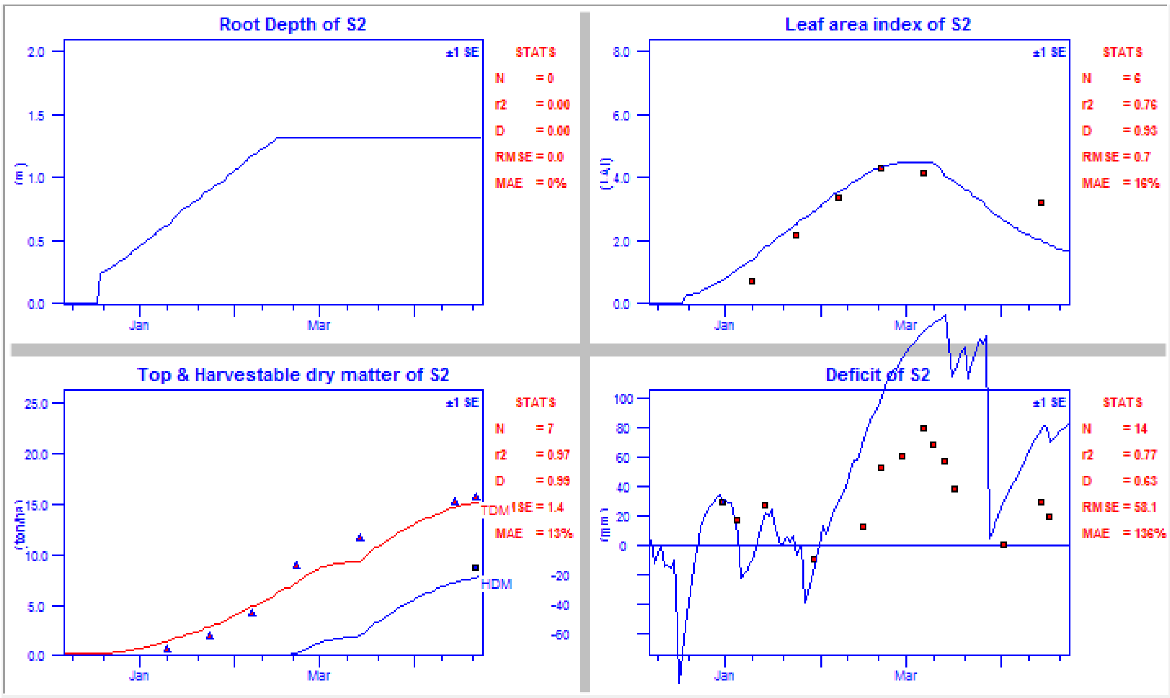

Fig 5.4: Measured and simulated leaf area index, total and harvestable dry matter yields, and soil water deficit for the Dry land treatment.

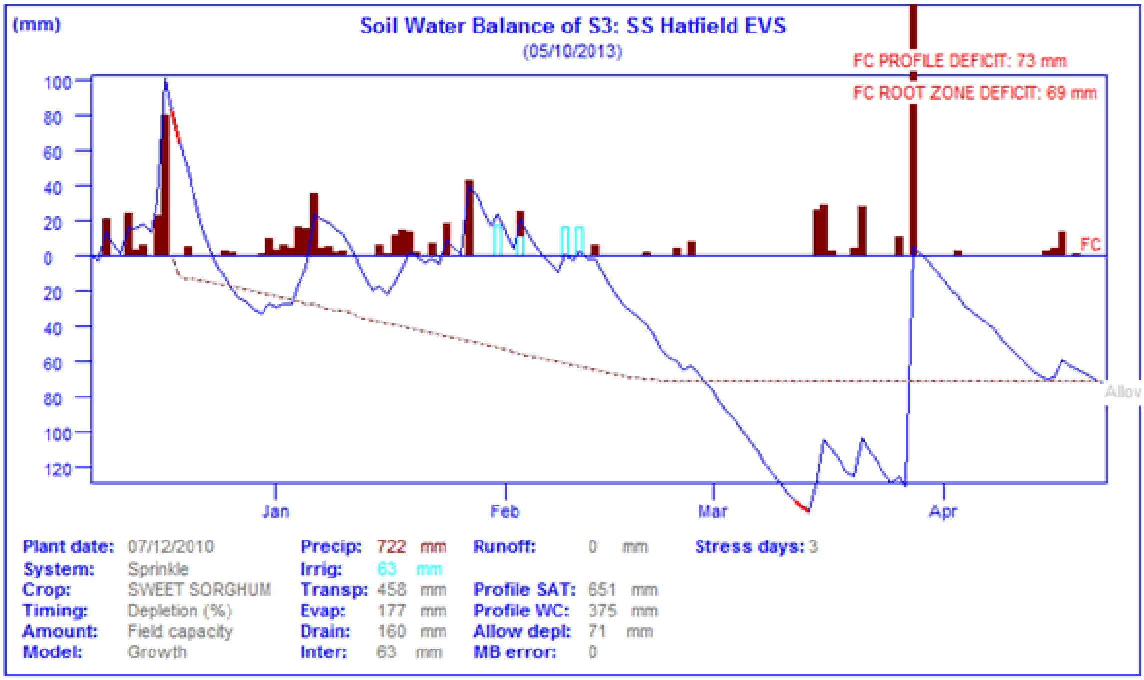

Fig 5.5: Soil water balance simulation results of sweet sorghum (EVS) at Hatfield, Pretoria in the 2010/11 season. Red colouring of the deficit line indicates water stress.

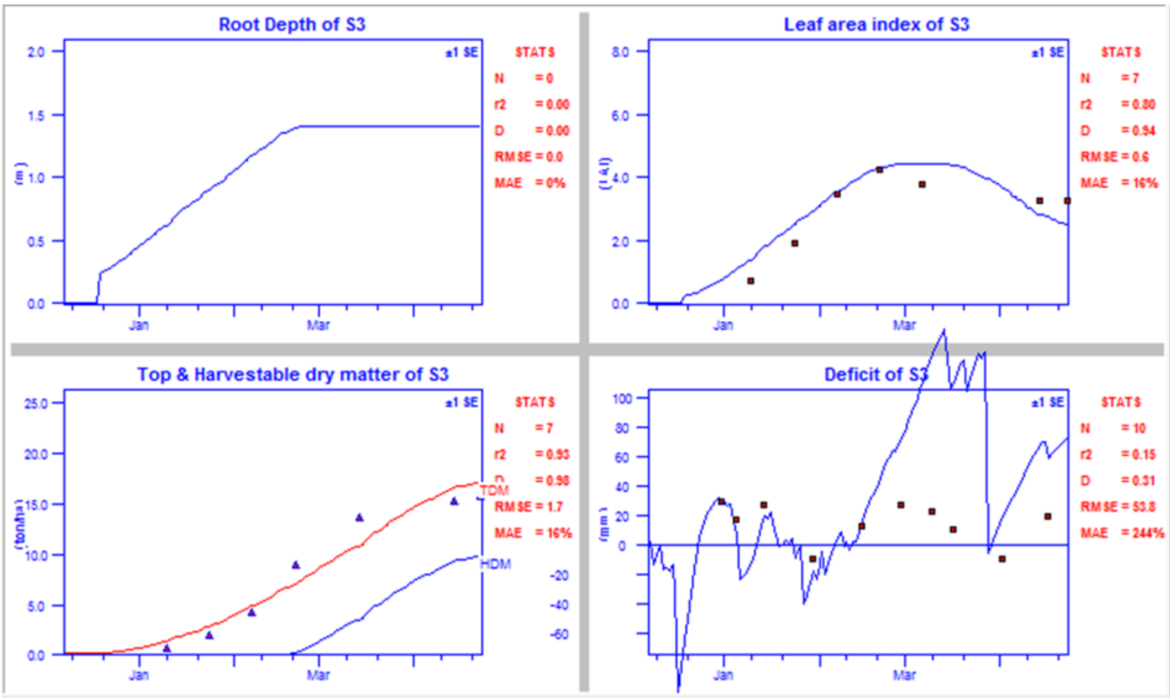

Fig 5. 6: Measured and simulated leaf area index, total and harvestable dry matter yields, and soil water deficits for the Early Vegetative Stage (EVS) irrigation treatment.

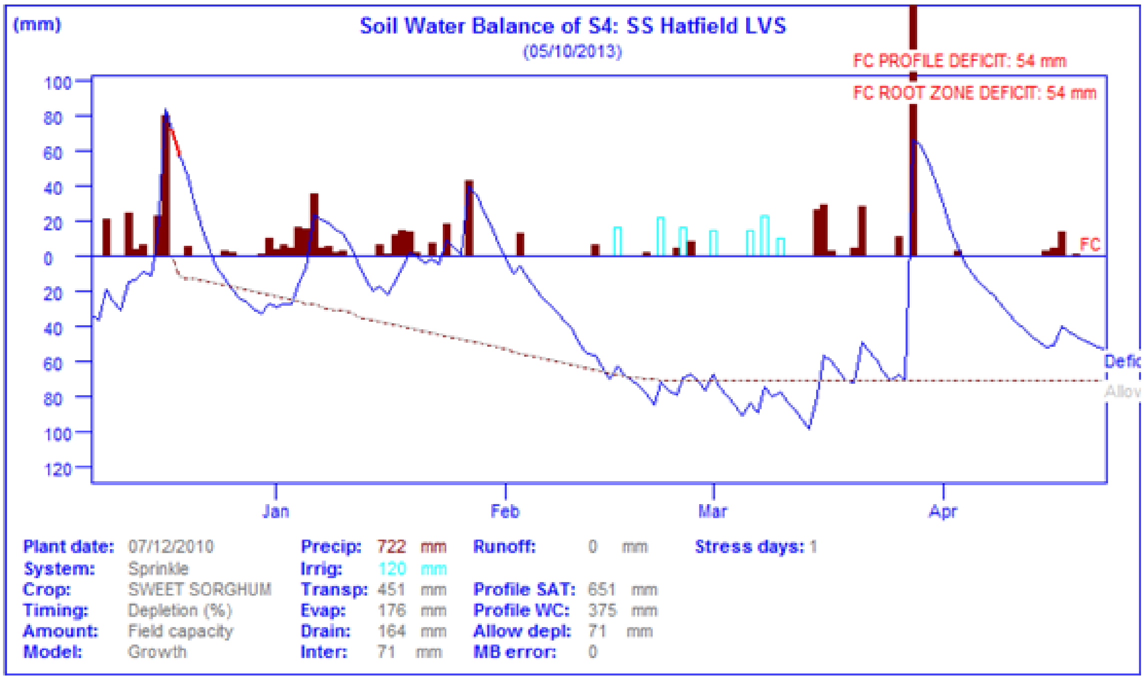

Fig 5.7: Soil water balance simulation results of sweet sorghum (LVS) at Hatfield, Pretoria in the 2010/11 season.

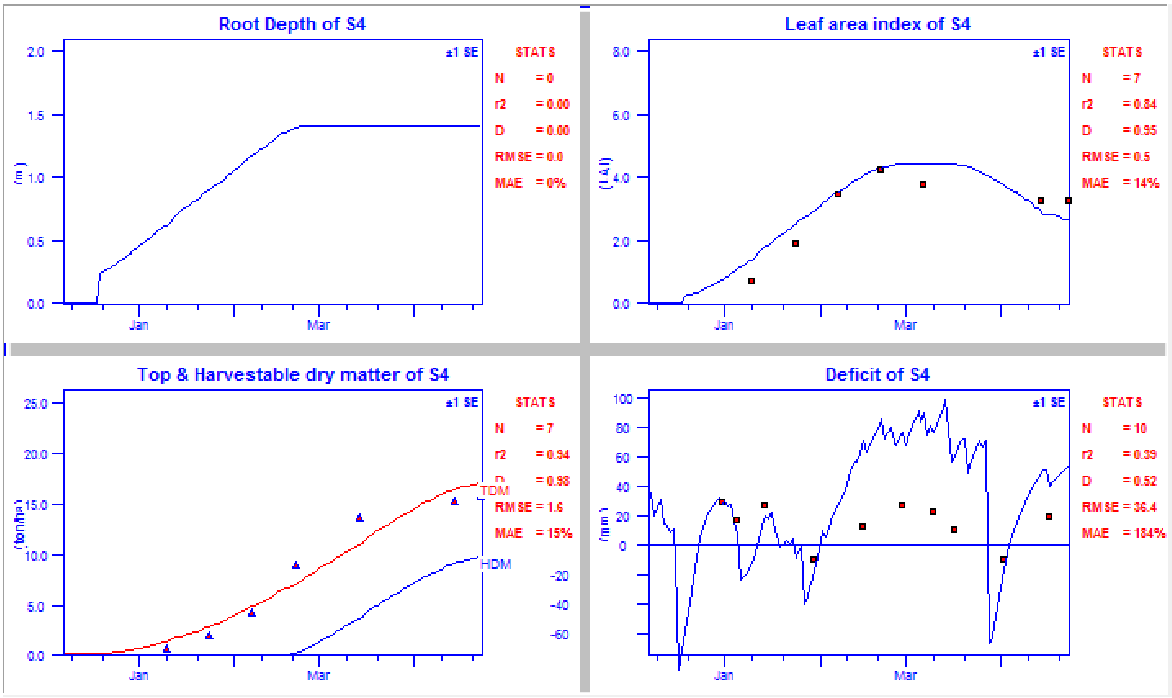

Fig 5.8: Measured and simulated leaf area index, total and harvestable dry matter yields, and soil water deficit for the Late Vegetative Stage (LVS) irrigation treatment.

From all the different scenarios, it can be seen that water stress had serious effects on total dry matter and leaf area index, more especially when the stress is applied early in the growth stages of the crop. This is agreement with the observations reported by Mastrorilli *et al.* (1999).

CHAPTER 6: GENERAL DISCUSSION AND CONCLUSION

Water deficit is a critical issue limiting crop growth by having an impact on anatomical, morphological, physiological and biochemical processes (Aydinsakir *et al*., 2013). Deficit irrigation practises affect not only water use and yield but also quality parameters such as sugar and protein content. In many studies and on several species of plants, it has been found that the critical stages which are sensitive to water stress include flowering stage, fruit setting and assimilate transfer (Katerji *et al*., 2008). During these critical stages, a moderate water deficit can lead to a severe yield reduction.

During the growth of sweet sorghum, two vegetative phases ('leaf' and 'stem') can be defined. In the first, leaf growth is predominant; while, in the second, stem growth is predominant. Manstrorilli *et al*. (1999) reported that the effect of temporary water stress on yield depended on the phenological stage during which it was applied. In comparison with a crop that is well-watered during the whole season, sweet sorghum biomass and stalk production was reduced when water stress was introduced early in the 'leaf' predominant stage. Manstrorilli *et al*. (1999) also reported that the late vegetative stages were less sensitive to a temporary water stress. It was also reported that a stress period experienced by sweet sorghum at the end of the vegetative stage resulted in only a slight decrease in stalk production. This was also true for the current study, where the Dry land and supplemental irrigation at the late vegetative stage (LVS) treatments gave lower biomass yields as compared to the control and treatment that received supplemental irrigation at the early vegetative stage (EVS). The same conclusion was also drawn by Robertson *et al*. (1999) for sugarcane, namely that severe water deficit (i.e Dry land in the case of this study) reduced all crop variables except stalk sucrose DM content, dry matter content, and stalk number. Uninterrupted water supply during the early stages of crop development (EVS) significantly increased plant height and leaf area index of sweet sorghum, which resulted in a high stalk mass. When supplementary irrigation was applied at the LVS, there was actually no beneficial gain to the crop in terms of height and biomass yield. Leaf area development was also positively correlated with water supply. According to Oktem (2008), under conditions of water stress, a plant decreases its leaf area index and economic yield. Leaves of water stressed plants also senesced much faster than those of well-irrigated plants.

The present study therefore illustrated the importance of sufficient water (or supplementary irrigation) in the early growth stages of sweet sorghum. From these results, plants that were stressed from the late vegetative stage until harvesting obtained higher sugar and ethanol yields, compared to those that were irrigated throughout the life cycle of the crop, or only during the LVS. These findings agree with those reported by Vasilakoglou *et al*. (2010) in this regard. It can then be concluded that supplemental irrigation not only influences ethanol production by the effect it has on biomass production, but also on the effect thereof on the Brix content.

The SWB model was calibrated for the well-watered control treatment of sweet sorghum that was grown at Hatfield, Pretoria in the 2010/11 season. After successful calibration, the model was validated by simulating water use, growth and biomass production of three treatments that were either grown under Dry land conditions, or that only received supplemental irrigation during different growth stages. From this it could be concluded that growth and productivity response of sweet sorghum to supplemental irrigation at different growth stages can be simulated with reasonable accuracy under well watered and Dry land conditions. Results from this study therefore suggest that sweet sorghum yields could generally be simulated well under a range of water supply conditions. The SWB model will therefore be a very useful tool for estimating water use and yield potential of sweet sorghum for different production areas of South Africa.

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APPENDIX A: Leaf dry mass statistical results for the different sampling dates

Leaf dry mass for sampling number 1 (6 January 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	10.53936875	3.51312292	1.07	0.4095
BLOCK	3	22.66551875	7.55517292	2.30	0.1459

R^2 = 0.52 CV = 19.89

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	10.285	4	LVS
A	9.223	4	Control
A	8.918	4	EVS
A	8.013	4	Dry_land

LSD = 2.90 P = 0.05

Leaf dry mass for sampling number 2 (24 January 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	238.416350	79.472117	0.90	0.4784
BLOCK	3	1849.131050	616.377017	6.98	0.0101

R^2 = 0.72 CV = 9.83

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	100.858	4	EVS
A	97.568	4	Control
A	92.890	4	LVS
A	91.045	4	Dry_land

LSD = 15.04 P = 0.05

Leaf dry mass for sampling number 3 (7 February 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	14961.79485	4987.26495	0.80	0.5262
BLOCK	3	49385.79930	16461.93310	2.63	0.1142

R^2 = 0.53 CV = 9.93

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	840.66	4	LVS
A	805.71	4	Control
A	784.04	4	Dry_land
A	757.12	4	EVS

LSD = 126.59 P = 0.05

Leaf dry mass for sampling number 4 (21 February 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	451.625000	150.541667	1.00	0.4374
BLOCK	3	8146.890000	2715.630000	17.99	0.0004

R^2 = 0.86 CV = 5.7

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	218.350	4	Control
A	218.025	4	LVS
A	213.125	4	EVS
A	205.200	4	Dry land

LSD = 19.65 P = 0.05

Leaf dry mass for sampling number 5 (7 March 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	2199.355000	733.118333	6.69	0.0114
BLOCK	3	721.815000	240.605000	2.19	0.1584

R^2 = 0.74 CV = 4.54

Means Separation using Least Significant Differences (LSD)

t Grouping		Mean	N	TRT
	A	242.375	4	LVS
	A	238.525	4	Control
B	A	227.650	4	EVS
	B	212.150	4	Dry land

LSD = 16.75 P = 0.05

Leaf dry mass for sampling number 6 (22 March 2011)

Source	F	Type I SS	Mean Square	F Value	Pr > F
TRT	3	1756.381875	585.460625	6.85	0.0106
BLOCK	3	708.016875	236.005625	2.76	0.1037

R^2 = 0.76 CV = 4.04

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	237.350	4	LVS
A	236.450	4	Control
A	230.250	4	EVS
B	211.325	4	Dry land

LSD = 14.79 P = 0.05

Leaf dry mass for sampling number 7 (14 April 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	9873.006875	3291.002292	17.25	0.0004
BLOCK	3	3745.301875	1248.433958	6.54	0.0122

R^2 = 0.88 CV = 6.38

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	241.400	4	Control
A	238.600	4	LVS
B	203.475	4	EVS
B	182.000	4	Dry land

LSD = 22.09 P = 0.05

APPENDIX B: Statistical Procedure for Dry stem mass

Stem dry mass for sampling 1 (6 January 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	2.02455000	0.67485000	0.59	0.6378
BLOCK	3	15.62305000	5.20768333	4.54	0.0336

R2 = 0.62 CV = 19.18

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	5.9350	4	LVS
A	5.9125	4	Control
A	5.4150	4	EVS
A	5.0875	4	Dry land

LSD = 1.71 P = 0.05

Stem dry mass for sampling 2 (24 January 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	146.872725	48.957575	0.48	0.7039
BLOCK	3	1346.908525	448.969508	4.41	0.0362

R2 = 0.62 CV = 13.33

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	78.965	4	EVS
A	77.870	4	Control
A	74.803	4	LVS
A	71.168	4	Dry land

LSD = 16.15 P = 0.05

Stem dry mass for sampling 2 (7 February 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	1989.650075	663.216692	0.62	0.6170
BLOCK	3	8272.963075	2757.654358	2.60	0.1169

R^2= 0.52   CV = 14.24

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	240.85	4	LVS
A	238.25	4	Dry land
A	223.08	4	Control
A	213.62	4	EVS

LSD = 52.13   P = 0.05

Stem dry mass for sampling 2 (21 February 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	27084.01500	9028.00500	2.71	0.1078
BLOCK	3	99727.99500	33242.66500	9.97	0.0032

R^2 = 0.81   CV = 10.25

Means Separation using Least Significant Differences (LSD)

t Grouping		Mean	N	TRT
	A	619.05	4	EVS
B	A	580.58	4	LVS
B	A	545.18	4	Control
	B	508.20	4	Dry land

LSD = 92.36   P = 0.05

Stem dry mass for sampling 2 (7 March 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	30407.57250	10135.85750	3.79	0.0524
BLOCK	3	90437.92250	30145.97417	11.27	0.0021
R2 = 0.83	CV = 5.72				

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	931.13	4	LVS
A	929.55	4	EVS
A	928.28	4	Control
B	829.00	4	Dry land
LSD = 82.74		P = 0.05	

Stem dry mass for sampling 2 (22 March 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	29898.25500	9966.08500	1.50	0.2792
BLOCK	3	39922.07500	13307.35833	2.01	0.1838

R^2 = 0.54   CV = 7.50

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	1139.40	4	EVS
A	1107.18	4	Control
A	1072.65	4	LVS
A	1022.78	4	Dry land

LSD = 130.3   P = 0.05

Stem dry mass for sampling 2 (14 April 2011)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	55958.2550	18652.7517	0.97	0.4500
BLOCK	3	102010.1250	34003.3750	1.76	0.2242

R^2 = 0.48   CV = 13.7

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	1089.65	4	EVS
A	1047.38	4	Control
A	984.40	4	LVS
A	934.78	4	Dry land

LSD = 222.25   P = 0.05

APPENDIX C: Statistical Analysis for Leaf area

Leaf area analysis for 6th January 2011

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	709909.280	236636.427	0.34	0.7977
BLOCK	3	3582829.948	1194276.649	1.71	0.2337

R^2 = 0.41 CV = 25.07

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	3677.4	4	LVS
A	3292.0	4	EVS
A	3243.8	4	Control
A	3111.1	4	Dry land

LSD = 1336.1 P = 0.05

Leaf area analysis for 24th January 2011

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	12876475.87	4292158.62	1.21	0.3600
BLOCK	3	87120579.73	29040193.24	8.20	0.0061

R2 = 0.76 CV = 10.82

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	18376	4	EVS
A	18189	4	Control
A	16633	4	LVS
A	16373	4	Dry land

LSD = 3009.5 P = 0.05

Leaf area analysis for 7th February 2011

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	8555852.2	2851950.7	0.59	0.6364
BLOCK	3	137002273.3	45667424.4	9.46	0.0038

R2 = 0.77 CV = 7.38

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	30404	4	Control
A	30404	4	LVS
A	29678	4	Dry_land
A	28618	4	EVS

LSD = 3514.5 P = 0.05

Leaf area analysis for 21 February 2011

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	21549070.84	7183023.61	4.45	0.0354
BLOCK	3	93974518.14	31324839.38	19.39	0.0003

R^2 = 0.88 CV = 3.34

Means Separation using Least Significant Differences (LSD)

t Grouping		Mean	N	TRT
	A	39084.4	4	Control
	A	39084.4	4	LVS
B	A	37691.9	4	EVS
B		36283.7	4	Dry land

LSD = 2033.2 P = 0.05

Leaf area analysis for 7th March 2011

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	55032330.29	18344110.10	10.08	0.0031
BLOCK	3	11333087.92	3777695.97	2.08	0.1739

R^2 = 0.80 CV = 3.81

Means Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	36981.4	4	Control
A	36981.4	4	LVS
A	35394.6	4	EVS
B	32439.2	4	Dry_land

LSD = 2158.3 P = 0.05

Leaf area analysis for 22 March 2011

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	72988731.91	24329577.30	12.33	0.0015
BLOCK	3	26962746.32	8987582.11	4.56	0.0332

R^2 = 0.85 CV = 4.07

Mean Separation using Least Significant Differences (LSD)

t Grouping	Mean	N	TRT
A	36369.5	4	Control
A	36369.5	4	LVS
B	34009.5	4	EVS
C	31180.7	4	Dry_land

LSD = 2246.5 P = 0.05

Leaf area analysis for 14th April 2011

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	223451630.1	74483876.7	28.33	<.0001
BLOCK	3	40560113.1	13520037.7	5.14	0.0242

R^2 = 0.92 CV = 4.94

Mean Separation using Least Significant Difference (LSD)

t Grouping	Mean	N	TRT
A	36351	4	Control
A	36351	4	LVS
B	30939	4	EVS
C	27586	4	Dry land

LSD = 2593.8 **P = 0.05**

APPENDIX D: Statistical Analysis for Final Yield

Final fresh stalk fresh mass analysis

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	28.68722500	9.56240833	3.22	0.0756
BLOCK	3	22.01502500	7.33834167	2.47	0.1283

R^2 = 0.654762 CV = 11.25

Mean Separation using LSD

t Grouping	Mean	N	TRT
A	16.715	4	EVS
B A	16.608	4	CONT
B A	14.128	4	LVS
B	13.855	4	Dry_land

LSD = 2.7569 P = 0.05

Final fresh leaf mass analysis

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	0.54861875	0.18287292	0.93	0.4648
BLOCK	3	1.19381875	0.39793958	2.03	0.1808

$R^2 = 0.496$ CV = 9.24

Mean Separation using LSD

t Grouping	Mean	N	TRT
A	5.0850	4	CONT
A	4.7700	4	Dry_land
A	4.7525	4	EVS
A	4.5700	4	LVS

LSD = 0.71 P = 0.05

Head Fresh Mass analysis

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	0.16751875	0.05583958	1.01	0.4331
BLOCK	3	0.79606875	0.26535625	4.79	0.0292

R-Square = 0.66 CV = 13.34

Mean separation using LSD

t Grouping	Mean	N	TRT
A	1.8875	4	EVS
A	1.8400	4	CONT
A	1.6900	4	Dry land
A	1.6400	4	LVS

LSD = 0.3765 P = 0.05

Stalk dry mass yield analysis

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	0.00561813	0.00187271	0.57	0.6461
BLOCK	3	0.04153437	0.01384479	4.25	0.0397

R-Square = 0.616401 CV = 11.83426

Mean Separation using LSD

t Grouping	Mean	N	TRT
A	0.50113	4	EVS
A			
A	0.49950	4	Dry land
A			
A	0.47288	4	LVS
A			
A	0.45650	4	CONT

LSD = 0.09 P = 0.05

Dry leaf mass analysis

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	0.01483555	0.00494518	2.60	0.1165
BLOCK	3	0.06815155	0.02271718	11.95	0.0017

R^2 = 0.829047 CV = 6.29

Mean Separation using LSD

t Grouping	Mean	N	TRT
A	0.72663	4	EVS
B A	0.70763	4	Dry land
B A	0.69275	4	LVS
B	0.64438	4	CONT

LSD = 0.0697 P = 0.05

Dry heads analysis

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	3	0.10624367	0.03541456	1.54	0.2703
BLOCK	3	0.38436905	0.12812302	5.57	0.0194

$R^2 = 0.70$ CV = 12.92

Mean Separation using LSD

t Grouping	Mean	N	TRT
A	1.2699	4	CONT
A	1.2379	4	EVS
A	1.1039	4	Dryand
A	1.0825	4	LVS

LSD = 0.2426 P = 0.05