MAXIMIZING DRY BEAN (*Phaseolus vulgaris* L.) PRODUCTION THROUGH SELECTED AGRONOMIC PRACTICES

By

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DECLARATION

I, Rudzani Mathobo declare that the thesis, which I hereby submit for the degree of Doctor of Philosophy in Agronomy at the University of Pretoria, is my own work and has never been submitted by myself at any other University. The research work reported is the results of my own investigation except where acknowledged.

Mathobo Rudzani

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Signature	Date

DEDICATION

This study is dedicated to my lovely husband, Dr Nkhumeleni Mathobo and my daughters, Dembe, Vhugala, as well as my son Wavhudi for their love, understanding, and support. It is also dedicated to my parents, mother Maatamela Elisa Rasilingwane and my late father Thilivhali Albert Rasilingwane for their prayers and support throughout my life not forgetting my late mother in law, Tshinakaho Mathobo, for her support.

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MAXIMIZING DRY BEAN (*Phaseolus vulgaris* L.) PRODUCTION THROUGH SELECTED AGRONOMIC PRACTICES

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ABSTRACT

Dry bean production in South Africa is lower than required for human consumption. Dry beans are rich in protein and thus an ideal replacement for expensive meat protein, especially for rural and poor communities in South Africa. To meet local demand, efforts to improve the yields obtained by small scale and subsistence farmers are needed. Therefore a series of experiments were conducted to investigate how dry bean production can be improved or optimized using selected agronomic practices. The objectives of the study were to determine the stability of dry bean varieties under the climatic conditions of Limpopo, to determine the impact of planting dry bean at lower or higher than recommended planting populations, to determine the effect of deficit irrigation and drought stress on dry bean production and to calibrate and validate SWB model in dry bean. The latter is of huge importance in South Africa where water resources are limited.

The desirable genotype in terms of high mean yield was OPS-RS1 and the desirable environment in terms of high mean yield was Tshiombo irrigation scheme. The GGE biplot analysis resulted in meaningful and useful summary of GE interaction data and assisted in examining natural relationships and variations in genotype performance across tested environments. According to GGE biplot OPS-RS1 can be characterized as the genotype with the highest mean yield and high in stability.

The results revealed that the interaction relationship between dry bean varieties and plant populations significantly influenced the grain yield per area, grain yield per plant, chlorophyll content, and plant height at 62 and 98 DAP (days after planting), while it affected dry matter production at 30, 62 and 98 DAP. The highest grain yield was achieved with OPS-RS2 at 150 000 plants per hectare (3.802 t ha^{-1}) in 2012. The number of seeds per plant was influenced by plant population and dry bean variety. The number of pods per plant was only influenced by plant population. A plant population of 150 000 plants per hectare was found to be the most suitable for both determinate and indeterminate dry bean varieties.

The introduction of deficit irrigation resulted in a significant reduction in plant height, number of seeds per plant and number of pods per plant. The reduction in number of seeds per plant and number of pods per plant resulted in a significant reduction in grain yield. The shelling % and 100 seed mass were not significantly influenced by deficit irrigation. Treatment S3 resulted in the poorest results throughout. The results revealed that deficit irrigation can result in substantial yield reduction in dry beans. There is thus a need for further research to develop drought tolerant varieties of dry beans.

The introduction of drought stress resulted in a reduction in dry matter production, leaf area index, number of seeds per plant, number of pods per plant, seed size and finally grain yield. The treatments S2 and S3 performed poorly throughout. The results also revealed that 100 seed mass, number of pods per plant, number of seeds per plant, total dry matter yield at 92 DAP and leaf area were all positively correlated to grain yield. Water use efficiency was significantly affected by drought stress. The results suggest that drought stress towards the end of the growing season may not cause serious harm in grain yield. The results of the study indicate that drought stress effects on photosynthetic rate were highly significant, with a reduction of up to 45%. The reduction of photosynthesis at 63 and 105 DAP was greatly due to reduced stomatal conductance. Drought stress resulted in a reduction in intercellular carbon dioxide concentration, stomatal conductance and transpiration. Chlorophyll fluorescence was also affected by drought stress. The minimal chlorophyll fluorescence (F_0) was increased by drought stress, accompanied by a reduction in the maximal chlorophyll fluorescence (F_m) and F_v/F_m. Drought stress can have serious effects on leaf gaseous exchange rate and chlorophyll fluorescence, depending on the growth stage of the plant and the duration of drought stress.

The SWB model was successfully calibrated and validated for dry beans. The results revealed that the model can be used for scenario simulation for future planning.

Keywords: Genotype x stability, plant population, deficit irrigation, drought stress, photosynthesis, modelling

CHAPTER 1

GENERAL INTRODUCTION

1.1 INTRODUCTION

Dry bean (*Phaseolus vulgaris* L.) is the most important food legume for direct consumption in the world (Jones, 1999). Dry bean is an important protein grain crop in South Africa grown mostly for human consumption. Of all the currently popular field crops that are grown in South Africa, dry beans have always commanded good producer prices relative to those of other crops. Dry bean is a very important crop especially in Limpopo where unemployment is estimated at 35.6%. Most of the people in Limpopo rely on agriculture for food security.

According to Sathe *et al*. (1984) dry beans have been referred to as the “poor man’s meat”. This is due to the fact that dry beans are very good source of proteins which is two or three times more than that found in cereal grains and they are also a good source of vitamins and certain minerals (Sinha & Hui, 2011). Dry bean have the advantage over other legumes in that the grain can be stored for long periods of time without any serious loss of nutritional value.

In 2000, the Millennium development goals (for 2015) were drafted and 147 heads of State and Governments, including South Africa, committed to it (Statistics South Africa, 2013). One sustainable development goal is zero hunger. To achieve this it will require sustainable food production systems and resilient agricultural practices, equal access to land, technology, markets and international cooperation on investments in infrastructure and technology to boost agricultural productivity. Sanchez *et al*. (2005) made recommendations for halving hunger. In this report they mentioned (1) that agricultural and nutritional research should be strengthened, (2) that small-scale water management should be improved and expanded, (3) that access to better seeds and other planting materials should be improved and (4) to improve nutrition for the chronically hungry and vulnerable.

In this light, dry beans can address the stated sustainable development goals of increased income and improved food security. This study will thus contribute to the knowledge needed (selective agronomic practices) to make dry beans one of the crops of choice for irrigated small scale production.

1.2 BACKGROUND OF THE STUDY

In South Africa the domestic consumption of dry bean exceeds domestic production (Figure 1.1). The average dry bean production in South Africa is about 65 thousand tons per annum while the average annual consumption is 129 thousand tons. This implies that the local market is only able to supply 51% of the local consumption requirements while the balance is met through imports.

In South Africa, mainly three types of beans are produced, namely red speckled beans, small white canning beans and large white kidney beans (Department of Agriculture, Forestry and Fisheries (DAFF), 2012). For this research the concentration is on red speckled beans due to the fact that it holds a large market in the dry bean industry and it is also the type of dry bean most often used in home preparation.

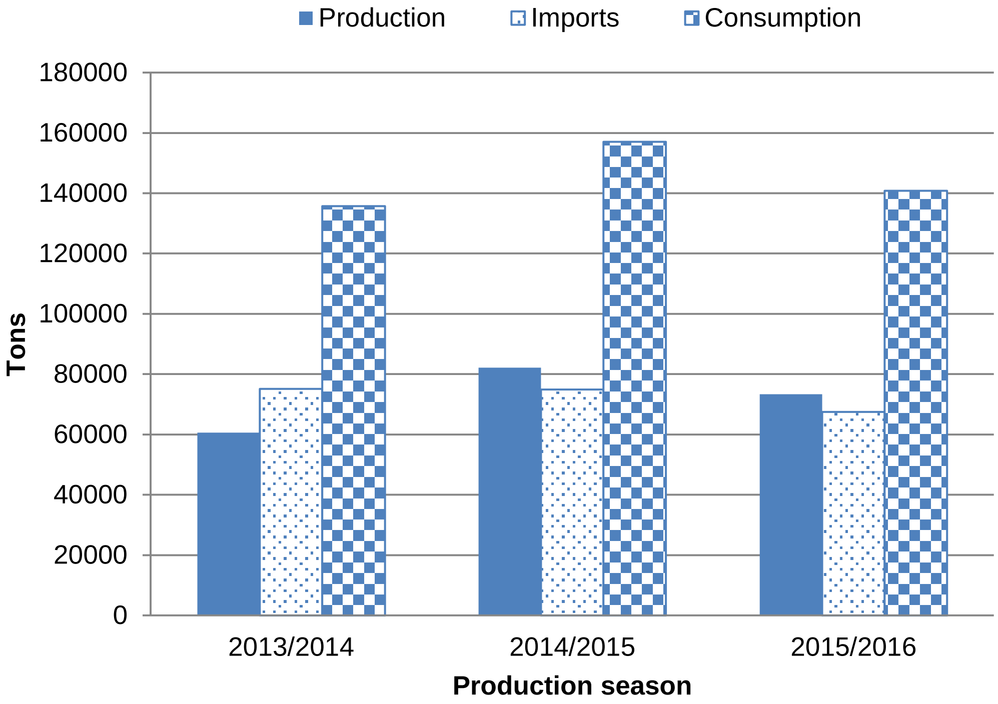

Figure 1.1 Quantities of dry bean produced, imported and consumed from 2013/2014 to 2015/2016 (DAAF, 2016)

1.3 PROBLEM STATEMENT

Limpopo dry bean Producers (Small scale) have been involved in a dry bean seed production project since 2005. The farmers are producing seed for other farmers to plant for grain production. The main challenge for dry bean production in Limpopo is that the producers mainly make use of a single variety, Kranskop. Unfortunately the Dry Bean Producer's Organization (DPO) is phasing out this variety. Therefore, there was a need to identify other stable dry bean varieties which the farmers of Limpopo could produce. To address this challenge, the current research started off by identifying alternative varieties for use by the Limpopo producers through means of a genotype x environment (GE) stability study.

Plant population differences were also identified as a cause for poor production in the Limpopo province, affecting both crop growth and yield. According to Dahmardeh *et al*. (2010) "Plant density is an important factor that affect yield and yield components in legumes". Plant population densities for common bean (*Phaseolus vulgaris* L.) varies due to cultivar growth habits, cropping systems, production environments and availability and cost of seed (Singh & Gutiérrez, 1990). Small scale farmers plant their beans using a wider spacing regardless of the growth habit. Cultivars of different growth habits respond differently to varying plant densities (Crothers & Westermann, 1976). The farmers need to be informed of the losses for using wider planting.

Another challenge faced by the Limpopo Producers is low production, mainly due to limited water resources. Water stress occurs when water available in the soil is reduced by transpiration and evaporation, with limited replacement via rain or irrigation. Water stress is one of the most important factors affecting plant growth (Rahman *et al*., 2004). Hsiao (1973) also confirmed that water stress affects all aspects of plant growth. Water stress interferes with normal plant growth and development and induces adaptive responses at different levels (Bray, 1997). In addition, South Africa is seen as a water scarce country and therefore knowledge of crop water productivity (CWP) which describes the relationship between applied water and agricultural product output (Annandale *et al*., 2011) is of utmost importance.

As dry bean is sensitive to drought stress there is a need to evaluate the applicability of deficit irrigation in dry bean production. Furthermore there is also a need to evaluate the impact of drought stress on dry bean. The unavailability of water for irrigation makes it necessary to have efficient irrigation scheduling system.

1.4 AIMS AND OBJECTIVES OF THE STUDY

Aim of the study was to maximize dry bean production in the Limpopo province.

Specific objectives of the study were to:

1. assess the genotype x environment interaction and yield stability of South African dry bean varieties.
2. investigate the response of dry bean varieties to different plant populations.
3. determine the effect of deficit irrigation on dry bean production.
4. determine the effect of drought stress on dry bean growth and yield.
5. assess the effects of drought stress on physiological processes of dry beans.
6. calibrate and validate the Soil Water Balance (SWB) model for dry bean production and use the model to predict dry bean yield for future planning.

1.5 FORMAT OF THE THESIS

Chapter one – Includes the general introduction, background, aim, and significance of the study, as well as the research objectives and content outline of the thesis.

Chapter two - A literature review on all the topics which have been addressed by the study from genotype x environment interaction and yield stability of South African dry bean varieties, investigating the response of dry bean varieties to different plant populations, the response of dry bean growth and yield to water stress, the water use efficiency in dry beans, the effects of water stress on physiological processes of dry beans, generation of crop growth parameters for the SWB modeland the calibration and validation of the SWB model for dry beans under different soil water regimes.

Chapter three - The assessment of genotype x environment interaction and yield stability of South African dry bean varieties. Chapter four – The investigation of the response of dry bean varieties to different plant populations. Chapter five – Deficit irrigation effects on yield and yield components of dry beans (*Phaseolus vulgaris* L.)

Chapter six – The effect of drought stress on dry bean. Chapter seven –Assessing the effects of moisture stress on physiological processes of dry beans. Chapter eight

–Generation of crop growth parameters for the SWB model, calibration and validation of the SWB model for dry beans under different moisture regimes. Chapter nine – General conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 GENOTYPE X ENVIRONMENT INTERACTION (GEI)

The development of varieties which produce high yield and are stable across a number of environments remain a challenge for breeders. South Africa is currently producing less dry beans than what is consumed (Department of Agriculture, Forestry and Fisheries, 2013), therefore the need to develop superior varieties and improve availability of seed becomes an urgent matter.

The term genotype (G) is defined as the cultivar (i.e. with material genetically homogeneous, such as pure lines or clones, or heterogeneous, such as open-pollinated populations) rather than to individual’s genetic make- up. The environment (E) is defined as the set of climatic, soil, biotic (pests and diseases) and management conditions in a particular trial at a given location (Annicchiarico, 2002). The genotypes may respond differently to different environments.

According to Bowman (1972), Genotype x Environment Interaction (GEI) can be defined as a change in the relative performance of a character of two or more genotypes measured in two or more environments. Baker (1988) has defined GEI as “the difference between phenotypic value and the value expected from the corresponding genotypic and environmental values”.

The GEI is considered to be a major factor limiting crop improvement in a targeted region (Kang, 1998). The GEI becomes important when the rank of genotypes changes in different environments and this change in rank is defined as crossover GEI (Baker, 1988). On the other side GEI offer opportunities in the selection and adoption of genotypes which are showing positive interaction with the location and its prevailing environmental conditions or by identifying genotypes with a low frequency of poor yield or crop failure (Simmonds, 1991; Ceccarelli, 1996).

Stability and GEI analysis have been deemed to be of great importance in common beans (Kang *et al*, 2006). High yield stability usually refers to a genotype’s ability to perform consistently, whether at high or low yield levels, across a wide range of environments (Annicchiarico, 2002). De Lange and Labuschagne (1999) studied the GEI and principal factor of seed characteristics related to canning quality of small white beans (*Phaseolus vulgaris* L.). The results indicated that the trait expression was strongly influenced by GEI, except for processed bean colour.

2.1.1 Statistical methods to measure GEI

There are several statistical methods used to measure GEI which are combined Analysis of variance (ANOVA), stability analysis and multivariate analysis.

2.1.1.1 Analysis of variance (ANOVA)

Combined analysis of ANOVA is most often used to identify the existence of GEI in multi-environmental experiments. The major limitation of this analysis is the assumption of homogeneity of variance among environments required to determine genotype differences. Although this analysis allows the determination of the components of variance arising from different factors (genotype, environment and the GEI), it does not allow to explore the response of the genotypes in the non-additive term: the GEI (Zobel *et al*., 1988; Gauch, 1992).

2.1.1.2 Genotype effects and genotype × environment Interaction effects (GGE) biplot

The GGE biplot was developed to address specific questions related to genotype by environment data. It allows for visual examination of the relationships among test environments, genotypes and the GEI and it easily shows which cultivar performed the best in which environment. The GGE biplot has been proposed by Yan and Kang (2003), Samonte *et al.* (2005), Fan *et al*. (2007) and Farshadfar *et al*. (2012).

Kang *et al*. (2006) investigated the adaptability and stability of bean cultivars as determined via yield stability statistic and GGE biplot analysis. Analysis of variance by year across locations revealed significant variation among cultivars as well as significant variation associated with cultivar by location interaction. The Kang's yield stability statistic (YS_i) and GGE biplot complemented each other in identifying cultivars which had general and/or specific adaptation cross locations.

2.1.1.3 Additive main effects and multiplicative interactions (AMMI)

The application of AMMI models to agricultural research was proposed by Kempton (1984) and Zobel *et al*. (1988). AMMI is the combination of ANOVA of the main effects of the genotypes and the environment together with the principal component analysis of the GEI (Gauch, 1988). The AMMI integrates additive main effects and multiplicative components, extracting first the additive main effects and then using principal component analysis to investigate the GE (Crossa *et al*., 1991) and it also provides a biplot (Zobel *et al*. 1988). The use of AMMI for multi-location trials has been performed by many researchers (Smith & Smith, 1992; Steyn *et al.*, 1993; Yau, 1995; Purchase, *et al.*, 2000; Ebdon & Gauch, 2002; Hugh & Gauch, 2006; Ramburan *et al*., 2011).

The success of AMMI models in predicting yields for lucerne cultivars was illustrated by Smith and Smith (1992). Steyn *et al*. (1993) found that the AMMI model was suitable for determining the reaction of potato cultivars/lines in an environment. Nel *et al*. (2000) studied the effect of environment and cultivar on sunflower seed. Laubscher *et al.* (2000) investigated the causes of GEI using AMMI in maize. Ma'ali (2008) used Additive Mean Effects and AMMI statistical model to determine yield performance and stability of different maize genotypes. Therefore one could expect good results for using it in testing the adaptability of different dry bean cultivars to different environments.

2.1.1.4 Linear regression analysis

Joint linear regression analysis was developed by Yates and Cochran in 1938 (Annicchiarico, 2002). Due to its simplicity, the joint regression has been the most popular approach for analysis of adaptation (Ramagosa *et al*., 1993). It has since been revised by a number of authors (Finlay & Wilkinson, 1963; Eberhart & Russell, 1966; Perkins & Jinks, 1968; Crossa, 1990). The analysis has some limitations which are:

1. environmental index is not independent of the analysed data,
2. regression coefficients are biased because one assumption in the regression analysis is that the independent variable (environmental mean) is measured without error,
3. in this method it is assumed that a linear relationship exists between GE and environmental mean and
4. relative stability of each pair of genotypes depends on the other genotypes in the experiment (Farshadfar, 2008).

Despite these limitations, linear regression is simple to interpret and has simple calculations (Carvalho *et al*., 2016). Linear regression has been used successfully in several studies by Kamutando *et al*. (2013) in maize, Farshadfar *et al*. (2013a) and Gowda *et al*. (2011) in chickpea and Fikere *et al*. (2014) in field pea.

2.1.1.5 Stability concept

This static concept means that a genotype has a stable performance across environments and there is no variation among environments (Kang, 2002). Becker (1981) referred to it as a biological concept of stability. It is equivalent to type 1 stability (Lin *et al*., 1986). In type 1 stability a genotype is regarded as stable if its among-environment variance is small.

Dynamic stability implies a genotype has a stable performance, but, for each environment, its performance corresponds to the estimated level or predicted level (Kang, 2002). Becker (1981) referred to it as an agronomic concept of stability. It is equivalent to type 2 stability (Lin *et al*., 1986). In type 2 stability if a genotype is stable its response to environment is parallel to the mean of all genotypes in a test.

Lin *et al*. (1986) grouped stability models into four which are: A, B, C and D, which they further grouped into 3 types of stability: Type 1, Type 2 and Type 3. Group A is based on deviation from the average genotype effect. Group B is based on the GEI term. Group C and D is based on either deviation from average genotype effect (DG) or GEI. The formulae of groups A and B represent sum of squares, and the formulae of groups C and D represent a regression coefficient or deviation from regression (Kang, 2002). Type 1 and 2 is as explained earlier, while in Type 3 the genotype is stable if the residual Mean Square from the regression model on the environmental index is small. Lin and Binns (1991) further came up with Type 4 stability which relates to consistency of yield exclusively in time, i.e. across years (or crop cycles) within location.

2.2 PLANT POPULATION DENSITY

Plant population is one of the factors that affect growth and yield. According to Dahmardeh *et al*. (2010) “Plant density is an important agent that affects yield and yield components in legumes”. Plant population densities for common bean (*Phaseolus vulgaris* L.) varies due to cultivar growth habit, cropping system, production environment, resource availability (example nutrients) and availability and cost of seed (Singh & Gutiérrez, 1990). Cultivars of different growth habits respond differently to varying plant densities (Crothers & Westermann, 1976). Singh and Gutiérrez (1990) indicated that determinate cultivars can be sown at high densities whereas indeterminate cultivars have a lower optimum plant population.

Morgade and Willey (2003) reported that variation in plant population affects total bean yields. High plant population adversely affects plant growth and development, while suboptimal plant population results in high yield per plant but lower yield per unit area (Singh *et al.,* 1992). Jamaati-e-Somarin *et al.* (2009) and Aminifard *et al.* (2010) reported that leaf chlorophyll content was decreased with increasing plant population.

Decreasing the distance between plants offers several potential advantages. The smaller amount of sun striking the ground decreases the potential for weed interference (Johnson *et al*., 1998), especially for shade intolerance species (Isaac *et al*., 2000). Less energy reaching the soil, also reduces evaporation, thus saves water.

Plant height increased with an increase in plant population (Moniruzzaman *et al*. 2009; El Naim & Jabereldar, 2010). This might have been caused by competition for light. According to Parvizi *et al*. (2009) and Dahmardeh *et al*. (2010) the number of pods per plant decreased with increasing plant population. This is due to more competition for space and minerals between plants. The snap bean (*Phaseolus vulgaris* L.) seed yield increased in high plant populations with determinate cultivars and with indeterminate cultivars grain yield remained constant (Crothers & Westermann, 1976; El Naim & Jabereldar, 2010). Knowledge of the effect of plant population on the seed yield components of beans (*Phaseolus vulgaris* L.) is needed to design management systems utilizing the genetic potential of different cultivars and to aid in the development of higher seed-yielding cultivars (Westermann & Crothers, 1977).

2.3 WATER STRESS

Water stress is the situation where water loss is more than water absorbed by the roots in the soil. Water stress occurs when water available in the soil is reduced by transpiration and evaporation. Water stress is one of the most important factors affecting plant growth (Rahman *et al*., 2004).

Kramer (1983) and Hsiao (1973) reported that moisture stress has an effect on all aspect of plant growth, including the anatomy, morphology and biochemistry. It was further indicated that moisture stress results in reduced plant size, leaf area, and crop yield. Pessarakli (1995) indicated that water stress is usually assessed by the change in water potential measured in the environment or within the plant. Loss of turgor affects the rate of cell expansion and cell size which leads to decrease in stem elongation growth rate , leaf size and stomatal aperture (Hale & Orcutt, 1987) as well as the size and number of potential storage sites for produced dry matter (Momen *et al*., 1979). When leaf size is reduced there is less photosynthates available for translocation to the fruits. A plant under water stress results in not only competition for water between plants but also in competition for water within the plant.

The effects of water stress on plants have been reported to be dependent on the developmental growth stage of a plant when stress occurs as well as the duration of the stress (Momen *et al*., 1979). It is therefore important to include these two factors in trails about water stress and its effect on growth, development and yield.

2.3.1 Irrigation scheduling

Proper irrigation management is very important as the world is faced with the challenge of water scarcity and ground water pollution. South Africa receives an average rainfall of 495 mm per annuum (Annandale *et al*., 2011), therefore proper irrigation scheduling becomes important in every farming community. Irrigation scheduling is a systematic method by which the producer decides when to irrigate and how much water to applied (Van der Gulik, 2006).

The adoption of irrigation scheduling technique appears to be very limited in South Africa (Leib *et al*., 2002). Stevens *et al*. (2005) confirmed this. They reported that in a survey conducted in 332 irrigation schemes of South Africa, irrigation scheduling is being practiced by only 18% of the farmers The rest rely on approaches based on ‘instinct, knowledge, experience and confidence gained over many years of farming’.

The primary objective of irrigation scheduling is to reduce loss of water and maximize transpiration, which is beneficial due to its connection with dry matter production (Tanner & Sinclair, 1983). Irrigation scheduling needs a water management strategy to prevent over-application of water while maximizing the net return. Proper accounting which indicates how much water the crop used provides the producer with an idea of how much water to be applied during the following irrigation opportunity (Waskom, 1994).

Effective irrigation scheduling requires knowledge of: soil water-holding capacity, current available soil moisture content, crop water use or evapotranspiration (ET), crop sensitivity to moisture stress at current growth stage, irrigation and effective rainfall received, availability of water supply and length of time it takes to irrigate a particular field (Waskom, 1994).

2.3.1.1Irrigation scheduling methods

Irrigation scheduling methods can be classified into three major categories: Soil moisture monitoring, crop canopy index and water budget approach (Table 2.1). The producer must choose the scheduling method which suits best their needs and capabilities.

Table 2.1 Irrigation methods and tools (Waskom, 1994)

Method	**Tools**	**Advantages/disadvantages**
1.Soil water monitoring (Indicates when and how much to irrigate)		
Hand feel and appearance	Hand probe	Variable accuracy, requires experience
Soil moisture tension	Tensiometers	Good accuracy, easy to read
Electrical resistance tester	Gypsum blocks	Works over broad range, limited accuracy
Indirect moisture content	Neutron probe	Expensive , many regulations in terms of the use of radio-active material
Gravimetric analysis	Oven and scale	Labour intensive
2. Crop canopy index (Indicates when to irrigate but not how much to apply)		
Visual appearance	Field observation	Variable accuracy
Water stress index	Infrared thermometer	Expensive
3. Water budget approach (No field work required, but needs periodic calibration since only estimates water use).		
Check book method	Computer / calculator	Indicates when and how much water to apply
Reference ET	Weather station data	Requires appropriate crop coefficients
Atmometer	Weather station data	Requires appropriate crop coefficients

2.4 CROP MODELLING

Modeling is based on the assumptions that a given process can be expressed in terms of a formal mathematical statement. The interest of the application of computer models in agriculture is increasing, particularly since personal computers have become accessible to crop producers (Jovanovic & Annandale, 1999). The model attempts to predict the way in which the crop will respond to a given environment. Crop modelling can be defined as the construction of the mathematical analogues of the cropping system and their use in dynamic simulation of constituent processes by numerical integration with the use of computers (Hammer, 1998).

According to Singels *et al*. (2010) models can be used to integrate knowledge and data across disciplines and assisting the synthesis of new knowledge. They further indicated that models also enable scientists to examine scientific hypotheses and investigate the impact of unprecedented agricultural and ecological conditions.

2.4.1 Types of models

Models can be deterministic or stochastic, dynamic or static, mechanistic or empirical (Thornley & France, 2007).

1. Deterministic models make definite predictions for quantities such as plant dry matter or animal intake without any associated probability distribution. These types of models are not satisfactory for variable quantities or processes like rainfall or immigration (of pests and predators).
2. Stochastic models include a random element as part of the model, so that the predictions have a distribution. A problem with stochastic models is that they can be difficult to construct.
3. Dynamic models predict how quantities vary with time, it is represented as a set of ordinary differential equations with time as the independent variable.
4. Static models do not contain time as a variable and do not make time-dependent predictions e.g. prediction of fruit dry matter at harvest.
5. Empirical models aim principally to describe the responses of a system often using mathematical or statistical equations without any scientific content and

unconstrained by any scientific principles. This model describes the responses belonging to a single level of the descriptional or organizational hierarchy.

6. Mechanistic models provide the degree of understanding or explanation of the phenomena being modelled. To achieve this, the model must be constructed on two levels of description (e.g. the plant and organ levels).

Several crop growth and water balance models have been developed with different levels of complexity depending on specific requirements (Whisler *et al*., 1986; Singels and De Jager, 1991; Crosby, 1996).

The soil water balance (SWB) model is a mechanistic, real time, generic crop, soil water balance, irrigation scheduling model (Jovanovic & Annandale, 1999). It is based on the improved crop version of NEWSWB (Campbell & Diaz, 1988). It gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop databases. Since SWB is a generic crop model, it requires specific parameters for each crop (Annandale *et al*., 1999).

The SWB model has been calibrated and validated for a number of crops. Jovanovic *et al*. (2000) reported that the SWB model was successfully calibrated for 19 summer vegetables grown at Roodeplaat and used to estimate seasonal crop water requirements. Various deficit irrigation strategies could be simulated reasonably with the mechanistic SWB model for sunflower (Jovanovic *et al*., 2000). Jovanovic *et al*. (2002) also reported that the SWB model can be used to accurately schedule irrigation in soybean.

CHAPTER 3

EVALUATION OF VARIETY X ENVIRONMENT INTERACTION USING GGE-BIPLOT IN DRY BEAN (*Phaseolus vulgaris* L.).

ABSTRACT

Dry bean varieties were evaluated for variety x environment interaction (GEI) and yield stability from 2010 to 2012. Six varieties of dry beans were planted in the 2010 and eight varieties in 2011 and 2012 seasons at five locations in the Limpopo province with different agro-climatic characteristics. The locations were Trichardtsdal (24°10’0’’S, 30°23’6’’E), Dalmada (23°55’6’’S, 29°28’6’’E), Dzindi irrigation Scheme (23°01’45’’S and 30°26’30’’E), Tshiombo (22°48’0’’S, 30°33’0’’E) and Phalaborwa (23°55’0’’S, 30°59’4’’E). The varieties used were OPS-RS1, Jenny, PAN 148, Kranskop, DBS310, OPS-RS4, DBS 360, OPS-RS2 and OPS-RS5. The results revealed that environment contributed more to total variation, followed by GEI and finally genotype. According to the GGE biplot, OPS-RS1 was regarded as the more stable variety and Tshiombo irrigation scheme the most desirable environment in Limpopo for dry bean production.

Keywords: Stability analysis, GEI, adaptation

3.1 INTRODUCTION

In South Africa dry bean remains one of the most important legume crops (Liebenberg, 2002) for human consumption. Food security of the world relies on the development of highly productive and stable varieties of legume crops. Variety trials are routinely conducted in order to compare multiple genotypes in multiple environments. Variety trials provide essential information for selecting and recommending crop cultivars (Yan and Tinker, 2006). Kranskop is one of the most popular varieties used in Limpopo. Unfortunately the Dry Bean Producers’ Organization is phasing out this variety. Therefore, there was a need to identify other stable dry bean varieties which the farmers of Limpopo could produce.

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Many stability indices have been proposed, as reviewed by Lin and Binns (1994) and Yan and Kang (2003). Several researchers have published books and symposium proceedings to document the advances in the study of GEI (Kang, 1990, 2003; Gauch 1992; Imrie & Hacker, 1993; Cooper & Hammer, 1996; Kang & Gauch, 1996). Most of the earlier studies concentrated more on quantifying GEI, while the more recent studies were more concerned about matching genotypes with environments. The gap between the two can be bridged by the use of biplot analysis methodology. According to Yan and Tinker (2006) a biplot is a scatter plot that approximates and graphically displays a two-way table by both its row and column factors such that relationships among row factors, relationship among the column factors, and the underlying interactions between the row and column factors can be visualized simultaneously.

The first application of biplots to agricultural data analysis was done by Bradu and Gabriel (1978), using data from cotton. Kroonenberg (1995) published an introduction to biplot analysis for G x E tables. The term “GGE biplot” was proposed to address the questions relative to genotype (G) by environment (E) data (Yan *et al.*, 2000). The term “GGE” was used to emphasize the understanding that G and GE are the two sources of variation that are relevant to genotype evaluation. The GGE biplot is an effective method based on principal component analysis (PCA) to fully explore Multi-environmental data.

The GGE biplot is an effective tool for mega-environment analysis (Yan & Tinker, 2006), genotype evaluation and environmental evaluation (Ding *et al*., 2007). It has been reported to be effective for GE interaction (Fan *et al*., 2007; Yan & Kang, 2003 and Samonte *et al*., 2005) and in variety evaluation of wheat (Yan & Hunt, 2001; Yan *et al*., 2000), maize (Fan *et al*., 2007) and soybean (Yan & Rajcan, 2002). Several researchers have studied the use of GGE-biplot methodology to analyse GE interactions in oil palm (Okoye *et al*., 2008), wheat-barley (Farshadfar *et al.,* 2012), chickpea (Farshadfar *et al*., 2013b) and wheat (Rad *et al*., 2013). The objectives of the present study was to (i) evaluate the stability performance of dry bean varieties under different environmental conditions using GGE biplot methodology, (ii) examine the relationship among test environments, (iii) examine the relationship among varieties and (iv) determine the relationship between varieties and environments.

3.2 MATERIALS AND METHODS

Six varieties of dry beans were planted in 2010 and eight varieties in 2011 and 2012 seasons at five locations in Limpopo with different agro-climatic characteristics. The locations were Trichardtsdal (24°10’0’’S, 30°23’6’’E), Dalmada (23°55’6’’S, 29°28’6’’E), Dzindi irrigation Scheme (23°01’45’’S and 30°26’30’’E), Tshiombo (22°48’0’’S, 30°33’0’’E) and Phalaborwa (23°55’0’’S, 30°59’4’’E). Dzindi was included in all the years, while Dalmada and Tshiombo were only used in 2010 and 2012 respectively. Trichardtsdal was used in 2010/2011, while Phalaborwa was used in 2011/2012 as well as 2012/2013. All the sites were under irrigation. The varieties used in 2010 were OPS-RS1, Jenny, PAN 148, Kranskop, DBS310 and OPS-RS4, in 2011 and 2012 the following genotypes were added: DBS 360, OPS-RS2 and OPS-RS5, while PAN 148 was left out due to unavailability of the seed. A randomized complete block design with three replications was used at each location. The plots consisted out of 4 rows each of 5 m in length. A within-row spacing of 7.5 cm and between-row spacing of 90 cm were used, giving a population of 150 000 plants ha^{-1}. All the management practices were done according to standard production practices (Liebenberg *et al*., 2002). Planting dates are presented in Table 3.1). Planting and weeding was done by hand. Data was collected from the two middle rows to eliminate border effects. Harvesting was done when the plants reached harvest maturity and natural drying was allowed. Yield is expressed at 10% seed moisture content. The following data was collected from ten randomly selected plants per plot from the two middle rows at harvest: 100 seed mass, number of seeds per pod, and number of pods per plant. The moisture content was determined was determined using Dickey John multigrain moisture meter, while unshelled and shelled grain mass was also collected. The grain yield data was collected from one square meter in the center of the plot.

The grain yield data were subjected to separate and combined analysis of variance (ANOVA) to determine the effects of environment, genotype and their interactions using Statistical Analysis System software (SAS 9.3 – 2010). Means were compared using the least significant differences (LSD) test at 5% probability level. The data for 2011 and 2012 were graphically analysed for interpreting the GE interaction using GGE biplot software (Yan, 2001). The GGE biplot methodology is composed of two concepts, the biplot concept (Gabriel, 1971) and the GGE concept (Yan *et al*., 2000).

3.3 RESULTS AND DISCUSSION

3.3.1 Separate ANOVA

In 2010 the lowest mean yields were recorded at Dalmada which might have been caused by frost damage during the last days of the growing season (Table 3.1). At Dzindi and Dalmada, PAN 148 was the best performer with mean grain yields of 0.65 and 1.75 t ha^{-1} respectively, while at Trichardtsdal, DBS 360 was the best performer with 2.19 t ha^{-1}. This was, however, not significantly higher than the yield obtained by PAN 148 (2.15 t ha^{-1}). The results indicated that genotypes responded differently to environments, but three genotypes: PAN 148, OPS-RS1 and DBS 360 ranked under the best three in eight of nine cases in 2010.

In 2011, plantings were again done at Dzindi, but the yields were almost half (0.72 t ha^{-1}) of that recorded in the 2010 season (1.49 t ha^{-1}). The drop in yield might have been caused by heavy rains received in June 2011, which resulted in weeding taking place at 10 weeks instead of 6 to 7 weeks. The average yields recorded at Trichardtsdal and Phalaborwa were 2.23 and 1.09 t ha^{-1} respectively. At Dzindi, OPS-RS5 was the best performer with a mean grain yield of 0.833 t ha^{-1}, at Trichardtsdal, Kranskop was the best with 3.34 t ha^{-1} and at Phalaborwa, Jenny performed the best with 1.60 t ha^{-1} (Table 3.1). In this season the yield rankings were not as tightly grouped as in the 2010 season, with OPS-RS4, Jenny and OPS-RS5 raking under the best three in six out of the nine cases. It was interesting to note that none of the top ranking genotypes from the 2010 season fell into this group in the 2011 season.

The 2012 season was a good season for production at all locations with the average yields ranging from just over 2 t ha^{-1} to just below 3 t ha^{-1}. At Phalaborwa and Dzindi, OPS-RS1 was the best performer with mean grain yield of 3.33 and 2.95 t ha^{-1} respectively and at Tshiombo Irrigation Scheme, DBS 310 performed the best with a mean grain yield of 3.51 t ha^{-1}. In this season, OPS-RS1, DBS 310 and OPS-RS5 ranked in the top three places in six out of the nine cases. At the hand of this analysis (top rankings), four genotypes can be identified for future cultivation: Jenny, OPS-RS1, DBS 360 and OPS-RS5, but the differences in genotype performance at the same locality in different seasons complicated genotype selection. There is thus a need for more in-depth analysis of the data for better genotype recommendations. The average yields of 2012 were much better compared to 2010 and 2011 due to heavy rains which fell in 2010 and 2011 production seasons.

Table 3.1 Grain yield and rankings of dry bean genotypes at different environments

	2010						**2011**						**2012**					
	Dalmada		**Dzindi**		**Trichardtsdal**		**Dzindi**		**Trichardtsdal**		**Phalaborwa**		**Dzindi**		**Phalaborwa**		**Tshiombo**	
Planting date	13 March 2010		03 April 2010		17 March 2010		14 April 2011		07 March 2011		22 March 2011		04 April 2012		24 April 2012		18 April 2012	
Genotype	**Yield**	**Rank**	**Yield**	**Rank**	**Yield**	**Rank**	**Yield**	**Rank**	**Yield**	**Rank**	**Yield**	**Rank**	**Yield**	**Rank**	**Yield**	**Rank**	**Yield**	**Rank**
Kranskop	0.598	4	1.32c	6	1.54b	6	0.718bc	5	3.34a	1	0.99 bcd	5	2.28c	5	2.48bc	4	3.50a	2
OPS-RS4	0.564	5	1.38c	5	1.79ab	4	0.784ab	2	1.30e	7	1.54a	2	2.09c	8	1.71d	6	2.79b	4
Jenny	0.550	6	1.56b	2	1.78 ab	5	0.735abc	4	2.80b	3	1.60a	1	2.77 ab	2	2.32c	5	2.42cd	7
PAN 148	0.653	1	1.75a	1	2.15a	2												
OPS-RS1	0.613	3	1.46bc	4	2.14a	3	0.630cd	7	2.98ab	2	1.11bc	4	2.95a	1	3.33a	1	2.37d	8
DBS 360	0.647	2	1.48bc	3	2.19a	1	0.596d	8	2.02cd	5	0.74 de	7	2.76 ab	3	1.30e	8	2.56bcd	6
OPS-RS2							0.780ab	3	2.34c	4	0.90 cde	6	2.68b	4	1.32e	7	2.74bc	5
DBS 310							0.706bcd	6	1.22e	8	0.66e	8	2.28c	6	2.69b	2	3.51a	1
OPS-RS5							0.833a	1	1.82d	6	1.16b	3	2.11c	7	2.68b	3	3.39a	3
Average yield	0.604		1.49		1.93		0.723		2.23		1.09		2.49		2.23		2.91	
LSD$_{0.05}$	NS		0.17		0.43		0.11		0.41		0.24		0.20		0.22		0.34	
CV	10.4		6.28		12.32		8.9		10.6		13.09		4.7		5.6		6.7	

Note: LSD: Least significant difference, NS: non-significant and CV: coefficient of variation

3.3.2 Combined analysis for all years

The combined analysis is for all environments and all genotypes. The yields from environments which were used more than once were analyzed individually since the performance of the genotypes differed significantly within the 3 years. The combined analysis of environments and seasons for dry bean yields showed a highly significant ($P \leq 0.001$) difference for yield among replications, environments, variety and variety x environment interactions (Table 3.2). The significance of the variety x environment interaction indicates that genotypes responded differently to the different environments. Due to the variety x environment interaction the selection process is complicated as variety x environment interaction reduces the usefulness of genotypes by confounding their yield performance through minimizing the association between genotypic and phenotypic values (Comstock & Moll, 1963). This results in change in yield ranking across environments. According to Table 3.2 the environment (68%) and variety x environment (19%) explained most of the variation.

Table 3.2 Combined analysis of variance for all three seasons (2010 - 2012) at all the locations ($P \leq 0.001$)

Source	DF	SS	MS	F Value	Pr > F	Explained %
REP	2	0.4526	0.2262	7.46	0.0009	
ENV	8	107.4719	13.4339	442.81	<.0001	68.476
VARIETY	8	7.3178	0.9147	30.15	<.0001	4.662
ENV*VARIETY	49	30.2869	0.6181	20.37	<.0001	19.297
Error	130	3.9439	0.0303			2.512
Corrected Total	197	156.9485				

3.3.3 GGE-BIPLOT ANALYSIS

For the GGE-biplot analysis, only data from the 2011 and 2012 seasons were used since less (5 versus 8) genotypes were tested in the 2010 season than in the other two seasons.

3.3.3.1 Interaction patterns between genotype and environment

The partitioning of GE interaction through GGE biplot analysis showed that PC1 and PC2 accounted for 50.6% and 26.8% of the GGE sum of squares, respectively (Figure 3.1). The vertex genotypes on this study were OPS-RS1, Jenny, OPS-RS2, DBS 360, OPS-RS4 and DBS 310 (Figure 3.1). These genotypes were the best or the poorest genotypes in some or all of the environments because they were the furthest from the origin of the biplot (Yan and Kang, 2003). From the polygon view of the biplot analysis the genotypes fell in four sections and the test environments fell into two sections. This crossover GE suggests that the target environments may be divided into mega-environments. The results indicate that OPS-RS1 was the best genotype for Dzindi 2011 and Phalaborwa 2012. The variety DBS 310 was the best performer at Tshiombo. The genotype OPS-RS1 and Kranskop gave the highest average yields (largest PC 1 scores), and they were also stable across all sites, due to the fact that they did not give small absolute PC 2 scores. On the other side genotype OPS-RS4, DBS 360 and OPS-RS2 were highly unstable and also resulted in below average yields in Phalaborwa 2012 and Trichardtsdal 2011.

The polygon view of the biplot has been reported to be the best way to visualize the interaction patterns between genotypes and environments (Yan & Kang, 2003). It also shows the presence or absence of cross over GE interaction which is helpful in estimating the possible existence of different mega environments (Gauch and Zobel, 1997). The which-won-where view of the GGE biplot (Yan *et al.*, 2000) is an effective tool in mega-environment analysis. The biplot was generated using the genotypic and environmental scores of the first two AMMI components (Varga and Crossa, 2000).

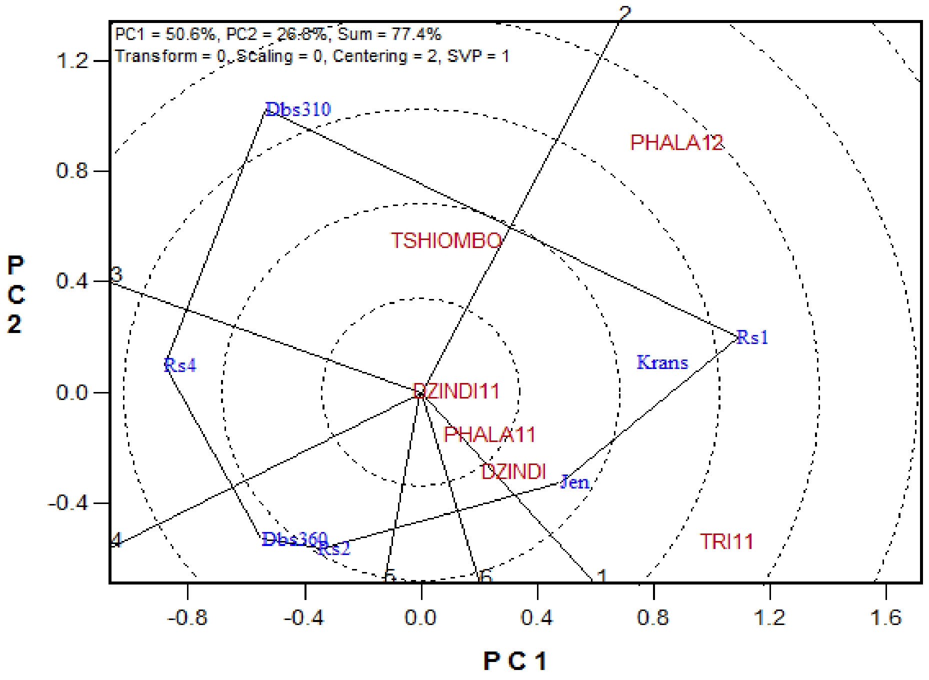


Figure 3.1 The which-won-where view of the GGE biplot to which dry bean varieties (in blue) performed best in which environments (in red)

3.3.3.2 Ranking varieties based on mean performance

Thus, DBS 310 was highly unstable whereas OPS-RS1 was highly stable. The genotype DBS 310 was highly unstable because it had the lowest yield in Trichardtsdal 2011 and Phalaborwa 2011, while in 2012 it gave the highest and second highest yields in Tshiombo and Phalaborwa respectively. The yield performance and stability of genotypes were evaluated by an average environment coordination (AEC) method (Yan, 2001; Yan & Hunt, 2001; Yan, 2002). The single-arrowed line is the average-environment coordination (AEC) abscissa, it points to the higher mean yield across environments. Therefore OPS-RS1 had the highest mean yield, followed by Kranskop, and then Jenny and finally OPS-RS4 had the lowest mean yield (Figure 3.2). The double-arrowed line is the AEC ordinate, it points to greater variability (poorer stability) in either directions.

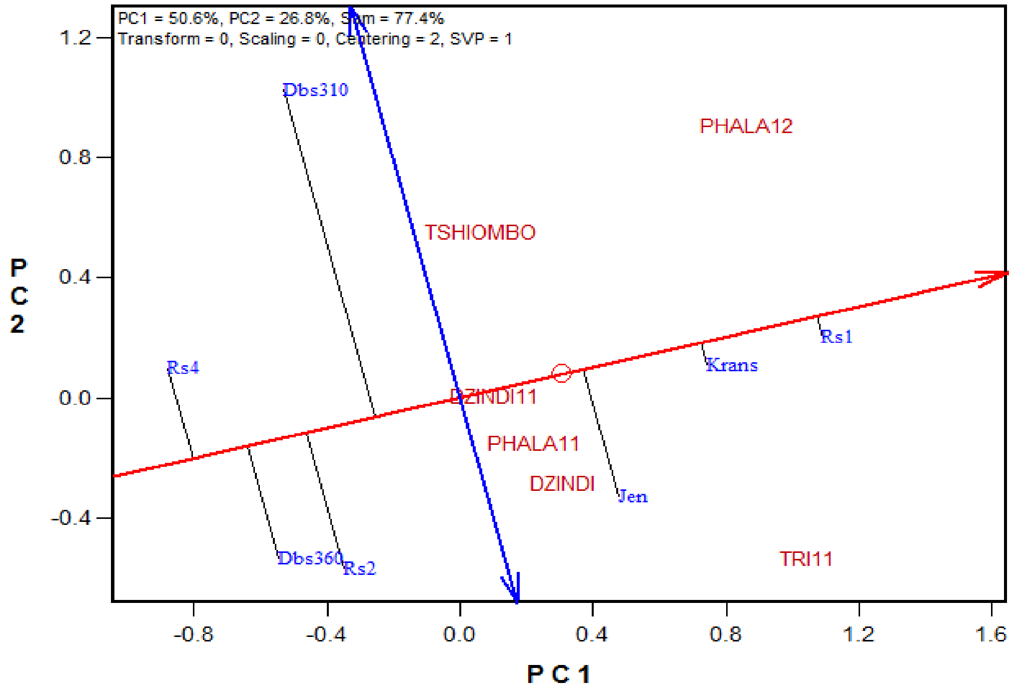


Figure 3.2 Ranking of dry bean varieties based on mean performance

3.3.3.3 Performance of the varieties in the specific environments

Performance of the genotypes in a specific environment can be visualized by drawing up both the genotype vectors and the environment vectors. The interpretation rule is: the performance of a genotype in an environment is better than the average, if the angle between its vector and the environment's vector is <90^o; it is poorer than average if the angle is >90^o; and it is near average if the angle is about 90^o. The variety OPS-RS1 was above average in all the environments except at Tshiombo were it was near the average (Figure 3.3). The variety OPS-RS4 was found to be below average in all the environments except in Tshiombo were it was above average.

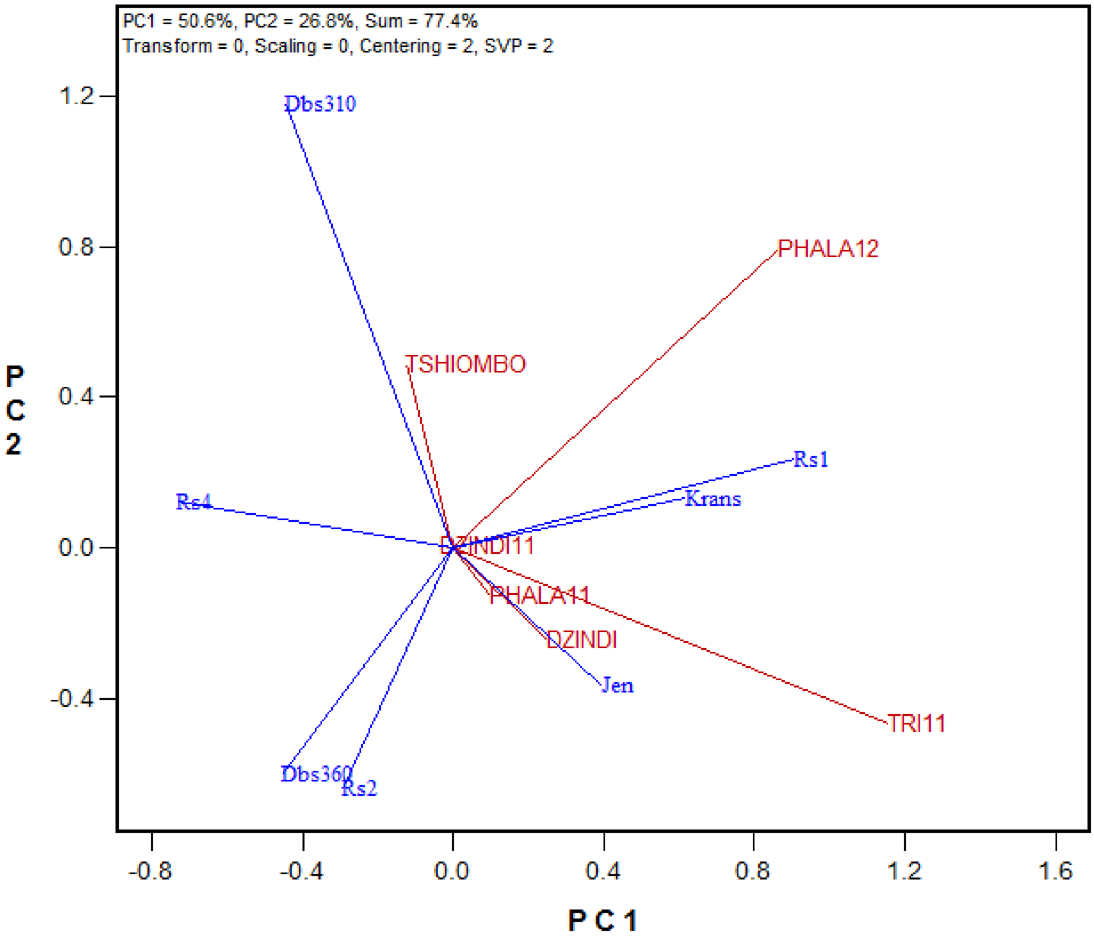


Figure 3.3 Performance of dry bean varieties (blue lines) in specific environments (red lines)

3.4 CONCLUSION

The combined ANOVA analysis indicated that the yield performance of dry beans was highly influenced by environment, followed by GE and finally varieties had the least effect (Table 3.2). The results revealed that there was a crossover GE interaction across environments and among varieties tested, meaning that varieties are adapted to different climatic conditions. The desirable varieties in terms of high mean yield was OPS-RS1, closely followed by Kranskop. The varieties OPS-RS1 gave above average yields in all the locations while OPS-RS4 gave below average yields in all locations except at Tshiombo 2012. The highest mean yields were obtained in 2012 at Tshiombo irrigation scheme, while in 2010 and 2011 the highest yields were recorded at Trichardtsdal. The GGE biplot analysis resulted in meaningful and useful summary of variety x environment interaction data and assisted in examining natural relationships and variations in variety performance across tested environments. According to the GGE biplot, OPS-RS1 can be characterized as the variety with the highest mean yield while also being highly stable. From the GGE biplot it also became clear that the performance of certain genotypes like DBS 310 and OPS-RS4 is strongly linked to the environment. These varieties were the only two that produced above average yields in Tshiombo (both) and Phalaborwa (DBS 310 only) in 2012, while in other years and other localities it consistently yielded below average.

From the results one can also deduct that dry beans could be produced with success in any of the locations, as long as the crop is not exposed to early frost, as was the case at Dalmada in 2010. In that season yields of 550 to 653 kg ha^{-1} were harvested at Dalmada as compared to 1.32 to 2.18 t ha^{-1} at Dzindi and Trichardtsdal.

CHAPTER 4

EFFECT OF PLANT POPULATION ON GRAIN YIELD OF DRY BEAN (*Phaseolus vulgaris* L.).

ABSTRACT

The trial was planted at Palmaryville irrigation scheme in Vhembe District (22°58’0’’S, 30°26’0’’E) in the Limpopo Province during the 2011 and 2012 seasons. The layout was a 3x3 factorial experiment involving three plant populations (150 000, 110 000 and 70 000 plants ha^{-1}) and three indeterminate varieties of dry bean (Kranskop, DBS 310 and Jenny) in a split-plot design with three replications. The 2012 trial was a 3x2 factorial experiment involving three plant populations (210 000, 150 000 and 70 000 plants ha^{-1}) and two varieties of dry bean which are OPS-RS2 (determinate) and Jenny (indeterminate) arranged in a split-plot design with three replications. In 2011 the results revealed that 150 000 plants ha^{-1} resulted in a significantly higher yield of 1.90 t ha^{-1}, while 70 000 plants ha^{-1} resulted in a higher grain yield per plant (420 g). Kranskop performed the best with a mean grain yield of 1.84 t ha^{-1}. In 2012 the results revealed that the interaction relationship between dry bean variety and plant population significantly influenced grain yield, 100 seed mass, plant height, and dry matter production. The highest grain yield was produced with 150 000 plants ha^{-1} using OPS-RS2. A plant population of 150 000 plants per hectare was suitable for both determinate and indeterminate growth type dry beans at this location.

Keywords: 100 seed weight, plant height, varieties

4.1 INTRODUCTION

Dry bean is an important leguminous crop in the world. It is regarded as the third most important food legume after soybean and peanut (Singh *et al*., 1999). Determination of the optimal plant population density necessary for optimal yield is a major agronomic goal (Hosseini *et al*., 2001). Plant population density plays a major role in determining expected yield in crop production. Population densities utilized for cultivation of common bean (*Phaseolus vulgaris* L.) vary from 50 000 to over 200 000 plants per hectare (Singh & Gutiérrez, 1990).

Dry bean varieties can be classified by their growth habit into determinate and indeterminate. Cultivars of different growth habits respond differently to varying densities (Crothers & Westermann, 1976; Nienhuis & Singh, 1985). Determinate (Type I) bush beans typically require higher plant populations to maximize yield as compared to semi-vining (Type II) or vining (Type III) beans (Nienhuis & Singh, 1985). The plants tend to compete for space, light, nutrients and water as they grow bigger and older.

Yield per unit area tend to increase as plant population increases up to a certain point and then declines (Akintoye *et al*., 2009). Several authors have reported that plant height increased with increasing population density (Khalil *et al*., 1993; Abdel-Aziz *et al*., 1999). A higher plant population in snap bean resulted in a lower number of pods per plant (Wahab *et al*., 1986). On the other hand, Dahmardeh *et al*. (2010) reported that for faba bean, the number of pods was not affected by plant population. The objective of the study was to evaluate the effects of plant population density on grain yield.

4.2 MATERIALS AND METHODS

4.2.1 Experimental site and treatments (Experiment 1 Palmaryville irrigation scheme)

The trial was planted at Palmaryville irrigation scheme in Vhembe District (22°58'0''S, 30°26'0''E) in Limpopo on the 28 March 2011. Palmaryville irrigation scheme is located 4 km west of Thohoyandou, Thulamela municipality, Vhembe District of the Limpopo Province, South Africa. The area has an annual rainfall of about 800 mm with 95% occurring between October and March. The daily temperatures range from about 25 to 40 ^{o}C in summer and between 22 to 26 ^{o}C in winter (Mzezewa *et al*., 2010). The layout was a 3x3 factorial experiment involving three plant populations (150 000, 110 000 and 70 000 plants ha^{-1}) and three indeterminate varieties of dry bean (Kranskop, DBS 310 and Jenny) in a split-plot design with three replications. The recommended population is 150 000 plants ha^{-1}. The spacing between the rows was 90cm. Plots consisted of 4 rows of 4 m in length each. The experiment was irrigated once a week.

4.2.2 Data collection (Experiment 1 Palmaryville irrigation scheme)

Data for plant height was collected at 110 days after planting (Physiological maturity) during harvest. Plant height represents the distance from ground level to the tip of apical of the growing point. The number of seeds per plant and number of pods per plant was collected from the middle 2 rows from 10 randomly selected plants per plot at harvest. Yield data were collected from 1 m^2 (2 middle rows) in the middle of each plot. The following data was collected at harvest: seed yield, 100 seed mass and yield expressed at 10% moisture content. Harvesting was done by hand.

Data was subjected to Analysis of variance using General linear Model procedure of the Statistical Analysis System software (SAS 9.3 – 2010) to determine the response of dry beans under different plant populations. Means were compared using the Least Significant Difference test at the 5 % level (LSD = 0.05) of probability.

4.2.3 Experimental site and treatments (Experiment 2 Dzindi irrigation scheme)

The trial was planted at Dzindi irrigation scheme (23°01'45''S, 30°26'30''E) on the 26 April 2012.. Dzindi irrigation scheme is located 6 km south west of Thohoyandou, Thulamela municipality, Vhembe District of the Limpopo Province, South Africa. The area has an annual rainfall of about 800 mm, with 95% occurring between October and March. The daily temperatures vary from about 25 to 40 ^oC in summer and between 22 to 26^oC in winter (Mzezewa *et al*., 2010).

The trial was a 3x2 factorial experiment involving three plant populations (210 000, 150 000 and 70 000 plants ha^{-1}) and two varieties of dry bean (OPS-RS2 and Jenny) in a split-plot design with three replications. The recommended population is 150 000 plants ha^{-1}. Genotype Jenny has an indeterminate growth pattern, while OPS-RS2 has a determinate growth pattern. The spacing between the rows was 90 cm. The plot consisted of 4 rows each 4 m in length. The trial was irrigated once a week.

4.2.4 Data collection (Experiment 2 Dzindi irrigation scheme)

Data was collected from the two middle rows. Number of plants germinated was determined nine days after planting. Destructive sampling was done by harvesting six plants per treatment at 30, 62 and 98 DAP. At 30, 62 and 98 days after planting (DAP) and plant height from the same six plants were determined. After the plants were harvested they were put in brown bags and they were dried at 75 ^oC for ±48 hours. Plant height was taken as the distance from ground level to the tip of the growing point. Yield data (seed yield, 100 seed mass) was collected from 1 m^2 (2 middle rows) in the middle of the plot. The number of pods per plant and number of seeds per plant were determined from 10 randomly selected plants per plot. Yield is expressed based on a 10% moisture content. Harvesting was done by hand.

Data were subjected to Analysis of Variance using General linear Model procedure of Statistical Analysis System software (SAS 9.3 – 2010) to determine the response of dry bean under different plant populations. Means were compared using the Least Significant Difference test at 5 % level of probability. Correlation analysis was done using SAS to determine the relationship between parameters.

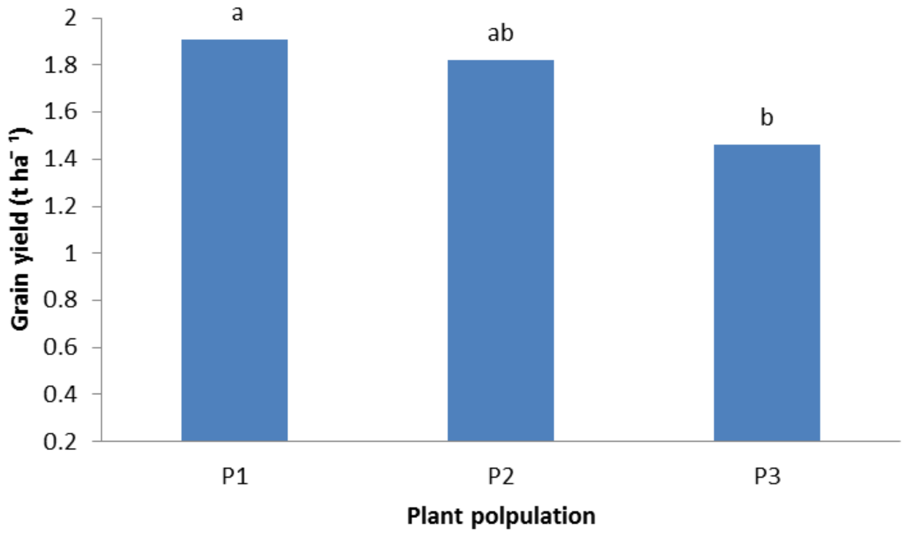
4.3 RESULTS AND DISCUSSION

EXPERIMENT 1 (PALMARYVILLE IRRIGATION SCHEME)

4.3.1 Effect of dry bean varieties and plant population on grain yield

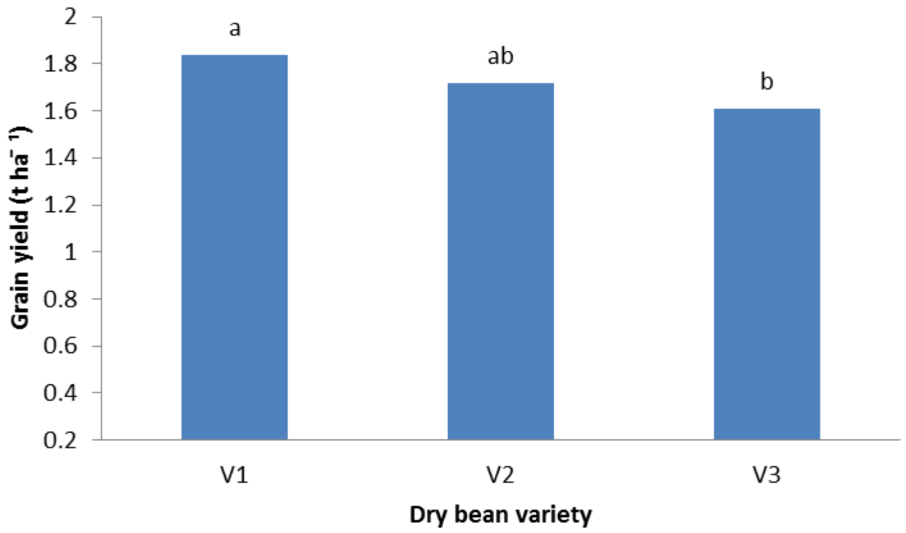
The results indicated that with 150 000 (P1) and 110 000 plants ha^{-1} (P2) the grain yield was higher than with 70 000 plant ha^{-1} (P3) by 23 and 20 % respectively, which was only significantly ($p \leq 0.05$) lower than that of P1 (Figure 4.1) . The higher grain yield for 150 000 plant ha^{-1} in this study was due to increased number of plants per unit area.The results further indicated that the lower plant population (P3) resulted in a high grain yield per plant by 20 and 39 % compared to P2 and P1 respectively (Table 4.1). The higher grain yield per plant for 70 000 plant ha^{-1} in the present study was due to high number of pods per plant and higher seed mass resulting from less plants per unit area, which resulted in less competition for water, light and nutrients. The results revealed that for higher grain yield 150 000 and 110 000 plants ha^{-1} can be suitable one for dry bean production.El-Naim and Jabereldar (2010) also reported that increased plant populations resulted in increased seed yield per unit area and decreased seed yield per plant in cowpea.

There was a significant ($p \leq 0.05$) effect of variety on grain yield. Kranskop (V1) resulted in the highest grain yield of 1.84 t ha^{-1} which was statistically similar to DBS 310 (V2) with 1.72 t ha^{-1}. Jenny (V3) resulted in the lowest yield of 1.61 t ha^{-1} which was 12.5 % reduction compared to Kranskop (V1) (Figure 4.2). The plant population x variety interaction was not significant.



Note: P1: 150 000 plants ha^{-1}; P2: 110 000 plants ha^{-1}; P3: 70 000 plants ha^{-1}. Bars with the same letter are not significantly different at p=0.05

Figure 4.1 Effect of plant population on grain yield of dry bean at Palmaryville irrigation scheme.



Note: V1: Kranskop, V2: DBS 360, V3: Jenny. Bars with the same letter are not significantly different.

Figure 4.2 Effect of dry bean variety on grain yield at Palmaryville irrigation scheme.

4.3.2 Effect of dry bean varieties and plant population on yield parameters

There was no interaction between plant population and dry bean varieties for any of the yield parameters. The effect of plant population on number of seeds per pod, shelling % and plant height was not significant. The effect of plant population was significant on 100 seed mass, number of pods per plant and grain yield per plant. El-Fieshawy and Fayed (1990) confirmed that the number of seed per pod was not affected by plant population. Field and Nkumbula (1986) reported that plant height was not influenced by plant population in green beans. Shirtliffe and Johnston (2002) indicated that plant populations did not influence 1000 seed mass in dry beans but cultivars had an effect.

Results indicated that the lowest plant population - P3 (8.69) resulted in significantly higher number of pods per plant than P2 (7.03) and the highest plant population - P1 (7.00) (Table 4.1). In the present study the high number of pods per plant for P3 was due to less competition for space, light and nutrients. The results are in line with the study by Moniruzzaman *et al*. (2009) and Dahmardeh *et al*. (2010).

The P3 treatment resulted in the highest mass of 100 seeds (49.83 g) and P1 in the lowest (42.33 g). The highest grain yield per plant was found in P3 (20.85 g) and the lowest at P1 (12.71 g). The high 100 seed mass in P3 for this present study was due to the availability of enough resources for the reproductive growth resulting in heavier seeds due to lower plant per unit area.

Only plant height and yield per plant were influenced by genetic differences (Table 4.2). Kranskop (V1) plants were significantly taller than plants from DBS 360 (V2) and Jenny (V3). Kranskop also had the highest yield per plant, which was only significantly different from the yield of Jenny plants. This differences is due to genetic differences among the varieties.

Table 4.1 Effect of plant population on dry bean yield parameters for Palmaryville

Plant population (plants ha^{-1})	Grain yield plant^{-1} (g)	No. of pods plant^{-1}	No. of seeds pod^{-1}	Shelling %	Plant height (cm)	100 seed mass (g)
150 000 (P1)	12.71b	7.00b	3.78	73.78	40.52	42.33b
110 000 (P2)	16.55b	7.03b	3.89	74.89	39.83	43.00b
70 000 (P3)	20.85a	8.69a	3.78	71.78	38.19	49.83a
LSD	3.87**	1.08*	ns	ns	ns	2.11*
CV	10.17	14.3	11.42	6.6	7.11	8.45

*Note: LSD: Least significance difference, CV: coefficient of variation, ns: non-significant, *: significant at p≤0.05, **: significant at p≤0.0001, Means in a column with the same letter are not significantly different.*

Table 4.2 Effect of dry bean variety on dry bean yield parameters for Palmaryville

Variety	Grain yield plant^{-1} (g)	No. of pods plant^{-1}	No. of seeds pod^{-1}	Shelling %	Plant height (cm)	100 seed mass (g)
Kranskop (V1)	17.78a	7.66	3.66	73.67	43.32a	49.00
DBS 360 (V2)	16.86ab	7.58	3.78	73.89	38.29b	43.00
Jenny (V3)	15.48b	7.48	4.00	72.89	36.93b	42.33
LSD	1.74*	ns	ns	ns	2.80**	ns
CV	10.17	14.3	11.42	6.6	7.11	8.45

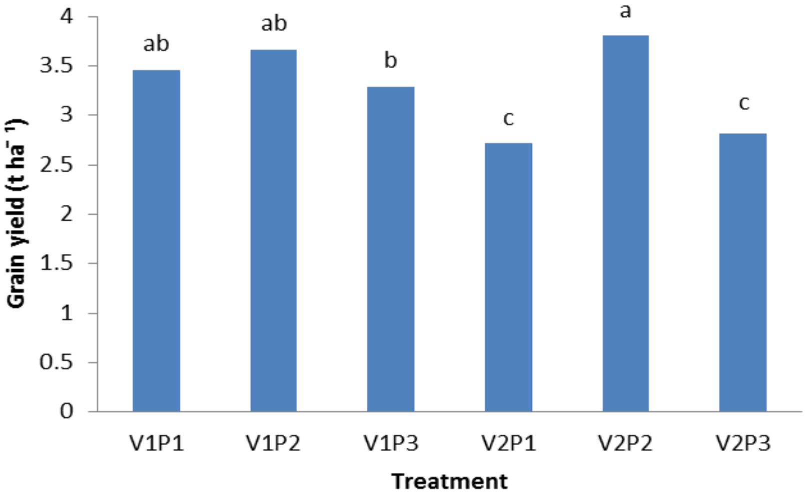
*Note: LSD: Least significance difference, CV: coefficient of variation, ns: non-significant, *: significant at p≤0.05, **: significant at p≤0.0001.Means in a column with the same letter are not significantly different.*

Experiment 2 (Dzindi irrigation scheme)

4.3.3 Effect of dry bean variety and plant population on grain yield

The variation in grain yield was significantly ($p \leq 0.05$) influenced by the interaction relationship between plant population and variety. The highest grain yield was achieved with OPS-RS2 (V2) at P2 (3.80 t ha^{-1}) (Figure 4.3). This yield was statically similar for Jenny (V1) at both P1 and P2. The adjustment of plant population of OPS-RS2 (V2) from P2 to P1 and P3 resulted in a 28% and 26% reduction in grain yield respectively. The grain yield of Jenny (V1) was statistically the same at P3 and P2. Grafton *et al*. (1988) reported that seed yield increased with higher plant populations. Abubaker (2008) indicated that the increase in plant population can result in an increased competition for available water, mineral nutrients and light.

From the results it is clear that 150 000 plants ha^{-1} (P2) would be suited to both determinate and indeterminate growers. The results are different from experiment 1 suggesting that the best population obviously depends on the balance between available resources and the degree of competition, which is affected by the cultivar and the specific environment. However, determinate growers (example OPS-RS2 – V2) are not as adjustable to higher (P1) or lower (P3) plant populations as an indeterminate grower (example Jenny – V1) (Figure 4.3). This suggests that Jenny (indeterminate) has a better potential to compensate for low plant stand than OPS-RS2 (determinate).

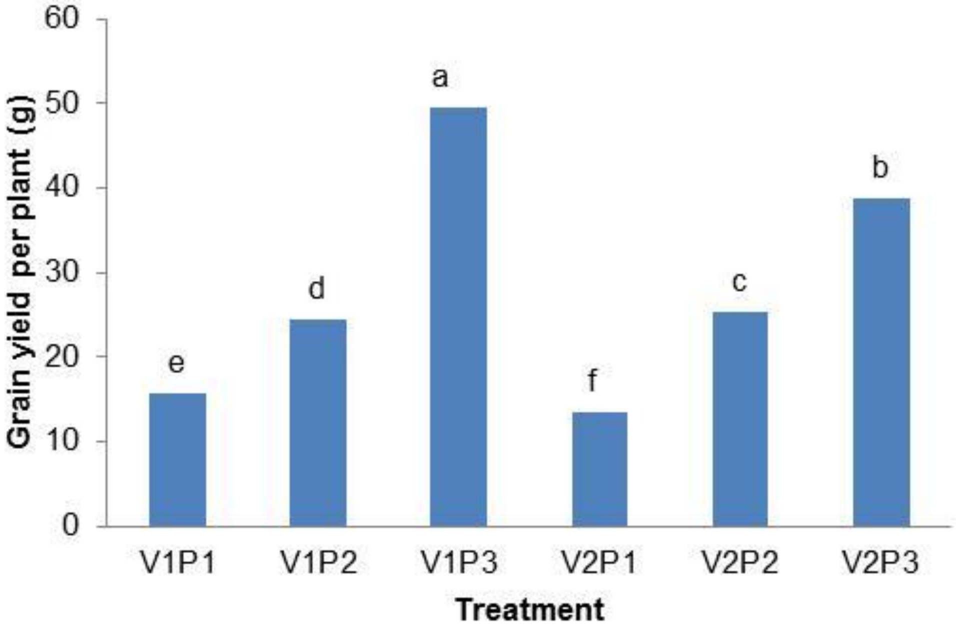


Note: Bars with the same letter are not significantly different. P1: 210 000 plants ha^{-1}; P2: 150 000 plants ha^{-1}; P3: 70 000 plants ha^{-1}; V1: Jenny; V2: OPS-RS2.

Figure 4.3 Effect of dry bean variety and plant population on grain yield for Dzindi irrigation scheme

4.3.4 Effect of dry bean varieties and plant population on grain yield per plant

The interaction effect of plant population and variety was highly significant ($p \leq 0.001$) on yield per plant. The combination of Jenny (V1) and P3 resulted in a significantly higher yield per plant than its yield at P2 (50.6%) and P1 (68%) (Figure 4.4). This yield was significantly higher than the yield of OPS-RS2 (V2) by 21.5%. The performance of OPS-RS2 at P3 was better than at P2 and P1 by 34.7% and 65% respectively. Yield per plant increased with reduction in plant populations from P3 to P1 in both varieties. This can also be due to less competition for water and nutrients, which leads in higher photosynthetic rates. This could explain the large difference between Jenny at P3 versus P2 as compared to OPS-RS2 for the same plant populations.The results are in line with the findings by Wahab (1986). Shirtliffe and Johnston (2002) reported that the vining ability of indeterminate beans allows for growth to compensate for low plant populations.



Note: Bars with the same letter are not significantly different. P1: 210 000 plants ha^{-1}, P2: 150 000 plants ha^{-1}, P3: 70 000 plants ha^{-1}, V1: Jenny, V2: OPS-RS2.

Figure 4.4 Effect of dry bean variety and plant population on grain yield per plant for Dzindi irrigation scheme

4.3.5 Effect of dry bean varieties and plant population on number of pods per plant

The results revealed that the effect of plant population density on the number of pods per plant was highly significant ($p \leq 0.0001$) (Table 4.3). The effects of variety as well as the interaction effect on the number of pods per plant were not significant. The number of pods per plant was reduced by increasing plant population to P2 (7%) and P1 (40%). For this study the higher number of pods per plant at P3 was due to less inter-plant competition for light, water and nutrients. Several authors have reported that increasing plant spacing resulted in an increased number of pods per plant (Malik *et al*., 1993; Kakiuchi & Kobata, 2004; Darmardeh *et al*. (2010).

Table 4.3 Effect of dry bean variety and plant population on number of pods per plant for Dzindi irrigation scheme

Treatments		Number of pods plant^{-1}
Plant population density	P1	8.483c
	P2	13.167b
	P3	14.087a
Varieties	V1	12.067
	V2	11.758
LSD	Plant population	0.481**
	Variety	ns
	Plant population X Variety	ns

*Note: LSD: Least significance difference, ns: non-significant, **: significant at p≤0.0001, P1: 210 000 plants ha^{-1}, P2: 150 000 plants ha^{-1}, P3: 70 000 plants ha^{-1}, V1: Jenny, V2: OPS-RS2 for a factor with the same letter are not significantly different*

4.3.6 Effect of dry bean variety and plant population on number of seeds per plant for Dzindi irrigation scheme

The effect of plant population on number of seeds per plant was highly significant ($p \leq 0.0001$) while the effect of variety was significant ($p \leq 0.05$) (Table 4.4). The insignificant plant population x variety interaction indicated that varieties reacted to plant population in the same way. The number of seeds at P3 and P2 were significantly higher than P1 by 48% and 42% respectively. Jenny had significantly more seeds per plant than OPS-RS2. At the highest plant population (P1) the number of seeds per plant of both V1 and V2 was reduced by 53% and 44% respectively (results not shown). The reduction in the number of seeds at high plant population for this study resulted from shading effect among the plants, competition for nutrients and water leading to poor seed development.

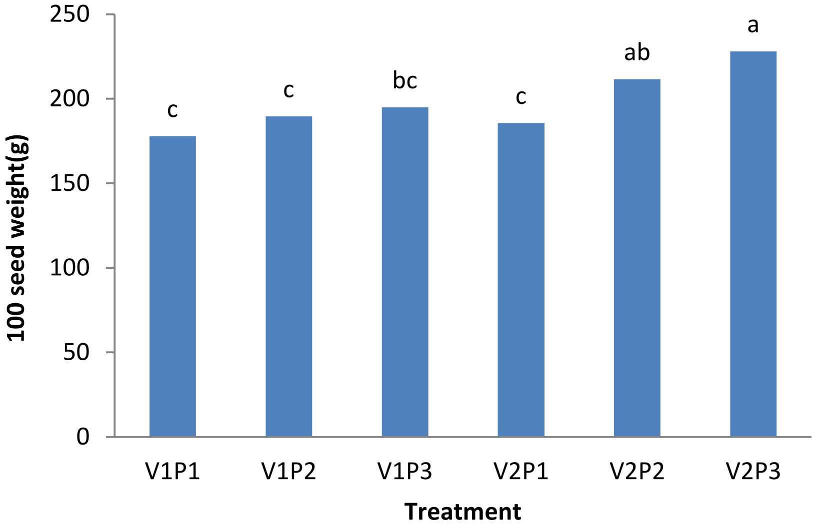
Table 4.4 Effect of dry bean variety and plant population on the number of seeds per plant for Dzindi irrigation scheme

	Treatments	No. seeds plant^{-1}
Plant population density	P1	21.58b
	P2	37.57a
	P3	41.83a
Variety	V1	35.54a
	V2	31.78b
LSD	Plant population	4.527**
	Variety	3.656*
	Plant population X Variety	ns

*Note: LSD: Least significance difference, ns: non-significant, *: significant at $p \leq 0.05$, **: significant at $p \leq 0.0001$, P1: 210 000 plants ha^{-1}, P2: 150 000 plants ha^{-1}, P3: 70 000 plants ha^{-1}, V1: Jenny; V2: OPS-RS2. Means for a factor with the same letter are not significantly different*

4.3.7 Effect of dry bean variety and plant population on 100 seed mass for Dzindi irrigation scheme

The mass of 100 seeds were significantly ($p \leq 0.05$) influenced by the interaction effect (Figure 4.5). The 100 seed mass of OPS-RS2 (V2) was the highest at P3 and it was similar to P2. The increase of plant population for OPS-RS2 to P1 resulted in an 18% decrease in the 100 seed mass. This means that at the highest plant population the size of the seeds were small and at the lowest plant population there were bigger seeds. The 100 seed mass of Jenny also decreased with an increase in plant density, but was statistically similar. Maynard and Scott (1998) confirmed that at high densities plants compete with each other for nutrients, water and light, which can result in poor seed development.



Note: Bars with the same letter are not significantly different. P1: 210 000 plants ha^{-1}, P2: 150 000 plants ha^{-1}, P3: 70 000 plants ha^{-1}, V1: Jenny, V2: OPS-RS2.

Figure 4.5 Effect of dry bean variety and plant population on 100 seed mass for Dzindi irrigation scheme

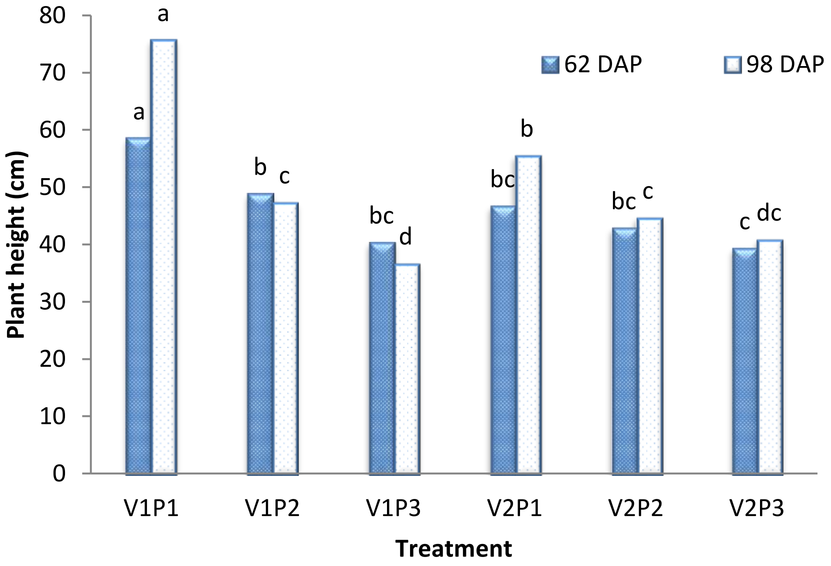
4.3.8 Effect of dry bean variety and plant population on plant height for Dzindi irrigation scheme

Neither of the treatment factors affected plant height at 30 DAP (Table 4.5). This means that at early stages of growth there was not much competition yet because plants were still small. Later when the plants were bigger, the competition effect was much stronger at high plant densities. The effect of interaction was highly significant on plant height at 62 DAP and 98 DAP (Figure 4.6). At both 62 and 98 DAP the maximum height was found in Jenny (V1) at P1 which was 58.5 and 75.67 cm respectively. The decrease in plant population of Jenny from P1 to P2 resulted in a 16% reduction of plant height; while a decrease in plant population from P1 to P3 resulted in a 31% reduction of plant height. The plant height of OPS-RS2 (V2) also tended to increase with an increase in plant density at both 62 and 98 DAPS. At 98 DAP the tallest plants were recorded for Jenny at P1 (75.67 cm). The decrease of plant population of Jenny from P3 to P2 and P1 resulted in a reduction of plant height of 37 and 51% respectively. The decrease in plant population density of OPS- RS2 from P1 to P2 and P3 resulted in a 20 and 26% respective reductions of plant height at 98 DAP. The increase in plant height with an increased plant population for this study was due to intra-plant completion for light.The increase in plant height with an increase in plant population density was also reported by Dahmardeh *et al*. (2010).

Table 4.5 Effect of dry bean variety and plant population on plant height at 30 DAP for Dzindi irrigation scheme

Treatments		plant height (cm)
Plant population density	P1	37.37
	P2	34.67
	P3	34.68
Variety	V1	36.09
	V2	35.06
$LSD_{0.05}$	Plant population	ns
	Variety	ns
	Plant population X Variety	ns

Note: LSD: Least significance difference; ns: non-significant, P1: 210 000 plants ha^{-1}, P2: 150 000 plants ha^{-1}, P3: 70 000 plants ha^{-1}, V1: Jenny, V2: OPS-RS2. Means in a column with the same letter are not significantly different

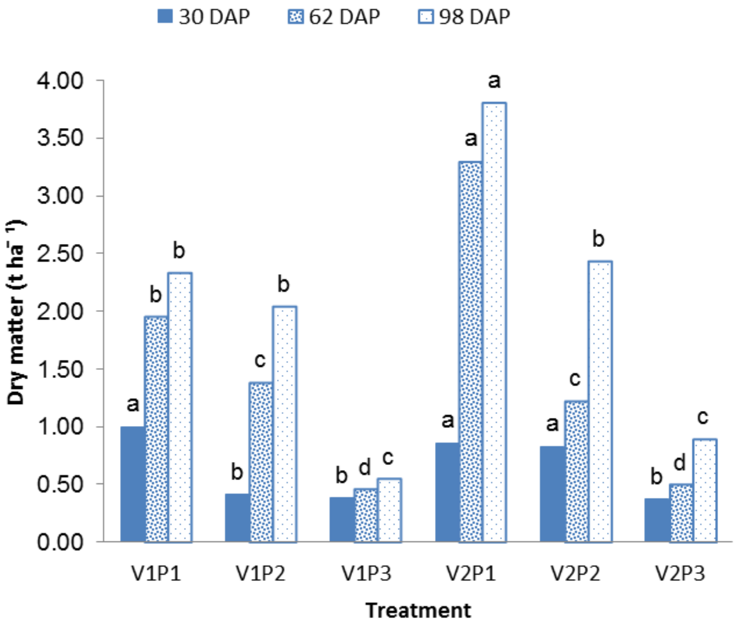


Note: Bars of the same style with the same letter are not significantly different, DAP: Days after planting, P1: 210 000 plants ha^{-1}*, P2: 150 000 plants ha*$^{-1}$*, P3: 70 000 plants ha*$^{-1}$*, V1: Jenny, V2: OPS-RS2.*

Figure 4.6 Effect of dry bean variety and plant population on plant height for Dzindi irrigation scheme

4.3.9 Effect of dry bean variety and plant population on dry matter yield for Dzindi irrigation scheme

The variation in dry matter production was influenced by interaction relationship between plant population and variety (Figure 4.7). At 30 DAP both Jenny (V1) and OPS-RS2 (V2) gave the highest dry matter yield at P1, which was not significantly different from OPS-RS2 at P2. The lowest dry matter yield was produced by OPS-RS2 at P3, which was not significantly different from the dry matter yield of Jenny at P2 and P3. At 62 DAP the variety OPS-RS2 at P1 resulted in the highest amount of dry matter yield, which was significantly different from the rest of the treatments. For both varieties, the dry matter yield decreased with a decrease in plant population which is a little bit different from grain yield where the highest was found in P2 for both varieties. At 98 DAP the dry matter yield followed a similar pattern as at 62 DAP with OPS-RS2 at P1 giving the highest dry matter yield while the lowest was found with Jenny at P3. The highest plant population density resulted in the highest dry matter yield due to improved vegetative growth due to intra-plant competition for light and space.



Note: Bars of the same style with the same letter are not significantly different, DAP=Days after planting, P1: 210 000 plants ha^{-1}*, P2: 150 000 plants ha*$^{-1}$*, P3: 70 000 plants ha*$^{-1}$*, V1: Jenny, V2: OPS-RS2.*

Figure 4.7 Effect of dry bean variety and plant population on dry matter production for Dzindi irrigation scheme

4.3.10 Correlation between grain yield per plant and yield parameters for Dzindi irrigation scheme

There was a significantly positive correlation between grain yield per plant and pods per plant (r = 0.922, p=0.001) and number of seeds per plant (r = 0.866, p=0.001) (Table 4.6). Plant height was also positively correlated with yield, but the correlation was weak (Table 4.6), as were correlations between plant height and the other parameters. There was a significantly positive correlation between pods per plant and number of seeds (r = 0.953, p<0.001). Daniel *et al*. (2011) reported that grain yield had a significant correlation with 100 seed mass, seeds per pod and pods per plant in soybean. Wallace *et al*. (1972) and Westermann and Crothers (1977) also reported that grain yield was highly correlated with the number of pods in dry bean. The number of pods per plant has often been recommended as an indirect selection criterion for increasing yield primarily because of its higher and more consistent correlation with yield (Bennet *et al*., 1977).

Table 4.6 Correlation among grain yield, yield components and growth parameters for Dzindi irrigation scheme

	Yield	Pods plant^{-1}	Seeds plant $^{-1}$	Plant height
Yield	1	0.922***	0.866***	0.484*
Pods plant^{-1}		1	0.953***	0.186
Seeds plant^{-1}			1	0.154
Plant height				1

*Note: *, **, ***- indicates significant difference at 0.05, 0.01 and 0.001 level of probability.*

4.4 CONCLUSIONS

In experiment 1 the results indicated that the interaction relationship did not influence the performance of different dry bean varieties with different planting populations. The results revealed that 150 000 plants ha^{-1} and 110 000 plants ha^{-1} had a significantly higher grain yield than 70 000 plants ha^{-1}. The results further indicated that the lower planting density resulted in higher grain yield per plant. Kranskop resulted in the highest grain yield, which was statistically similar to DBS 310. Jenny resulted in the lowest yield. Results further indicated that 70 000 plants ha^{-1} resulted in significantly higher number of pods per plant than 110 000 plants ha^{-1} and 150 000 plants ha^{-1}. The effect of plant population on number of seeds per pod, shelling %, plant height and 100 seed weight was not significant. The plant height and 100 seed weight were influenced by genetic differences.

In experiment 2 the interaction relationship between dry bean varieties and plant populations significantly influenced the grain yield, grain yield per plant, plant height at 62 and 98 DAP, and dry matter production. The highest grain yield was achieved with OPS-RS2 at 150 000 plants ha^{-1} (3.802 t ha^{-1}). The number of seeds per plant was influenced by plant population and dry bean variety. The number of pods per plant was only influenced by plant populations. There was a significantly positive correlation between grain yield per plant and pods per plant and number of seeds per plant. The plant population of 150 000 plants ha^{-1} was found to be the most suitable for both determinate and indeterminate dry bean varieties under these conditions.

CHAPTER 5

DEFICIT IRRIGATION EFFECTS ON YIELD AND YIELD COMPONENTS OF DRY BEANS (*Phaseolus vulgaris* L.)

ABSTRACT

A rain shelter field experiment was conducted at the Hatfield Experimental Farm of the University of Pretoria, Pretoria, South Africa (25°45'0''S, 28°16'0''E of 1327 m.a.s.l.) during 2011/2012. Dry bean cultivar DBS 360 was subjected to four levels of deficit irrigation, arranged in a randomized complete block design with three replications. For the first 40 days the seedlings were not stressed and irrigated once a week to refill the soil root zone back to field capacity (FC). The deficit irrigation treatments were as follows: S1=irrigated 90% of the measured deficit to FC from 41 DAP (Days after planting) to thephysiological maturityphysiological maturity, S2= irrigated 40% of the measured deficit to FC from 41 DAP to thephysiological maturity, S3= irrigated 40% of the measured deficit to FC from 60 DAP to thephysiological maturity and S4= irrigated 40% of the measured deficit to FC during flowering only. The results revealed that deficit irrigation reduced plant height, number of seeds per plant, number of pods per plant and grain yield. The grain yield was reduced by 53% when plants were stressed from 60 DAP to thephysiological maturity (S3) as compared to the unstressed control (S1). Treatment S3 resulted in the lowest grain yield and number of seeds per plant. There was no significant effect on 100 seed weight and shelling %. Deficit irrigation of irrigated 40% of the measured deficit to FC from 41 DAP to thephysiological maturity (S2), irrigated 40% of the measured deficit to FC from 60 DAP to thephysiological maturity (S3) and irrigated 40% of the measured deficit to FC during flowering only (S4) cannot be recommended for dry bean production since it results in significant reduction in grain yield. The highest water use efficiency was obtained from the highest irrigation.

Keywords: Grain yield, plant height and number of pods per plant.

5.1 INTRODUCTION

The scarcity of water and its growing demand is reducing the amount of water which will be available for agriculture in the future. Irrigated agriculture is the primary user of diverted water globally (Fereres & Soriano, 2007). Global food production is highly influenced by irrigation, especially in low rainfall areas. Irrigation is applied to replace water lost through evapotranspiration. Even though irrigation improves the overall plant growth rate, returns to irrigation diminish with increasing amounts of irrigation, with excess water leading to poor grain yields in common beans and other legumes (Wakrim *et al.*, 2005).

Deficit irrigation is considered to be one of the practices which can reduce the amount of water used without a significant reduction in crop yield (Kirda, 2000). This is one way to meet the growing demand for food without increasing the water demand. Deficit irrigation (DI) can be defined as the application of water below full crop-water requirements (evapotranspiration) (Fereres & Soriano, 2007). It is an important tool to achieve the goal of reducing irrigation water use. In DI the crop is exposed to a certain level of water stress, either during a particular period or throughout the whole growing season. Deficit irrigation is widely practiced over millions of hectares for a number of reasons, from inadequate network design to excessive irrigation expansion relative to catchment supplies, but it has not received sufficient attention in research (Fereres & Soriano, 2007).

The main objective of deficit irrigation is to increase the water use efficiency of a crop by cutting irrigations that have little impact on yield. At the same time water saved can be used to irrigate bigger areas or other crops which were not going to get water if traditional irrigation scheduling is being practiced.

Advantages of deficit irrigation

1. It maximizes water productivity (Geerts & Raes, 2009).
2. Creates a less humid environment around the crop, decreasing the risk of fungal diseases (Cicogna *et al.*, 2005).
3. Reduce nutrient loss through leaching from the root zone, resulting in improved ground water quality (Ünlü *et al.*, 2006) and lower fertilizer needs (Pandey *et al.*, 2000).

4. In areas where water is the limiting factor for crop production, maximizing water productivity by deficit irrigation is often economically more profitable for the farmer than maximizing yield (Geerts & Raes, 2009).

Previous studies suggest that increased water productivity (WP) can be attributed to the following reasons:

1. unproductive water loss through soil evaporation is reduced (Geerts & Raes, 2009);
2. the negative effect of drought stress during specific phenological stages on biomass partitioning between reproductive and vegetative biomass (harvest index) (Fereres & Soriano, 2007; Hsiao *et al.*, 2007; Reynolds and Tuberosa, 2008) is avoided. This stabilizes or increases the number of reproductive organs and/or the individual mass of reproductive organs (filling) (Karam *et al.*, 2009);
3. Water productivity for the net assimilation of biomass is increased as drought stress is mitigated or crops become more hardened. This effect is thought to be rather limited, given the conservative behaviour of biomass growth in response to transpiration (Steduto *et al.*, 2007);
4. Water productivity for the net assimilation of biomass is increased due to the synergy between irrigation and fertilization (Steduto & Albrizio, 2005). This includes cases where irrigation is reduced if fertilizer levels and native fertility are low (Geerts *et al.*, 2008);
5. Negative agronomic conditions are avoided during crop growth, such as pests, diseases, anaerobic conditions in the root zone due to waterlogging, etc. (Pereira *et al.*, 2002; Geerts *et al.*, 2008).

Shortcomings of deficit irrigation

1. Lack of knowledge on the response of a crop to water stress to determine proper time for irrigation application (Kirda & Kanber, 1999).
2. Lack of knowledge on the allowable level of transpiration deficiency without significant reduction in crop yield (Geerts & Raes, 2009).

Many previous studies have evaluated the feasibility of deficit irrigation and the significant savings in irrigation water without significant reduction in yield. Stegman

(1982) reported that the yield of maize, sprinkler irrigated to induce a 30 – 40 percent depletion of available water between irrigations, was not statistically different from the yield obtained with trickle irrigation maintaining the water potential in the root zone near zero. Ziska and Hall (1983) reported that cowpea had the ability to maintain seed yields when subjected to drought during the vegetative stage, provided subsequent irrigation intervals did not exceed eight days. The work of Korte *et al.* (1983b), Eck *et al.* (1987), Speck *et al.* (1989), and of many others, has shown that soybean is amenable to limited irrigation. Stegman *et al.* (1990) indicated that although short-term water stress in soybean during early flowering may result in flower and pod drop in the lower canopy, increased pod set in the upper nodes compensates for this where there is a resumption of normal irrigation.

Since South Africa is known as being a dry country, there was a need to come up with ways to reduce irrigation water loss without significantly reducing yield. Little has been reported on the effects of deficit irrigation on dry beans. The objective of the study was to determine the effects of deficit irrigation introduced at different growth stages on yield and yield parameters of dry bean.

5.2 MATERIALS AND METHODS

5.2.1 Experimental site and treatments

A rain shelter field experiment was conducted at the Hatfield Experimental Farm of the University of Pretoria, Pretoria, South Africa (25°45’0’’S, 28°16’0’’E of 1327 m.a.s.l.) during 2011/2012. Dry bean cultivar DBS 360 (Indeterminate growth) was subjected to four levels of deficit irrigation arranged in a randomized complete block design with three replications. For the first 40 days the seedlings were not stressed and received enough water once a week to bring back the soil to field capacity (FC). The deficit irrigation treatments are tabulated in Table 5.1

Table 5.1 Deficit irrigation treatments applied in the rain shelter trial in 2011/2012

Treatment	Irrigation amount (mm)

1. Irrigated 90% of the measured deficit to FC* from 41 DAP (Days after planting) to the physiological maturity (S1) (Control).	419
2. Irrigated only 40% of the measured deficit to FC from 41 DAP to the physiological maturity (S2).	343
3. Irrigated only 40% of the measured deficit to FC from 60 DAP to the physiological maturity (S3).	391
4. Irrigated only 40% of the measured deficit to FC during effective flowering only (41- 60 DAP) (S4).	371

*Note: FC=field capacity

The plots consisted of 4 rows of 3 m in length each. A within-row spacing of 7.5 cm and between-row spacing of 90 cm were used, giving a population of 150 000 plants ha^{-1}. All management practices were done according to standard production practices (Liebenberg, 2002). Planting and weeding was done by hand. Data were collected from the two middle rows to eliminate border effects. A top dressing was done 28 DAP using limestone ammonium nitrate (LAN-28%N) at a rate of 30 kg ha^{-1} LAN.

5.2.2 Data collection

Grain yield and yield components were determined by harvesting 1 m^{2} at maturity. The plants were harvested by hand. Plant height was measured from 3 plants per randomly selected from the plot at physiological maturity. Plant height was taken as the distance from ground level to the tip of the growing point. The number of seeds per plant and number of pods per plant were counted and 100 seed mass was measured. The moisture content was determined was determined using Dickey John multigrain moisture meter. Shelled seed mass was measured to determine the shelling %. Yield was expressed at 10% seed moisture content. Soil water content was monitored using a calibrated 503DR CPN hydro probe neutron water meter (Campbell Pacific Nuclear, California). Readings were taken twice week at 0.2 m increments to a depth of 1.0 m, from access tubes installed in the middle of each plot and positioned between the rows. Irrigation was applied using drip irrigation to reach field capacity or as per treatment. Harvesting was done when the plants reached maturity and natural drying was allowed. Yield is expressed at 10% seed moisture content.

Water use (ET) in mm and water use efficiency (WUE) in kg ha^{-1}mm^{-1} was calculated using equation 5.1 and 5.2.

$$ET\ (Loss) = I + P - Dr - \Delta S - R \text{.................Equation 5.1}$$

Where I is irrigation in mm, P is precipitation, Dr is drainage, ΔS is change in soil water storage (mm) and R is runoff in mm.

$$WUE = \left(\frac{Y}{ET}\right) \text{..Equation 5.2}$$

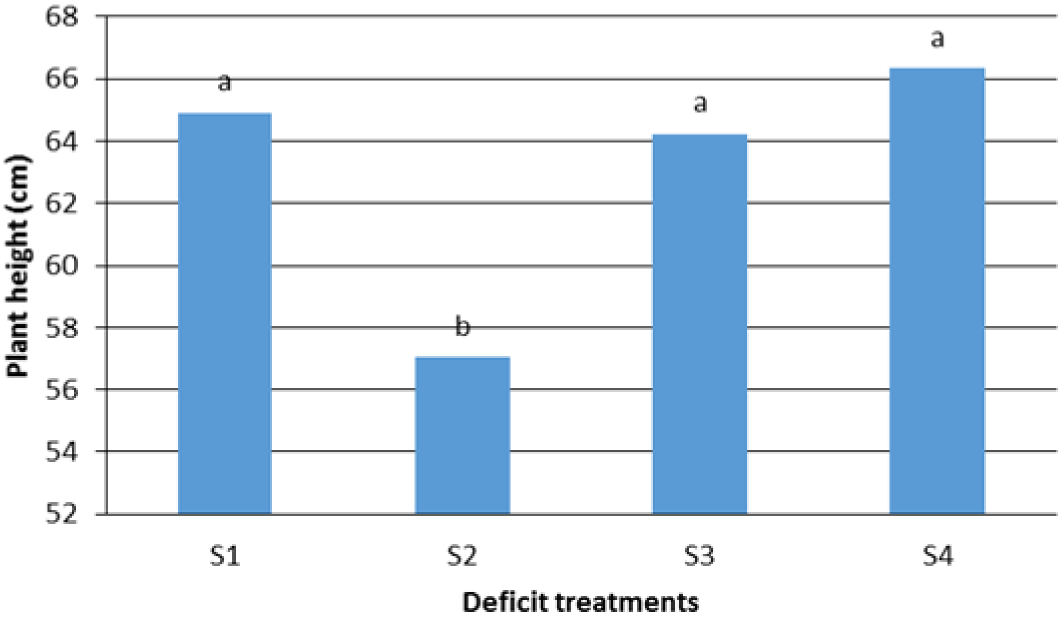
Where Y is grain yield kg ha^{-1}.

The analysis of variance was performed using General linear models of Statistical Analysis System software (SAS 9.3). Means were compared using the least significant differences (LSD) test at a 5% probability level.

5.3 RESULTS AND DISCUSSION

5.3.1 Effect of deficit irrigation on plant height

The results revealed that deficit irrigation significantly affected plant height. The tallest plants were recorded for plants which were only stressed during the effective flowering period (S4) (66.33 cm), while plants that were subjected to deficit irrigation from 41 DAP until thephysiological maturity (S2) resulted in significantly shorter plants (57.03 cm) (Figure 5.1). This could indicate that under control conditions, the plants possibly received too much water.Significant reduction in plant height due to water stress was reported by Aminifar *et al*. (2012) in soybean.

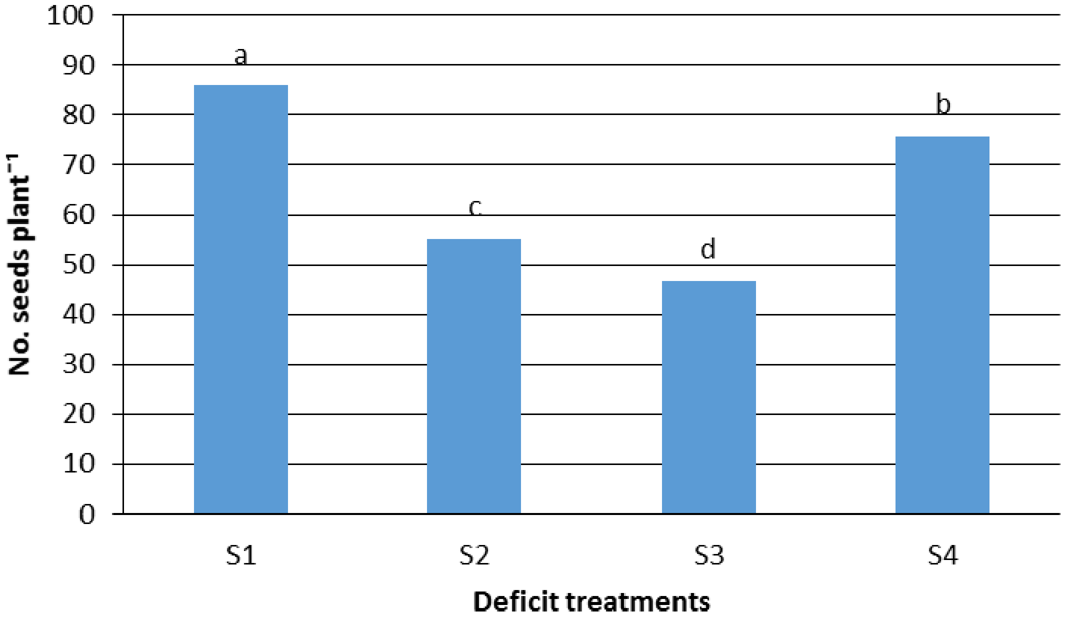


Note: Bars with the same letter are not significantly different. S1= irrigated 90% of deficit to FC from 41 DAP (Days after planting) to thephysiological maturity, S2= irrigated 40% of deficit to FC from 41 DAP to thephysiological maturity, S3= irrigated 40% of deficit to FC from 60 DAP to thephysiological maturity and S4= irrigated 40% of deficit to FC during flowering only.

Figure 5.1 Effect of deficit irrigation treatments on dry bean plant height

5.3.2 Effect of deficit irrigation on number of seeds per plant

The number of seeds per plant was significantly affected by deficit irrigation at P≤ 0.001. The control (S1) resulted in the highest number of seeds per plant (85.9) while plants stressed from 60 DAP until physiological maturity (S3) had the lowest number of seeds per plant (46.7) (Figure 5.2). The introduction of deficit irrigation S2, S3 and S4 resulted in 36%, 46% and 12 % reduction in number of seeds per plant, respectively. The results revealed that dry bean is very sensitive to the introduction of deficit irrigation at around 60 DAP (S3), which is during flowering to pod filling stage, as compared to stressing the plants during the flowering stage only (S4). The reduction in number of seeds per plant in S3 was due to flower and pods sescence during deficit irrigation (Figure 5.3). The higher seed yield in S1 may be due to greater photosynthesis and therefore more photosynthates available for translocation to the pods (Nandan & Prasad, 1998; Sarkar & Kar, 1995). Several studies have confirmed that water stress during reproduction stage resulted in reduced number of seeds per plant (Dubetz & Mahalle, 1969; Nielsen & Nelson, 1998; Panda *et al*., 2003; Zhang *et al*., 2004; Karam *et al*., 2007 & Gohari, 2013). The reduction in number of seeds per plant might have been caused by abscission of flowers (Figure 5.3), increased number of barren plants and incomplete seed setting due to water shortage, as was reported by Teran and Singh (2002).



Note: Bars with the same letter are not significantly different. S1= irrigated 90% of deficit to FC from 41 DAP (Days after planting) to thephysiological maturity), S2= irrigated 40% of deficit to FC from 41 DAP to thephysiological maturity, S3= irrigated 40% of deficit to FC from 60 DAP to thephysiological maturity and S4= irrigated 40% of deficit to FC during flowering only.

Figure 5.2 Effect of deficit irrigation treatments on number of seeds per plant for dry beans

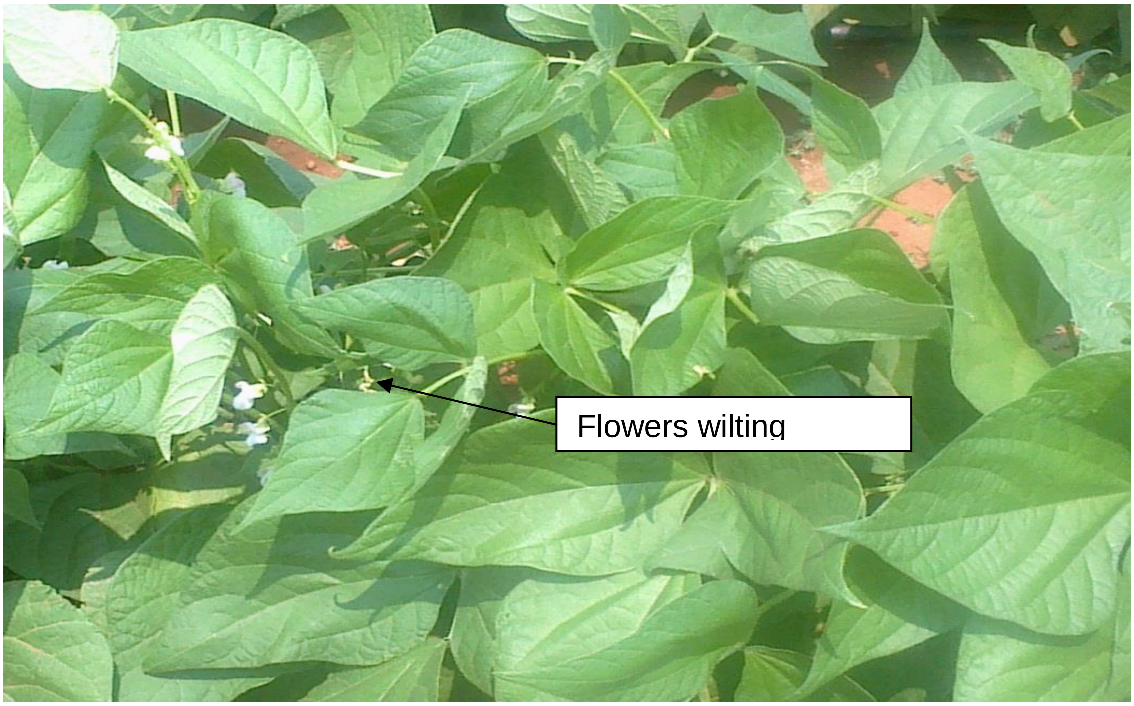
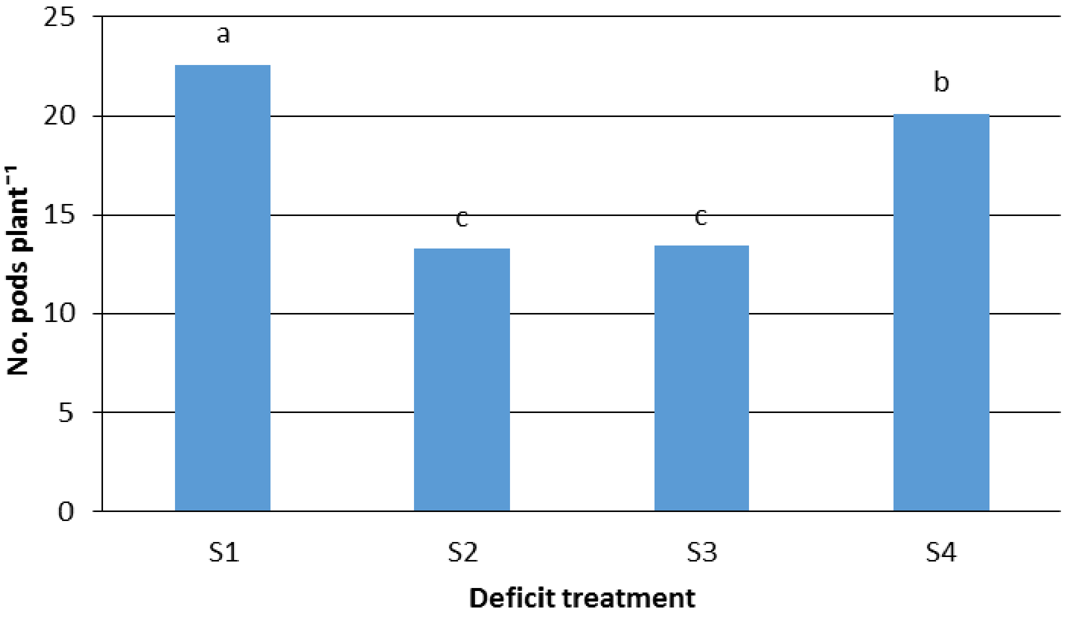


Figure 5.3 Dry bean flowers wilting as a result of water stress for treatment S3 (irrigated 40% of deficit to FC from 60 DAP to thephysiological maturity)

5.3.3 Effect of deficit irrigation on number of pods per plant

The number of pods per plant is one of the most important yield components in determining grain yield (Fageria & Santos, 2008). Deficit irrigation significantly affected the number of pods per plant. The highest number of pods per plant resulted from the control plants (S1), with 22.60 pods per plant, and the lowest number of pods per plant resulted from treatment S2 (Figure 5.4). The results from the two treatments stressed from 41 (S2) and 60 DAP (S3) gave statistically similar results, while the plants stressed during flowering only (S4) performed far better. The introduction of deficit irrigation at S2, S3 and S4 resulted in a 41, 40 and 11 % decrease in the number of pods per plant, respectively. The number of pods at S2 and S3 were not significantly different because they went through deficit irrigation during flowering and pod development leading to senescence of flowers and young pods. The introduction of deficit irrigation is highly dependent on crop the growth stage and the extent of deficit irrigation.When water stress is imposed at flowering and post flowering it results in a reduction in the number of pods due to abortion of the embryo (Gardner *et al.*, 1985), which can also lead to the pod abortion (Manjeru *et al.*, 2007). Pandey *et al*. (1984) reported that water stress reduced flower production in maize. Wakrim *et al.* (2005) reported a reduction in the number of pods per plant due to deficit irrigation occurring during flowering stage in common bean and Bourgault *et al.* (2010) reported a reduction in the number of pods per plant due to deficit irrigation occurring during flowering stage in common bean and mungbean.

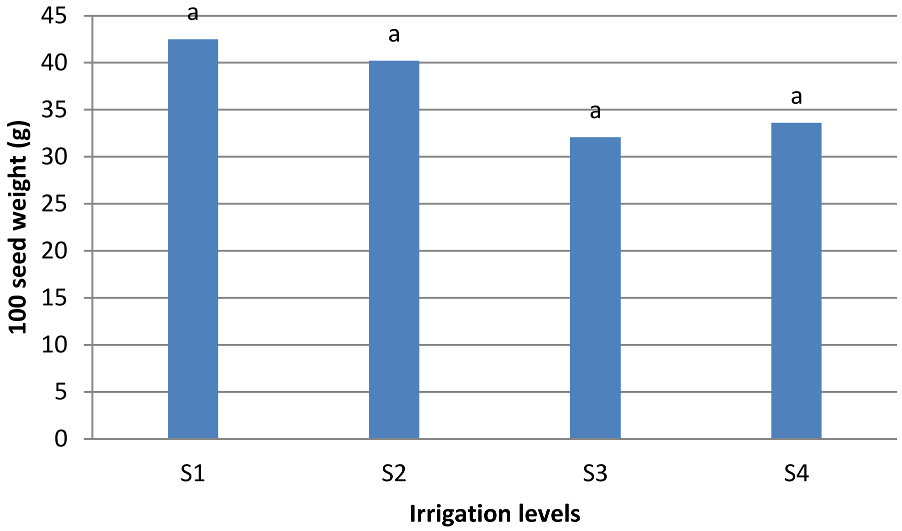


Note: Bars with the same letter are not significantly different. S1= irrigated 90% of deficit to FC from 41 DAP (Days after planting) to thephysiological maturity, S2= irrigated 40% of deficit to FC from 41 DAP to thephysiological maturity, S3= irrigated 40% of deficit to FC from 60 DAP to thephysiological maturity and S4= irrigated 40% of deficit to FC during flowering only.

Figure 5.4 Effect of deficit irrigation treatments on the number of pods per plant of dry bean

5.3.4 Effect of deficit irrigation on 100 seed mass

100 seed mass is an important yield component in dry bean, but although it was reduced by deficit irrigation, the reduction was not significant (Figure 5.5). Although not significant, it is interesting to note that the S2 treated plants compensated for the loss in seeds and pods per plant by producing bigger seeds. The same was, however, not true for S3 treated plants. The 100 seed mass ranged between 42.51 g (S1) and 32.07 g (S3). A non-significant effect of deficit irrigation on 100 seed mass was also reported in common bean by Ghassemi-Golezani and Mardfar (2008), Manjeru *et al.* (2007) and Bourgault *et al.* (2010).

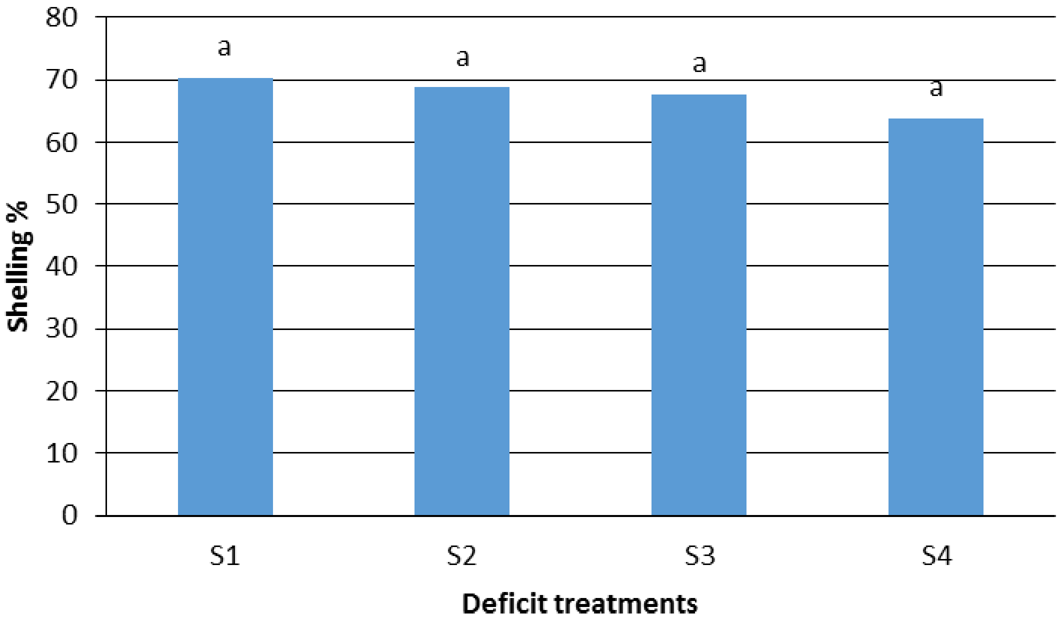


Note: Bars with the same letter are not significantly different. S1= irrigated 90% of deficit to FC from 41 DAP (Days after planting) to thephysiological maturity), S2= irrigated 40% of deficit to FC from 41 DAP to thephysiological maturity, S3= irrigated 40% of deficit to FC from 60 DAP to thephysiological maturity and S4= irrigated 40% of deficit to FC during flowering only.

Figure 5.5 Effect of deficit irrigation treatments on 100 seed mass of dry bean

5.3.5 **Effect of deficit irrigation on shelling %**

Shelling % was reduced by deficit irrigation, but the reduction was not significant (Figure 5.6). The shelling % ranged from 70.3% (S1) to 63.7% (S4).



Note: Bars with the same letter are not significantly different. S1= irrigated 90% of deficit to FC from 41 DAP (Days after planting) to thephysiological maturity), S2= irrigated 40% of deficit to FC from 41 DAP to thephysiological maturity, S3= irrigated 40% of deficit to FC from 60 DAP to thephysiological maturity and S4= irrigated 40% of deficit to FC during flowering only.

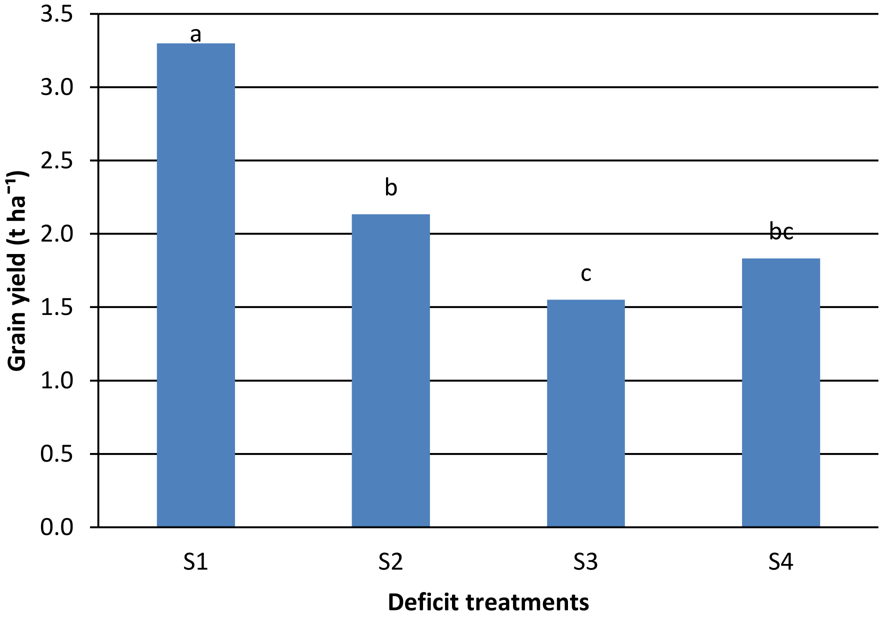
Figure 5.6 The effect of deficit irrigation treatments on shelling % of dry bean

5.3.6 Effect of deficit irrigation on grain yield

There was a significant difference ($P \leq 0.05$) in grain yield due to deficit irrigation. The control (S1) (3.30 t ha^{-1}) had a significantly higher yield than S2 (2.13 t ha^{-1}), S3 (1.55 t ha^{-1}) and S4 (1.83 t ha^{-1}) (Figure 5.7). Similar results have been reported by several authors (Singh, 1995; Board & Harville, 1998 & Manjeru *et al.*, 2007). Compared to the Control, grain yields of deficit irrigation treatments S2, S3 and S4 were reduced by 35%, 53% and 44%, respectively.

Webber *et al.* (2006) and Bourgault *et al.* (2013) reported non- significant yield differences between water stressed and well-watered treatments in common bean. However, several other researchers confirmed a reduction in yield due to water stress (Calvache *et al.*, 1997; Nielsen & Nelson, 1998; Dapaah *et al.*., 2000; Karam *et al.*, 2007; Bourgault *et al*., 2010; Istanbulluoglu *et al.*, 2010; Bourgault *et al.*, 2013). Moderate water stress was reported to reduce yield by 41% (Foster *et al.*, 1995) and severe water stress reduced yield by up to 92% (Castellanos *et al.*, 1996). Generally, water stress interferes with the normal metabolism of the plant during flowering and grain filling as these stages are crucial for yield production.

The reduction in yield was caused mainly by the reduction in the number of pods per plant and number of seeds per plant (Figure 5.4). The results revealed that 53 % of the variation in grain yield was due to the number of seeds per plant (Figure 5.8), while 47% of the variation was due to number of pods per plant (Figure 5.9). The reduction in yield due to number of pods per plant and number of seeds per plant under stress have been reported previously (Dubetz & Mahalle, 1969; Wallace *et al.,* 1972; Stoker, 1974; Acosta-Gallegos & Shibata, 1989; Acosta-Gallegos & Adams, 1991; Castellanos *et al.*, 1996, Nielson & Nelson 1998; Boutraa & Sanders, 2001a). Bennet *et al.* (1977) reported that among the yield components, number of pods per plant has been recommended as an indirect selection criterion for increasing yield due to its consistent correlation with yield. Unfortunately for the current trial the correlation was relatively low.



Note: Means with the same letter are not significantly different. Bars with the same letter are not significantly different. S1= irrigated 90% of deficit to FC from 41 DAP (Days after planting) to thephysiological maturity), S2= irrigated 40% of deficit to FC from 41 DAP to thephysiological maturity, S3= irrigated 40% of deficit to FC from 60 DAP to thephysiological maturity and S4= irrigated 40% of deficit to FC during flowering only.

Figure 5.7 Effect of deficit irrigation on grain yield of dry bean

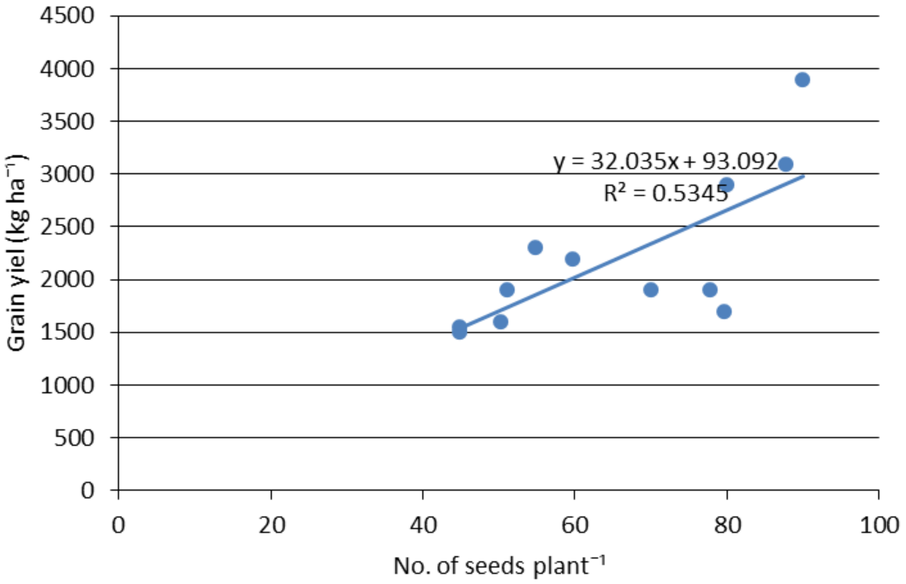


Figure 5.8 The relationship between number of seeds per plant and dry beans grain yield

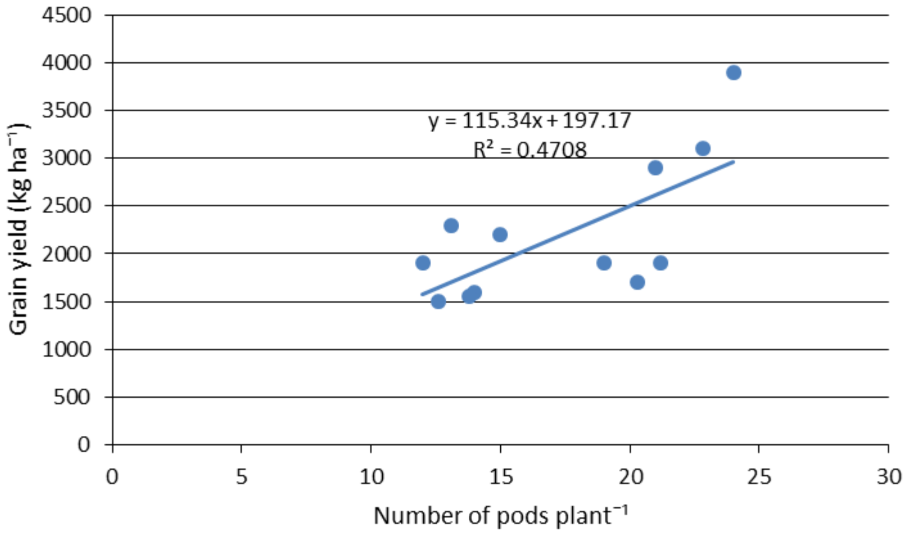


Figure 5.9 The relationship between number of pods per plant and dry bean grain yield

5.3.7 Water use and water use efficiency (WUE)

The effect of deficit irrigation on water use was highly significant at $P \leq 0.001$ (Table 5.2). The highest amount of water use was by S1 (419mm) and the lowest by S2 (343mm). Deficit irrigation had a highly significant effect on WUE at $P \leq 0.001$. The highest water use efficiency was obtained by S1 (7.87 kg ha^{-1} mm^{-1}) and the lowest at S3 (3.97 kg ha^{-1} mm^{-1}). The increase in water use efficiency in S1 is possibly due to developed canopy resulting from high irrigation water amount. The increase in WUE with increased irrigation water has been reported in dry bean (Ucar *et al*., 2009).

Table 5.2 Crop water use efficiency (kg ha^{-1} mm^{-1}) of dry bean subjected to different deficit irrigation levels

Deficit irrigation treatment	Water use (mm)	Yield (kg ha^{-1})	WUE (kg ha^{-1} mm^{-1})
S1	419a	3300a	7.87a
S2	343d	2133b	6.22b
S3	391b	1550c	3.97c
S4	371c	1833bc	4.94bc
CV%	0.78	12.87	12.49
LSD	5.94**	0.57*	1.43**

*S1= irrigated 90% of deficit to FC from 41 DAP (Days after planting) to thephysiological maturity), S2= irrigated 40% of deficit to FC from 41 DAP to thephysiological maturity, S3= irrigated 40% of deficit to FC from 60 DAP to thephysiological maturity and S4= irrigated 40% of deficit to FC during flowering only. *; significant at p≤0.05, **: significant at p≤0.001*

5.4 CONCLUSIONS

The introduction of deficit irrigation resulted in a significant reduction in plant height, number of seeds per plant and number of pods per plant. The reduction in number of seeds per plant and number of pods per plant resulted in a significant reduction in grain yield. The shelling % and 100 seed mass were not significantly influenced by deficit irrigation. The results revealed that deficit irrigation using these treatments can result in substantial yield reduction in dry beans, especially if it starts during the late flowering/early pod developing stage (S3). The yields as affected by deficit irrigation during early flowering (S2 and S4) were significantly better than that of S3, but still it is not a system that could be recommended to farmers to reduce irrigation water use. Deficit irrigation reduced water use efficiency in dry bean plants. In future deficit treatment could be adjusted to irrigate higher fraction like 50 or 60%. Based on this, there is a need for further research to develop drought tolerant varieties of dry beans as well as alternative water saving mechanisms/systems. In the following chapter the latter will be further explored by subjecting the dry beans to drought stress at different growth stages and for different durations of stress.

CHAPTER 6

THE EFFECTS OF DROUGHT STRESS ON GROWTH AND YIELD OF DRY BEAN (*Phaseolus vulgaris* L.)

ABSTRACT

The effects of drought stress on growth and yield of dry bean were evaluated in a rain shelter field experiment in 2013. The variety DBS 360 was exposed to the following drought stress levels: the control: Irrigated to field capacity on a weekly basis throughout the growing season (S1), Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season (S2), irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season (S3), irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season (S4) and then irrigated to field capacity on a weekly basis up to 36 DAP, whereafter it was only irrigated to field capacity on a fortnightly basis (S5). Drought stress resulted in reduced dry matter production, leaf area index, pods per plant, number of seeds per plant, 100 seed mass and grain yield. Grain yield was positively correlated with yield components such as 100 seed mass, number of pods per plant and number of seeds per plant. Withholding water during the early reproductive phase (S2) resulted in the lowest total dry matter production per plant, followed by S3 and S4, with no significant differences between them and S5. The results revealed that S5 resulted in a grain yield statistically similar to S1. The highest water use efficiency was also found at S5. This indicates that water savings can be made without significantly reducing yields in dry bean.

Keywords: Water stress, leaf area index, 100 seed mass and water use efficiency

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6.1 INTRODUCTION

Water appears to be the most important determinant of crop productivity (Taylor *et al*., 1986). Boutraa and Sanders (2001a) have reported that drought stress during vegetative and reproductive stages is one of the most limiting factors of bean growth. Rahman *et al*. (2004) further indicated that drought stress is one of the factors affecting every aspect of plant growth. Physiological changes in plants, which occur in response to drought stress conditions decrease photosynthesis and respiration, which result in the reduction of the overall production of the crop (Rashidi & Seyfi, 2007). High yield production is dependent on the adequate balance between various physiological processes or yield components (Fageria & Santos, 2008). Plant growth stages are modified by the soil water availability patterns during the growth cycle (Ramirez-Vallejo & Kelly, 1998).

The effect of drought stress on seed yield is highly dependent on the stage of growth, intensity and extent at which drought stress was introduced. In legumes flowering and pod filling stages are the most sensitive to drought stress, as it impacts negatively on flower development, pollination (Boyer & McPherson, 1975), pod setting and grain filling, leading to a reduction in the number of pods per plant, seed mass and consequently low seed yield (Chiulele *et al*., 2011). . It is further indicated that the introduction of drought stress during flowering and pod filling has been reported to reduce yield and seed mass (Singh, 1995; Miller & Burke, 1983). According to Stoker (1974) the reduction in yield is mostly caused by abscission of flowers and young pods. The results from chapter 5 of this thesis indicated that the introduction of deficit irrigation resulted in a reduction in grain yield, number of seed per plant and number of pods per plant.

Acosta-Gallegos (1988) reported that drought stress negatively affected the leaf area, which resulted from loss of leaves, reduced size of younger leaves and total reduction in the development of the leaf. The reduction in leaf development leads to the reduction in photosynthesis and finally to reduction in yield. Many aspects of plant growth are affected by drought stress (Hsiao, 1973), including leaf expansion, which is reduced due to the sensitivity of cell growth to drought stress. The reduction of leaf area reduces crop growth and biomass production (Akyeampong, 1985). Leaf area is an essential component of plant growth analysis and evapotranspiration studies (Bhatt & Chanda, 2003). Leaf area is important for light interception and therefore has a great influence on growth (Boote *et al*., 1988), transpiration (Enoch & Hurd, 1979) and growth rate (Leith *et al*., 1986). Leaf area index (LAI) is thus an important plant parameter which determines photosynthesis and final yield. LAI is influenced by environmental factors like temperature, mineral nutrition, water supply, and light (Fageria & Santos, 2008).

Information on the effects of drought stress on yield and water use efficiency of dry bean plant has not been well investigated under field conditions of Pretoria. Therefore, the objective of the study was to determine whether the timing of drought stress in plant development affects yield and water use efficiency and also to check the possibility of saving water without losing biomass.

6.2 MATERIALS AND METHODS

6.2.1 Experimental site and treatments

A rain shelter field experiment (Figure 6.1) was conducted at the Hatfield Experimental Farm of the University of Pretoria, Pretoria, South Africa (25°45’0’’S, 28°16’0’’E of 1327 m.a.s.l.) in 2013. Drought stress was applied through subjecting the dry bean cultivar DBS 360 to five levels of drought stress arranged in a randomized complete block design with six replications. The plot size was 2 x 2.5 m^2, using an inter-row spacing of 30 cm and intra-row spacing of 7.5 cm, giving a plant population of 150 000 plants ha^{-1}. Top dressing was done 28 DAP using limestone ammonium nitrate (LAN-28%N) at the rate of 30 kg N ha^{-1}.

Drought stress treatments were as follows:

1. The control: Irrigated to field capacity on a weekly basis throughout the growing season (S1).
2. Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days (S2), then irrigated to field capacity to the end of the growing season.

3. Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days (S3), then irrigated to field capacity to the end of the growing season.
4. Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season (S4).
5. Irrigated to field capacity on a weekly basis up to 36 DAP, whereafter it was only irrigated to field capacity on a fortnightly basis for the duration of the trial (S5).

Figure 6.1 Dry bean trial in 2013 under a rainshelter on the Hatfield Experimental Farm, Pretoria.

6.2.2 Data collection

To quantify the effects of drought stress on dry bean, weather, physiological, growth, soil water content and yield data were collected.

Weather data were collected from an automated weather station close to the experimental site. Daily solar radiation, maximum and minimum relative humidity, maximum and minimum temperatures and wind speed data were collected.

Soil water content was monitored using a 503DR CPN hydro probe neutron water meter (Campbell Pacific Nuclear, California), which was calibrated for the experimental site. Readings were taken twice a week, at 0.2 m intervals to a depth of 1.0 m, from access tubes installed in the middle of each plot and positioned between the rows. A drip irrigation system was used for irrigating the trial and a water flow meter was used to measure the amount of water applied to each treatment.

The effect of drought stress on dry bean growth was monitored through harvesting three plants per plot at 48 DAP, 64 DAP and 95 DAP. The samples were divided into leaves, stems and pods. There after the samples were oven-dried for 72 hours at 65 ^{o}C to determine dry matter yield (DM) of the different plant components. The leaf area was measured using a LI 3100 belt-driven leaf area meter (Li Cor, Lincoln, Nebraska, USA) and leaf area index (LAI) was calculated using Equation 6.1. Thereafter the samples were oven-dried to a constant mass (for ± 72 hours) at 65^{o}C to determine dry matter yield (DM). The total above-ground dry matter yield was determined by adding together the dry mass of the leaves, stems and pods.

$$LAI = \frac{Measured\ total\ leaf\ area}{Sampled\ ground\ area} \quad \text{..............Equation 6.1}$$

Grain yield and yield components were determined by harvesting 1 m^{2} at maturity. The plants were harvested by hand. The number of plants per plot, number of seed per plant and number of pods per plant were counted and 100 seed mass was measured. The moisture content of the seed was determined by using a multi grain moisture meter (Dickey John, Auburn, Illinois, USA). Unshelled seed mass was measured to determine the shelling %. Yield was expressed on 10% seed moisture content basis.

An analysis of variance was performed using General Linear Models of the Statistical Analysis System software (SAS, 2010). Means were compared using the least significance differences (LSD) test at 5% probability level. Correlation analysis was done using SAS.

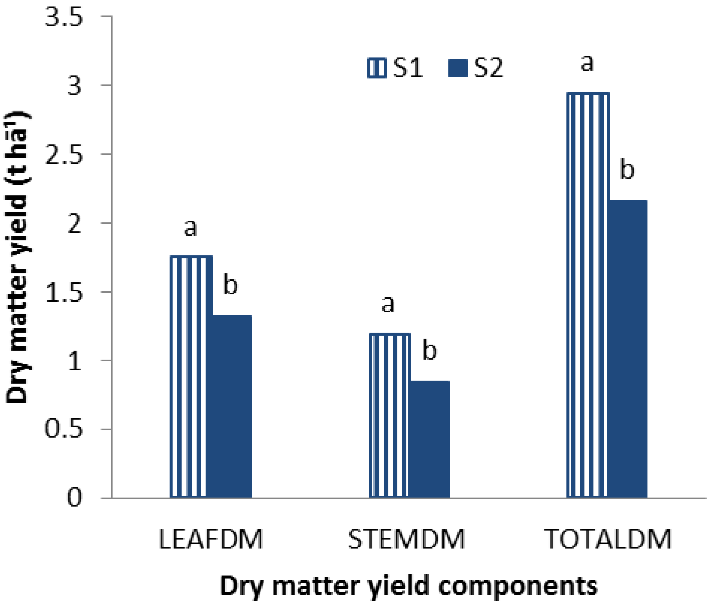
6.3 RESULTS AND DISCUSSIONS

6.3.1 Effect of drought stress on dry matter partitioning

Drought stress highly affected dry matter partitioning at 48 DAP at $P \leq 0.001$ (Figure 6.2). Withholding water from day 36 (S2) resulted in a reduction of 24, 29 and 26 % respectively in terms of leaf, stem and the total plant dry matter yield. The results also revealed that drought stress highly affected dry matter partitioning at 64 DAP (Figure 6.3). By irrigating the crop once in two weeks from day 37 onwards (S5) resulted in the highest leaf, stem and total plant dry matter yield. The control (S1), and withholding water for 24 days during late vegetative/early flowering (S2) or flowering (S3) stages resulted in a 6, 15 and 18% reduction in dry matter yield respectively, as compared to S5.

At the 92 DAP sampling time dry matter partitioning was also affected by drought stress (Figure 6.4). The highest dry matter yield in terms of leaves, stems, pods and total plant mass was found under control conditions. The leaf, stem, pod and total plant dry matter yields were the most severely affected by withholding water from day 37 – 60 (S2), which coincided with early flowering. Withholding water during flowering only (S3) or during the pod development and pod growth stages (S4) also resulted in lower dry matter yields as compared to the control, but there were no significant differences between the two treatments.

The highest leaf and stem dry matter yield was found at 64 DAP and the lowest at 92 DAP, due to the fact that more photo-assimilates were translocated to pods. The results also indicate that even at 32 days after drought stress was terminated for S2, the plants could not recover and still produced the lowest total dry matter yield. The results suggest that the introduction of drought stress during early growth stages reduced the photosynthetic potential of the plants.

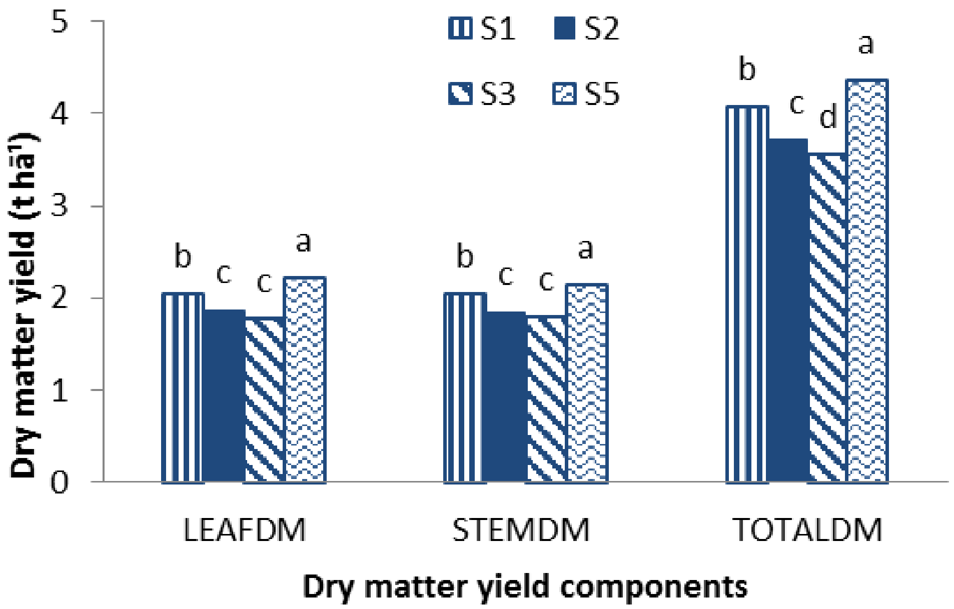


Note: Means of bars of the same plant part with the same letter are not significantly different, DAP=Days after planting,

S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season

Figure 6.2 Effect of drought stress on dry matter yield components of dry beans subjected to different water regimes at 48 DAP



Note: Means of bars of the same plant part with the same letter are not significantly different, DAP=Days after planting

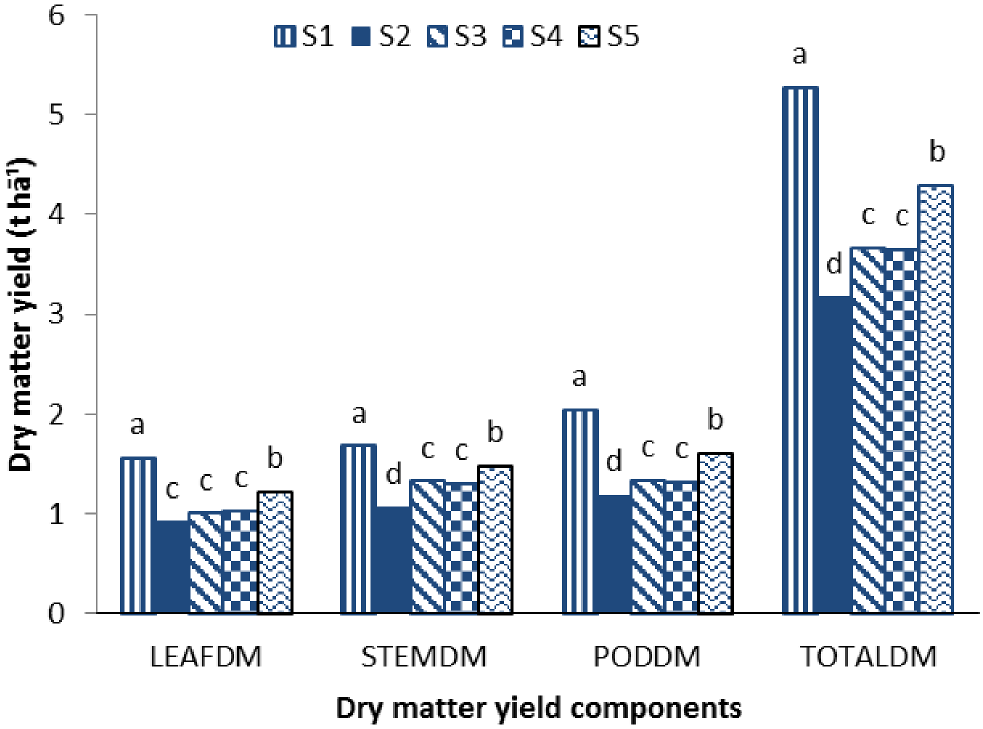
S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season,

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

Figure 6.3 Effect of drought stress on dry matter yield components of dry beans subjected to different water regimes at 64 DAP



Note: Means of bars of the same plant part with the same letter are not significantly different, DAP=Days after planting

S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season,

S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

Figure 6.4 Effect of drought stress on dry matter yield components of dry beans subjected to different water regimes at 92 DAP

6.3.3 Effect of drought stress on leaf area index

Drought stress resulted in a reduction in leaf area index (LAI) (Table 6.1). At 48 DAP treatment S1 had significantly the highest LAI, with drought (S2) resulting in a reduction in leaf area index by 12% ($P \leq 0.05$).

At 64 DAP, irrigating every week (S1) resulted in the highest LAI, compared to the other treatments ($P \leq 0.001$). The treatments S2, S3 and S5 resulted in a 21, 49 and 14% reduction in LAI respectively.

At 92 DAP S1 had the highest LAI, with S2, S3, S4, and S5 resulting in 66, 32, 14 and 38% reduction in LAI respectively ($P \leq 0.001$). The reduction in leaf area index could be the result of reduced leaf size through decrease in expansion of individual actively growing leaves (Akyeampong, 1986), decreased number of leaves through the cessation of development of new leaves (Acosta- Gallegos, 1988) as well as premature senescence. The abscission of leaves is a plant defence mechanism against drought stress (Taiz & Zeiger, 2006). Many studies have confirmed accelerated leaf senescence due to drought stress (Thomas & Stoddart, 1980; Gan & Amasimo, 1997) in dry bean (Gunton & Evenson, 1980; Emam, 1985), chick pea (*Cicer arientinam* L.) (Davies *et al*., 1999), maize (*Zea mays* L.) (Aparicio-Tejo & Boyer, 1983), sunflower (*Helianthus annuus* L.) (Whitfield *et al*., 1989), cowpea (*Vigna unguiculata*) (Akyeampong, 1985) and soybean (*Glycine max* L.) (Brevedan & Egli, 2003).

Table 6.1 Effect of drought stress on dry bean leaf area index

Stress level	48 DAP	64 DAP	92 DAP
S1	2.23a	3.13a	1.052a
S2	1.96b	2.46c	0.361d
S3		1.604d	0.712c
S4			0.907b
S5		2.679b	0.654c
CV %	3.85	5.05	16.29
LSD$_{0.05}$	0.119*	0.153**	0.144**

*Note: Means for values in a column with the same letter are not significantly different, DAP=Days after planting, *: significant at $p \leq 0.05$, **: significant at $p \leq 0.001$*

S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season,

S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

6.3.4 Effect of drought stress on number of pods per plant

The number of pods per plant was highly influenced by drought stress ($P \leq 0.001$) in all the stressed treatments except S5 (Table 6.2). The application of irrigation every second week (S5) resulted in a 9.7% reduction in number of pods per plant and the application of stress at 36, 49 and 73 DAP resulted in a 17, 20 and 19% reduction in the number of pods, respectively. The results also indicated that S2, S3 and S4 were not significantly different from each other, and neither were S5 and S2 ($P \leq 0.05$). Mwanamwenge *et al*. (1999) and Wein *et al*. (1973) observed that drought stress resulted in pod abortion. The number of pods seems to be highly affected by drought stress introduced at flowering and can result in the reduction of up to 70% depending on the duration and intensity of the stress period (Lopez *et al*., 1996). Similarly, Szilagyi (2003) reported that drought stress resulted in a 60% reduction of number of pods per plant.

6.3.5 Effect of drought stress on number of seeds per plant

The number of seeds per plant was significantly influenced by drought stress treatments ($P \leq 0.05$). The results revealed that S1 and S5 had seed numbers which were similar and that the number at S5 was similar to S3 and S4 (Table 6.2). The lowest number of seeds was found at S2. The introduction of drought stress at 36, 49, and 73 DAP and irrigating once in two weeks resulted in a seed number reduction of 22, 16, 18 and 10 %, respectively. When drought stress was introduced during flowering stage (S2) the reduction was much greater, as was also reported by Miller and Burke (1983).

6.3.6 Effect of drought stress on 100 seed mass and shelling percentage

The results revealed that the largest seeds were produced by S1 (Table 6.2) and the smallest was produced by S2, which is similar to S3, while S3 had seeds similar in mass to S4, which in turn was similar to S5. The reduction in the 100 seed mass from S1 to S2 was 19.74 %. This suggests that introducing drought stress from 36 DAP can result in a serious reduction in seed size. The results are in line with the findings by Singh (1995) and Szilagyi (2003). There was no effect of drought stress on the shelling percentage (Table 6.2).

Table 6.2 Effect of drought stress during different growth stages on dry bean yield components

Stress level	Pods per plant	Seeds per plant	100 seed mass	Shelling %
S1	10.45a	36.43a	39.03a	78
S2	8.63bc	28.31c	31.57d	77
S3	8.35c	30.58bc	32.81cd	64
S4	8.41c	29.91bc	35.21bc	79
S5	9.43b	32.75ab	37.43ab	77
CV%	8.37	9.82	7.34	ns
$LSD_{0.05}$	0.913**	3.73*	3.11**	15.32

*Note: Means for values in a column with the same letter are not significantly different, DAP: Days after planting, *: significant at $p \leq 0.05$, **: significant at $p \leq 0.01$.*

S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season,

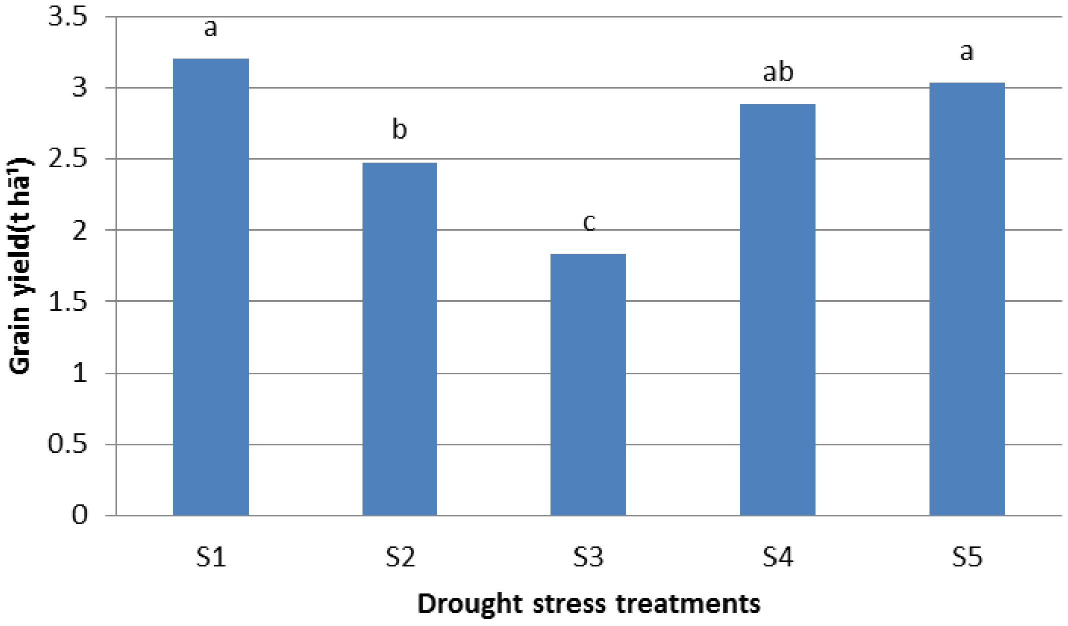
S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

6.3.7 Effect of drought stress on grain yield

The effect of drought stress on grain yield was highly significant at $P \leq 0.001$ (Figure 6.5). The results revealed that there was no significant loss in yield by irrigating the crop once every two weeks (S5) compared to the control (S1). Treatments S2 and S3 were significantly affected by drought stress, resulting in a 23-42% reduction in grain yield. Maleki *et al*. (2013) also reported lowest grain yield from treatments that were stressed during flowering and grain filling stages. There were no significance differences between S1, S4 and S5. The results suggest that stress levels S5 and S4 can be adopted without compromising grain yield significantly.

Several studies have reported a reduction in grain yield due to drought stress (Boutraa & Sanders, 2001b; Zlatev & Stoyanov, 2005; Brevedan & Egli, 2003; Doss *et al*., 1974; Sionit & Kramer, 1977; Ashley & Ethridge, 1978; Egli *et al*., 1983; Korte *et al*., 1983a). The reduction in grain yield due to drought stress between reports in literature is variable due to differences in the timing and intensity of stress imposed and the genotype used (Frahm *et al*., 2004; Shenkut & Brick, 2003; Ramirez-Vallejo & Kelly, 1998; Foster *et al*., 1995; Haterlein, 1983).



Note: Means with the same letter are not significantly different

S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season,

S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

Figure 6.5 Effect of drought stress during different growth stages on grain yield of dry bean at harvest

6.3.8 Correlations

The mass of 100 seed, number of pods per plant, number of seeds per plant, total dry matter at 92 DAP and leaf area index were all positively correlated to grain yield (r=0.581, r=0.562, r=0.471, r=0.432, r=0.375 respectively) (Table 6.3).Some of the correlations were not very strong, indicating that multiple factors influence yield.

Table 6.3 Correlation coefficients among selected agronomical traits in dry bean

	Yield	**100 seed mass**	**# Pods plant^{-1}**	**# Seeds plant^{-1}**	**Total dry matter yield**	**Leaf area index**
Yield	1					
100 seed mass	0.581**	1				
# Pods plant^{-1}	0.562**	0.616**	1			
# Seeds plant^{-1}	0.471*	0.640**	0.791***	1		
Total dry matter	0.432*	0.682***	0.556**	0.591**	1	
Leaf area index	0.375*	0.598**	0.394*	0.571**	0.837***	1

*Note: *, **, ***- indicates significant difference at 0.05, 0.01 and 0.001 level of probability.*

6.3.9 Water use and water use efficiency (WUE)

The effect of drought stress on water use was highly significant at $P \leq 0.001$ (Table 6.4).The highest amount of water used was by the control plants (S1, 4201 mm) and the lowest by the plants irrigated every second week (S5, 251 mm). Drought stress had a highly significant effect on WUE at $P \leq 0.001$. The highest WUE was obtained by S5 (12.11 kg $ha^{-1}mm^{-1}$) followed by S2 (9.00 kg $ha^{-1}mm^{-1}$), S4 (8.73 kg $ha^{-1}mm^{-1}$), S1 (7.61 kg $ha^{-1}mm^{-1}$) and finally S3 (4.83 kg $ha^{-1}mm^{-1}$) (Table 6.4). Where plants were subjected to drought from 49 days after planting for 24 days (S3), it had a severe negative effect on yield and resulted in the lowest WUE. The increase in water use efficiency at lower irrigation rates was also reported in tomato (Gohari, 2013) and common bean (De Costa and Liyanage, 1997).

Table 6.4 Crop water use efficiency (kg ha^{-1} mm^{-1}) of dry bean subjected to different drought stress levels

Stress level	Water use (mm)	Yield (kg ha^{-1})	WUE (kg ha^{-1} mm^{-1})
S1	421a	3203a	7.61b
S2	276d	2479b	9.00b
S3	382b	1840c	4.83c
S4	330c	2888ab	8.73b
S5	251e	3044a	12.11a
CV%	3.69	14.87	14.87
$LSD_{0.001}$	14.77	482.21	1.516

Note: Means for values in a column with the same letter are not significantly different, DAP: Days after planting,

S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season,

S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

6.4 CONCLUSIONS

The introduction of drought stress resulted in a reduction in dry matter production, leaf area index, number of seeds per plant, number of pods per plant, seed size and finally grain yield. The treatments irrigated to field capacity on a weekly basis, followed by withholding irrigation from 36 days after planting (DAP) for 24 days (S2), and irrigated to field capacity on a weekly basis, followed by withholding irrigation from 49 DAP for 24 days (S3) performed poorly throughout. Withholding irrigation from 36 days after planting for 24 days (S2) coincided with the late vegetative stage and withholding irrigation from 49 days after planting for 24 days (S3) coincided with the early flowering stage of the dry beans. The results also revealed that mass of 100 seeds, number of pods per plant, number of seeds per plant, total dry matter at 92 DAP and leaf area were all positively correlated with grain yield. It is thus of importance to ensure that the correct plant population, good crop protection measures, etc. are practiced to facilitate a plant canopy that stays green and active as long as possible. Water use efficiency was significantly affected by drought stress. The results suggest that drought stress towards the end of the growing season may not cause serious harm to grain yield, with the advantage of less water being used. Dry bean producers planting under irrigation conditions should therefore be advised to ensure good water supply during the flowering stages. At pod development and growth stages irrigation is still important, but the interval between irrigations can be lengthened without a significant impact on yield and at the same time WUE is improved.

CHAPTER 7

THE EFFECTS OF DROUGHT STRESS ON THE PHYSIOLOGY OF DRY BEAN (*Phaseolus vulgaris* L.) PLANTS

ABSTRACT

Drought stress effects on the physiology of dry bean were evaluated in a rain shelter field trial. The variety DBS 360 was exposed to the following drought stress levels: the control: Irrigated to field capacity on a weekly basis throughout the growing season (S1), Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season (S2), irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season(S3), irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season (S4) and irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP (S5) until the end of the growing season. Drought stress resulted in a reduction in photosynthesis, intercellular carbon dioxide concentration, stomatal conductance, transpiration, minimal fluorescence (Fm) and photochemical efficiency of PSII (Fv/Fm). Drought stress increased minimal fluorescence (Fo). Drought stress can result in serious physiological challenges and therefore negatively affect seed yield. In conclusion, photosynthesis, intercellular carbon dioxide concentration, stomatal conductance, transpiration, Fm and Fv/Fm can be useful parameters to monitor drought stress in plants.

Keywords: Photosynthesis, transpiration, stomatal conductance, chlorophyll fluorescence

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7.1 INTRODUCTION

Water is the major limiting factor affecting plant growth, development and yield in areas where plants are often exposed to drought stress. Photosynthesis can be defined as the conversion of light energy by photosynthetic pigments using water and carbon dioxide and producing carbohydrates and oxygen (Taiz & Zeiger, 2006). Water is essential for photosynthesis, plays an important role in transpiration and regulates the opening and closing of stomata. Chemically, water is a reactant in photosynthesis, the chemical reaction which is the basis of carbohydrate production in the plant:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \quad \text{………………Equation 7.1}$$

Carbon dioxide Water Carbohydrate Oxygen

Photosynthesis is very sensitive to drought stress. Photosynthesis can be affected by drought stress in three ways: first and secondly, the closure of the stomata cuts off access of the chloroplast to the atmospheric supply of CO_2 while transpiration is also stopped and thirdly, low cellular water potential directly affects the structural integrity of the photosynthetic machinery (Hopkins & Hüner, 2004).

According to Medrano *et al.* (2002) the debate about the cause of the limitation of photosynthesis during drought has been running for some time. Currently it is not clear whether it results from stomatal closure or metabolic impairment. Several reports indicated that stomatal closure was generally accepted as the main determinant for decreased photosynthesis under mild to moderate drought stress (Sharkey, 1990; Chaves, 1991; Ort *et al.*, 1994; Cornic & Massacci, 1996; Taiz & Zeiger, 2006). Stomata close in response to leaf turgor decline due to drought stress to reduce the loss of water to the atmosphere. Although this process limits water loss, it also limits carbon uptake by the leaves (Chaves, 1991; Cornic & Massacci, 1996). As drought progresses, stomatal closure occurs for longer periods. This depression in gas exchange reduces daily carbon assimilation. (Chaves *et al.*, 2002). In addition to reduced CO_2 diffusion through the stomata, drought stress results in the reduction of CO_2 diffusion through the leaf mesophyll i.e. reduced mesophyll conductance of CO_2 (g_m) (Chaves *et al.*, 2009). This limitation of carbon availability at the carboxylation sites in the chloroplasts result in an excessive excitation of the photosynthetic apparatus, particularly photosystem II (PSII) (Pastenes *et al.*, 2004).

Chlorophyll fluorescence analysis has become one of the most powerful and widely used techniques available to plant physiologists and eco-physiologists (Maxwell & Johnson, 2000). According to Fernandez-Jaramillo *et al*. (2012) chlorophyll fluorescence can be defined as red and far-red light emitted by photosynthetic tissue when excited by a light source. Chlorophyll fluorescence is a defense mechanism or a method to dissipate excess energy (Stirbet & Govindjee, 2011), which is highly linked to the photosynthetic process.

There is a consensus that a decrease in the photosynthetic rate under drought stress can be due to both stomatal and non-stomatal limitations (Shangguan *et al.*, 1999). Little has been reported on the effect of drought stress on chlorophyll fluorescence of dry beans. Many studies have reported about the effects of drought stress on photosynthesis but little has been reported on the effects of drought stress on chlorophyll fluorescence and the after-drought stress effects on photosynthesis and fluorescence. Therefore, the objectives of the study was to determine the effects of drought stress on leaf gaseous exchange and chlorophyll fluorescence parameters of dry bean under field conditions and also to investigate the after-effects of drought stress upon lifting drought.

7.2 MATERIALS AND METHODS

Drought stress management was the same as reported in Chapter 6.

Drought stress treatments were as follows:

1. The control: Irrigated to field capacity on a weekly basis throughout the growing season (S1).
2. Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days (S2), then irrigated to field capacity to the end of the growing season.
3. Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days (S3), then irrigated to field capacity to the end of the growing season.
4. Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season (S4).

5. Irrigated to field capacity on a weekly basis and irrigated to field capacity on a fortnightly basis from 36 DAP (S5).

7.2.1 Leaf gas exchange parameters

The following parameters were measured three times during the growing season: Net photosynthesis, transpiration, stomatal conductance and intercellular carbon dioxide concentration using a portable gas exchange measuring system (Li 6400, Li-Cor, USA). At 105 DAP there were no measurements for S2 and S3 because the weather became cloudy. Instantaneous water use efficiency (iWUE) was calculated according to Bogale *et al.* (2001).

$$iWUE = \frac{Pn}{E} \quad \text{……………………………………………………………Equation 7.2}$$

Where iWUE is the instantaneous water use efficiency, Pn is photosynthesis and E is transpiration rate.

Chlorophyll content was measured using a portable chlorophyll content meter (CCM-200, Opti Sciences, USA). The measurements were made from the top most expanded leaf (3 leaves per plot) at 48, 53, 61, 77, 80, 89 and 104 DAP.

7.2.2 Chlorophyll fluorescence measurements

Chlorophyll fluorescence was measured using a 6400-40 leaf chamber fluorometer. The measurements were taken from the top most expanded leaf. Minimal fluorescence (F_o) was measured for 60 minute dark-adapted leaves and maximal fluorescence (F_m) was measured after a 0.8s saturation light pulse for the same leaves. Maximal variable fluorescence (F_v=F_m-F_o) and the photochemical efficiency of PSII (F_v / F_m) for dark adapted leaves were calculated. In light adapted leaves steady state fluorescence (F_s) yield, maximal fluorescence (F'_m) after an 0.8s saturating light pulse and minimal fluorescence (F'_o) were measured when actinic light was turned off. Photochemical (qP) and non-photochemical (qN) quenching parameters were calculated according to Schreiber *et al.* (1986), using the nomenclature of Van Kooten and Snel (1990).

7.3 RESULTS AND DISCUSSION

7.3.1 Effect of drought stress on chlorophyll content

The effect of drought stress on chlorophyll content was significantly high across all the stressed treatments. Drought stress resulted in a 12% reduction at 48 DAP for S2. At 61 DAP drought stress resulted in 18, 8 and 9% chlorophyll content reduction at S2, S3 and S5 compared to S1 respectively. At 80 DAP drought stress resulted in 20, 17 and 15% chlorophyll content reduction for S2, S3 and S5 compared to S1 respectively. At 104 DAP drought stress resulted in 33, 35, 31 and 25% chlorophyll content reduction compared to S1 respectively. S2 was the most affected treatment on all days, except at 77 and 104 DAP, resulting in between 11 and 39% reduction in chlorophyll content. The results indicated that the maximum chlorophyll content was found at 80 DAP and thereafter it started declining. The results also suggest that treatment S2 was recovering slowly after re-watering (Table 7.1) on day 61. The decrease in chlorophyll content might have resulted from the damage to the chloroplasts caused by active oxygen species (Smirnoff, 1995).A decrease in chlorophyll content due to drought stress has been reported in wheat (Talebi, 2011; Fotovat *et al*., 2007; Ommen *et al*., 1999), pea (Inaki-Iturbe *et al*., 1998) chickpea (Mafakheri *et al*., 2010), and rice (Chutia & Borah, 2012). Nikolaeva *et al*. (2010) reported a 13-15% reduction in chlorophyll content after 7 days of drought in wheat. Similarly, drought stress was also found to reduce chlorophyll content in maize (Mohammadkhani & Heidari, 2007). Several studies have reported damage to leaf pigments as a result of water deficit (Montagu & Woo, 1999; Nilsen & Orcutt, 1996). Drought stress leads to the production of reactive oxygen species (ROS) such as O_2- and H_2O_2, which lead to chlorophyll destruction (Mirnoff, 1993; Foyer *et al*., 1994).

Table 7.1 Effect of drought stress treatments on chlorophyll content of dry bean leaves (µmolm^{-2})

Treatment	48 DAP	53 DAP	61 DAP	77 DAP	80 DAP	89 DAP	104 DAP
S1	12.02a	11.00a	17.22a	20.66a	24.29a	23.21a	20.34a
S2	10.51b	9.81b	14.19c	15.17c	19.46c	14.13c	13.58cd
S3	-	-	15.90b	14.42d	20.11bc	15.02c	13.25d
S4	-	-		-	-	17.41b	13.94c
S5	-	-	15.68b	16.96b	20.67b	18.33b	15.17b
CV %	2.11	3.77	3.91	3.52	4.29	5.73	3.41
LSD	0.35**	0.69*	0.98**	0.72**	1.11**	1.21**	0.62**

*Note: Means in a column with the same letter are not significantly different, DAP : Days after planting, CV: coefficient of variation, *: significant at p≤0.01, **: significant at 0.001*

S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season,

S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

7.3.2 Effect of drought stress on photosynthesis (P_n)

The introduction of drought stress had a significant effect on photosynthesis at all three measurement days ($P \leq 0.01$) (Table 7.2). At 63 DAP drought stress reduced photosynthetic rates by 32, 23 and 7% at S2, S3 and S5 compared to S1 respectively. At 100 DAP drought stress reduced photosynthetic rates by 28, 45, 30 and 20% at S2, S3, S4 and S5 compared to S1 respectively. At 105 DAP drought stress reduced photosynthetic rates by 29 and 17% at S4 and S5 compared to S1 respectively. The highest photosynthetic rates were found for S1 (63 DAP) and the lowest for S3 (100 DAP) and S4 (both at 100 and 105 DAP). These results suggest that drought stress during any growth stage of dry bean can result in serious reduction of photosynthetic rates. The reduction can be as high as 45%, with treatment S3 being the most affected. During drought stress water deficit inside the plant tissue develops, leading to a significant inhibition of photosynthesis. A reduction in bean photosynthetic rates due to stomatal closure has previously been reported (Sharkey & Seemann, 1989). Tang *et al.* (2002) argued that a combination of stomatal and non-stomatal effects on photosynthesis exists, depending on the extent of drought stress (Yu *et al.* 2009). Tezara *et al.* (1999) concluded that water stress inhibits photosynthesis through diminished ribulose-1,5-bisphosphate (RuBP) supply caused by low ATP synthesis. Considering the biochemical reactions, water deficit can also increase the oxygenase activity of the RuBP carboxylase/oxygenase (Rubisco), reducing carboxylation efficiency. Therefore, decreases in the rate of photosynthesis in drought-stressed plants can be caused by stomatal closure (*i.e*. reduction of CO_2 availability) and/or impairments in photochemical (*i.e*. decrease in NADPH and ATP supply) and/or biochemical (*i.e*. reduced RuBP regeneration and carboxylation efficiency) reactions. It is also important to consider that low biochemical activity may cause photochemical down-regulation, decreasing the demand for photochemical products under drought stress

Table 7.2 Effect of drought stress treatments on dry bean photosynthesis rate (µmolm^{-2}s^{-1})

Treatment	63 DAP	100 DAP	105 DAP
S1	22.92a	9.89a	12.62a
S2	15.40d	7.14bc	
S3	17.44c	5.36d	
S4		6.93cd	8.88c
S5	21.26b	8.68ab	10.50b
CV%	6.50	18.6	4.011
LSD	1.542**	1.703*	0.550**

*Note: Means in a column with the same letter are not significantly different, DAP: Days after planting, CV: coefficient of variation, *: significant at $p \leq 0.01$, **: significant at 0.001*

S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

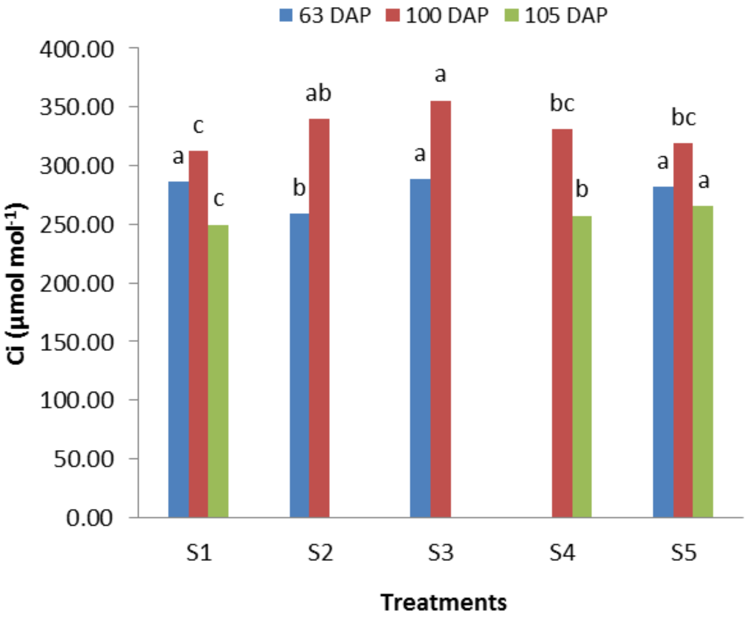
S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season,

S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

7.3.3 Effect of drought stress on intercellular carbon dioxide concentration (Ci)

The introduction of drought stress had a significant effect on intercellular carbon dioxide concentration (Ci) ($P \leq 0.01$) (Figure 7.1). The results indicated that at 63 DAP drought stress reduced Ci, with S2 resulting in the lowest of 259.31µmol mol^{-1}. At 100 DAP S3 resulted in the highest Ci of 355.51 µmol mol^{-1} and the lowest at S1. The results further indicate that at 100 DAP S3 and S2 had statistically similar Ci. The results revealed that that severe drought stress increases Ci and mild drought stress reduces it which is similar to the findings of Lawlor (1995). A decrease in Ci indicates that stomatal limitations dominated under moderate drought stress (Flexas & Medrano, 2002). When Ci increases it suggests the predominance of non-stomatal limitation to photosynthesis. If Ci is low, it means that the photosynthesis machinery could still make use of CO_2 that was taken up before closure of stomata, thus the main reason for reduction in photosynthesis is stomata closure. Conversely, if Ci is high, it means that the machinery is damaged and even if the stomata are open, the leaf cannot use the CO_2 that was taken up.



Note: Means for bars of the same colour with the same letter are not significantly different, DAP=Days after planting,

S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season,

S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

Figure 7.1 Effect of drought stress treatments on dry bean leaf intercellular carbon dioxide concentration (Ci)

7.3.4 Effect of drought stress on stomatal conductance (g_s)

The stomatal conductance at 63, 100 and 105 DAP (P≤ 0.05), was significantly affected by drought stress (Table 7.3). The results indicated that g_s was reduced by drought stress, with S2 resulting in lowest g_s of 0.287 mmol $m^{-2}s^{-1}$. This was a 48 % reduction as compared to S1. At 100 DAP, S3 and S2 resulted in the highest of g_s of 0.362 mmol $m^{-2}s^{-1}$ which was not significantly different from S1 and S4. The treatment S5 resulted in the lowest g_s of 0.293 mmol $m^{-2}s^{-1}$ at 100 DAP. The highest g_s was observed when the plants were still small and reduced as the plants grew. Similar reductions with ageing of the plant in gs were also reported by Uprety and Bhatis, (1989). At 63 DAP (Figure 7.2A) and 105 DAP (Figure 7.2C) there was a very strong relationship (r^2= 0.956, r^2= 0.940) between photosynthetic rate and stomatal conductance, while at 100 DAP (Figure 7.2B) it was weak (r^2= 0.480). The strong relationship between P_n and g_s indicates that the reduction in P_n was regulated mostly by stomatal closure and weak relationship indicates that the reduction in P_n was regulated by non-stomatal factors (Siddique *et al.*, 1999).

Table 7.3 Effect of drought stress on dry bean stomatal conductance (g_s) (mmol $m^{-2}s^{-1}$)

Treatment	63 DAP	100 DAP	105 DAP
S1	0.554a	0.321ab	0.188a
S2	0.287c	0.362a	-
S3	0.398b	0.362a	-
S4	-	0.324ab	0.134b
S5	0.470ab	0.293b	0.169a
CV %	18.84	11.00	15.40
$LSD_{0.05}$	0.099**	0.044*	0.032*

*Note: Means in a column with the same letter are not significantly different, DAP = Days after planting, CV= coefficient of variation, *: significant at p≤0.05, **: significant at 0.001, S1= Irrigated to field capacity on a weekly basis throughout the growing season (control), S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season, S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season, S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.*

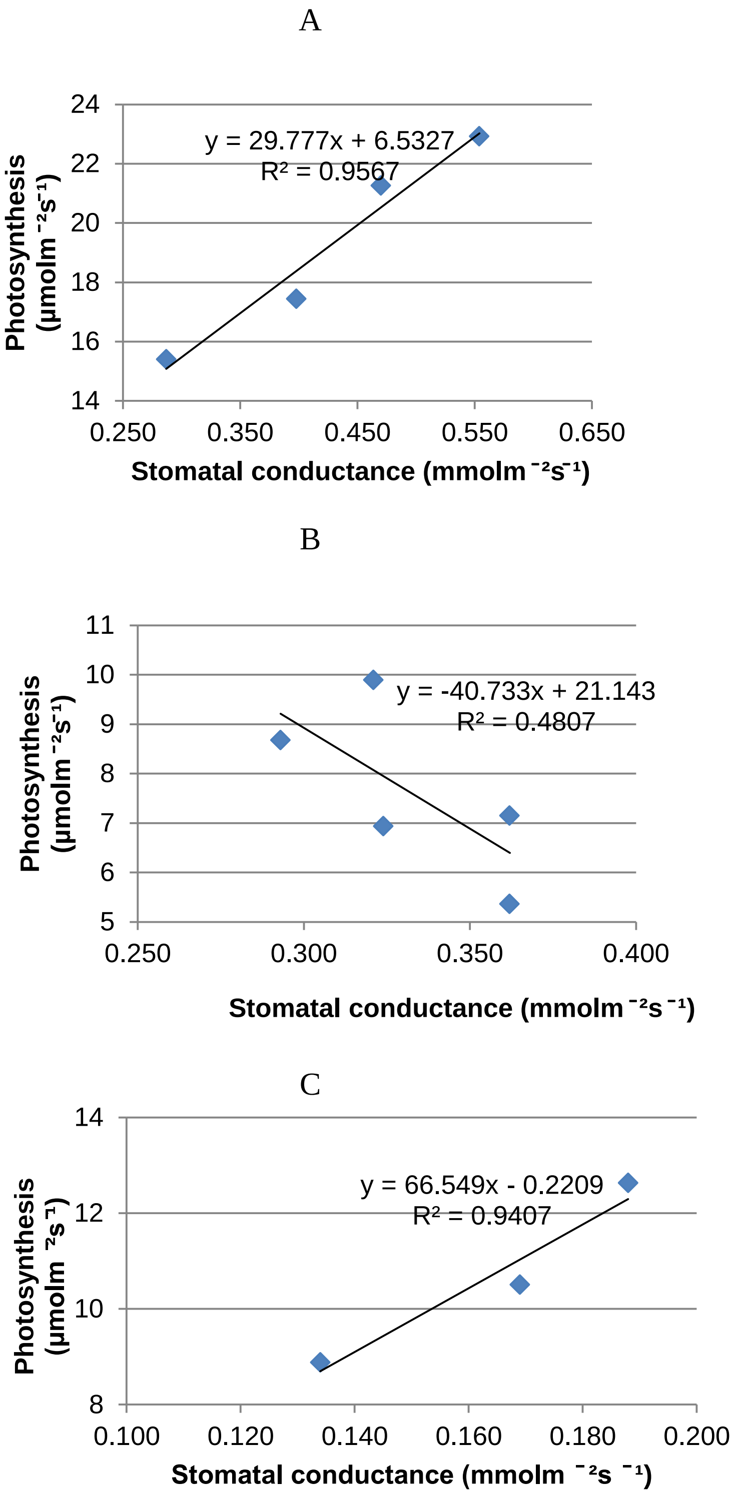
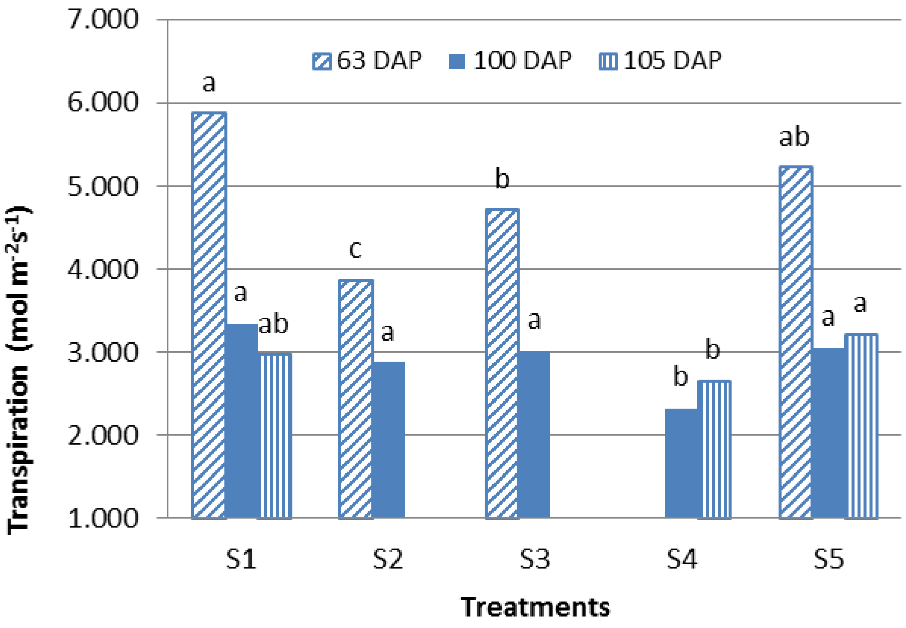


Figure 7.2 The relationship between photosynthesis and stomatal conductance of dry bean at 63 DAP (A), 100 DAP (B) and 105 DAP (C).

7.3.5 Effect of drought stress on transpiration

The results revealed that at 63 DAP drought stress reduced transpiration rate ($P \leq 0.001$) by 34% for S2 (Figure 7.3). The treatment S1 resulted in the highest transpiration rate. The treatment S3 and S5 were statistically the same. At 100 DAP drought stress reduced transpiration rates ($P \leq 0.01$) by 30% at S4. The treatments S1, S2 S3 and S5 were statistically the same since they were not under drought stress. At 105 DAP the transpiration of S5 was not significantly different to S1 but significantly different from S4. A similar decrease in transpiration due to drought stress has been reported by Hall and Schulze, (1980); Osorio *et al.* (1998); Yordanov *et al.* (2001) and Aroca *et al.*, (2006). At 63 DAP the stomatal closure was the most prominent determinant for the increased transpiration efficiency (r^2=0.999) (Figure 7.4). The positive correlation between transpiration and stomatal conductance suggests that the reduction of transpiration at S2 was due to stomatal closure. At 100 and 105 DAP there were weak relationship between transpiration and stomatal conductance with r^2=0.007and r^2=0.481 respectively. A weak relationship between transpiration and stomatal conductance suggests that there were non stomatal factors leading to a reduced transpiration. The results also revealed that at 63 DAP there was a strong correlation between transpiration and photosynthesis (r^2=0.951) (Figure 7.5A). At 100 and 105 DAP there were weak relationship between transpiration and photosynthesis with r^2=0.256 (Figure 7.5B) and r^2=0.247 (Figure 7.5C) respectively.



Note: Means for bars of the same style with the same letter are not significantly different, DAP=Days after planting, S1= Irrigated to field capacity on a weekly basis throughout the growing season (control), S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season, S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

Figure 7.3 Effect of drought on transpiration of dry bean

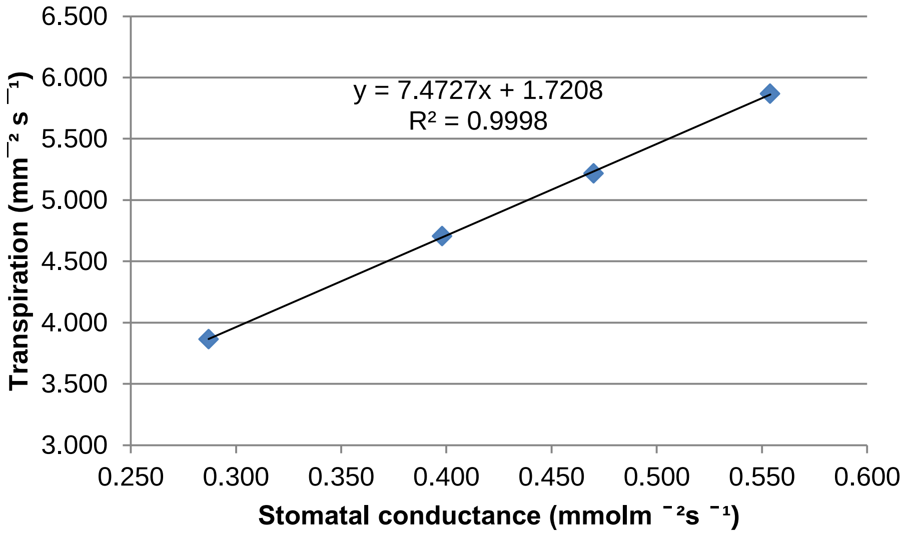


Figure 7.4 The relationship between transpiration and stomatal conductance of dry bean at 63 DAP

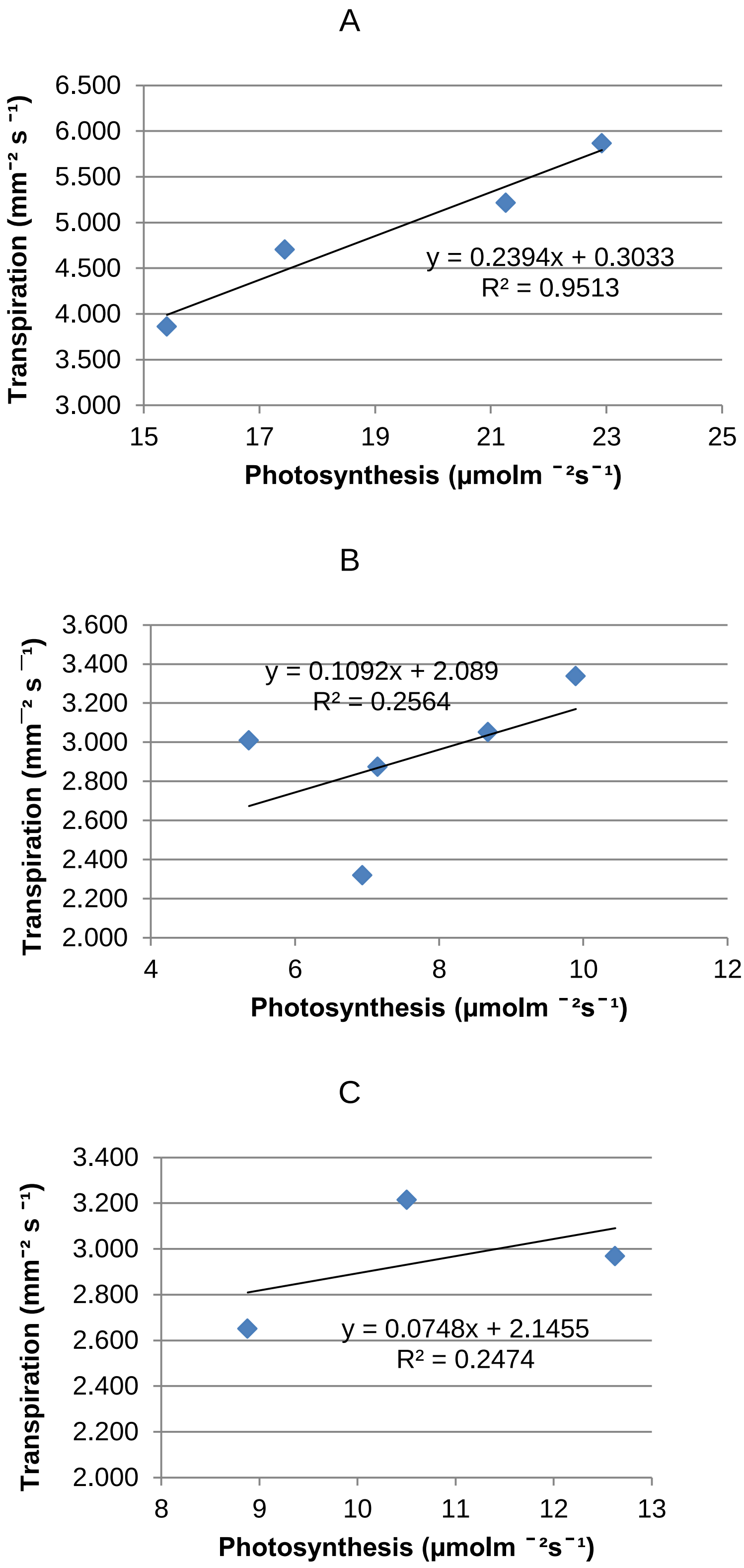


Figure 7.5 The relationship between transpiration and photosynthesis of dry bean at 63 DAP (A), 100 DAP (B) and 105 DAP (C)

7.3.6 Effect of drought stress on minimal chlorophyll fluorescence (F_0)

The effect of drought stress on F_0 was significant during 52, 94 and 100 DAP ($P \leq 0.01$) (Table 7.3). The results revealed that drought stress increased F_0 at all data collection dates. At 52 DAP S3 resulted in a 12% increase in F_0 and S2 with 4% increase. The treatment S3 resulted in an increased F_0 of 5.7% at 93 DAP. At 100 DAP S4 resulted in a 13% increase in F_0. An increase in F_0 due to drought stress has been reported by Zlatev and Yordanov (2004). An increased F_0 is a characteristic of PSII inactivation. Even after termination of drought stress the F_0 values are higher than for the control (e.g S3 at 93 DAP) which suggests that recovery is taking place slowly.

Table 7.4 Effect of drought stress on minimal chlorophyll fluorescence (F_0) of dry bean

Treatment	52 DAP	93 DAP	100 DAP
S1	157.48c	164.15b	139.74d
S2	164.17b	164.17b	145. 20c
S3	177.77a	173.55a	152.68b
S4		160.53b	158.69a
S5	159.29c	163.42b	141.64cd
CV %	1.44	2.68	1.76
LSD	3.81**	6.82*	4.01**

*Note: Means in a column with the same letter are not significantly different, DAP = Days after planting, CV= coefficient of variation, **: significant at p=0.01, *: significant at p=0.05*

S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

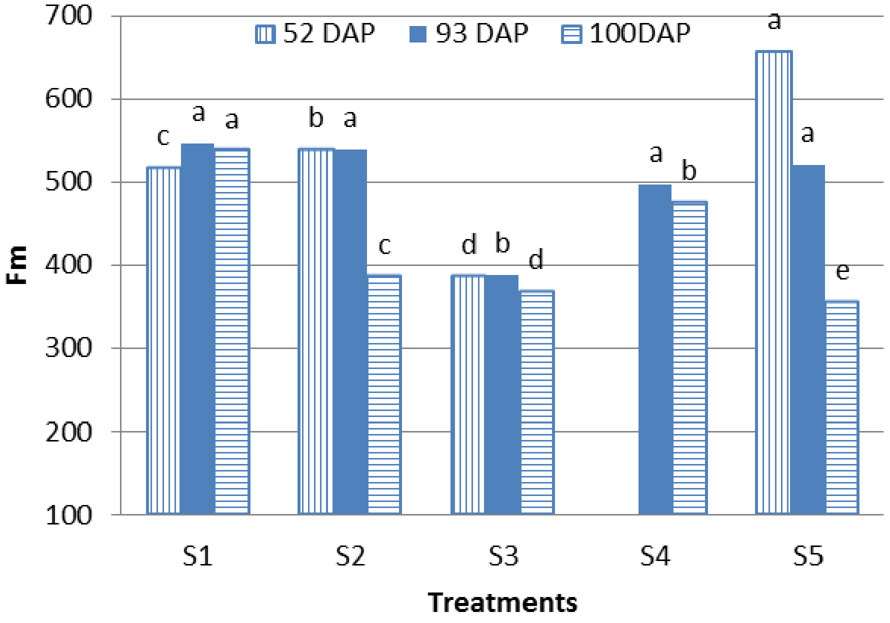
S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season,

S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

7.3.7 Effect of drought stress on maximal chlorophyll fluorescence (F_m)

The effect of drought stress was significant at 52 DAP, 93 DAP and 100 DAP ($P \leq 0.05$) (Figure 7.6). At 52 DAP S5 and S2 resulted in a 4.3 and 27% increase in F_m respectively as compared to the control, but S3 resulted in a 25% reduction. At 93 DAP S3 resulted in a 29 % reduction in F_m while S1, S2, S4 and S5 were statistically similar. At 100 DAP drought stress resulted in an 11, 28, 31 and 33 % reduction at S4, S2, S3 and S5 respectively. At both dates S3 resulted in a serious reduction of F_m. The decrease in F_m may be related to a decrease in the activity of the water splitting enzyme complex (Aro and Virgin, 1993). Throughout all the data collection dates S3 fail to recover from water stress.



Note: Means for bars of the same style with the same letter are not significantly different, DAP=Days after planting, S1= Irrigated to field capacity on a weekly basis throughout the growing season (control), S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

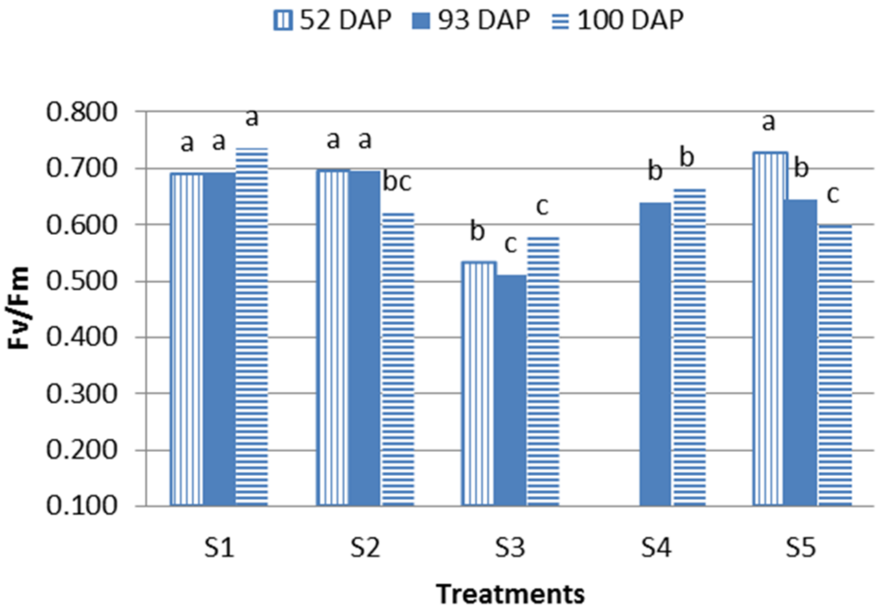
S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season, S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

Figure 7.6 Effect of drought stress on maximal chlorophyll fluorescence (F_m) of dry bean

7.3.8 Effect of drought stress on maximum quantum efficiency of PSII photochemistry (F_v/F_m)

This parameter is widely considered to be a sensitive indication of plant photosynthetic performance (Kalaji & Guo*,* 2008). The results revealed that drought stress had a significant effect at all three sampling dates on F_v/F_m ($P \leq 0.01$) (Figure 7.7). The decreases in Fv/Fm ratio during 93 DAP for S5 and 100 DAP for S2 suggests that the recovery from water stress is accompanied by structural damage (Schapendonk *et al.* 1989). This occurrence of chronic photo-inhibition is due to photo-inactivation of PSII centers (Zlatev & Yordanov, 2004). In bean leaves which has gone through drought, photo-inhibitory impact on PSII could occur due to increased light intensity under stress conditions, which usually limits photosynthetic activity (Verhoeven *et al.*, 1997).

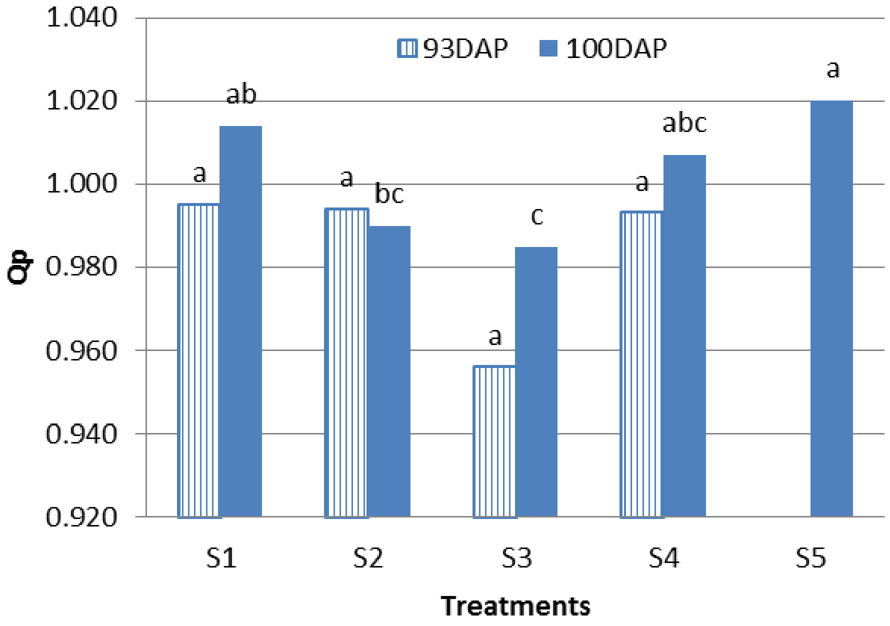


Note: Means for bars of the same style with the same letter are not significantly different, DAP=Days after planting, S1= Irrigated to field capacity on a weekly basis throughout the growing season (control), S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season, S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season, S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

Figure 7.7 Effect of drought stress on the maximum quantum efficiency of PSII photochemistry (F_v/F_m) of dry beans

7.3.9 Effect of drought stress on coefficient of photochemical quenching (Q_p)

Q_p is an indication of the proportion of open PSII reaction centers, and translates light quantum energy into chemical energy process, which reflects the photosynthetic efficiency and the light use situation of a plant (Liu *et al.*, 2012). At 93 DAP there was no significant difference among treatments. At 100 DAP the effects of drought stress are significant with S3 resulting in the lowest which was not significantly different to S2 and S4. The decrease in Q_p might have been caused by an increase in the proportion of closed PS II centers. The results revealed that at 100 DAP there was no significant difference between S1 and S4 and S5 (Figure 7.8), S4 was still going through drought stress. The reduction in Q_p due to drought was also reported by Zlatev and Yordanov (2004).



Note: Means for bars of the same style with the same letter are not significantly different, DAP=Days after planting, S1= Irrigated to field capacity on a weekly basis throughout the growing season (control), S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season, S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season, S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

Figure 7.8 Effect of drought stress on coefficient of photochemical quenching (Q_p)

7.3.10 Effect of drought stress on coefficient of non-photochemical quenching (Q_n)

The effect of drought stress on Q_n was significant ($P \leq 0.05$) (Table 7.5). At 93 DAP S3 resulted in the highest Q_n followed by S4 which was not statistically different from each other. S3 resulted in a 48% increase in Qn compared to S1. At 100 DAP S1 and S4 resulted in the highest and also statistically similar Q_n values. The increase in Q_n might have been caused by the large proportion of absorbed light energy not being used by plants in the photosynthesis process. An increase in Q_n due to drought stress have been reported (Zlatev & Yordanov, 2004; Vassilev & Manolov 1999).

Table 7.5 Effect of drought stress on minimal chlorophyll fluorescence (Q_n)

Treatment	93 DAP	100DAP
S1	0.235c	3.795a
S2	0.303b	2.402b
S3	0.379a	2.209b
S4	0.349a	3.438a
CV %	6.42	14.01
LSD	0.032**	0.663*

*Note: Means for values in a column with the same letter are not significantly different, DAP=Days after planting, *: significant at p≤0.01, **: significant at 0.001*

S1= Irrigated to field capacity on a weekly basis throughout the growing season (control),

S2= Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days, then irrigated to field capacity to the end of the growing season,

S3= Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days, then irrigated to field capacity to the end of the growing season,

S4= Irrigated to field capacity on a weekly basis and withholding irrigation from 73 DAP to the end of the growing season and

S5= Irrigated to field capacity on a weekly basis and Irrigated to field capacity on a fortnightly basis from 36 DAP.

7.4 CONCLUSIONS

The results of the study indicate that drought stress effects on photosynthetic rate were highly significant. The reduction in photo synthetic rate was up to 45%. The reduction of photosynthesis at 63 and 105 DAP was greatly due to poor stomatal conductance. Drought stress resulted in a reduction in intercellular carbon dioxide concentration, stomatal conductance and transpiration. Chlorophyll fluorescence was also affected by drought stress. The minimal chlorophyll fluorescence (F_0) was increased by drought stress accompanied by a reduction in the maximal chlorophyll fluorescence (F_m) and F_v/F_m. Drought stress can have serious effects on leaf gaseous exchange rate and chlorophyll fluorescence depending on the growth stage of the plant and the duration of drought stress.

CHAPTER 8

CALIBRATION AND VALIDATION OF THE SWB MODEL FOR DRY BEAN (*Phaseolus vulgaris*) AT DIFFERENT DROUGHT STRESS LEVELS

ABSTRACT

The worldwide decrease in available irrigation water is driving the need for the development of methods to minimize irrigation water losses. A field experiment was conducted at the Hatfield Experimental Farm of the University of Pretoria, Pretoria, South Africa (25°45’0’’S, 28°16’0’’E and altitude of 1327 m.a.s.l.) in 2013. The objectives of the study were to determine crop-specific model parameters for dry beans and to successfully calibrate and validate the Soil Water Balance model for predicting dry bean yield and water use from historical weather data. Model simulations of leaf area index, total dry mass, fractional interception of solar radiation, harvestable dry mass, and soil water deficits agreed reasonably well with measured values and statistical parameters for most variables were within acceptable limits. Regarding the validation data set, the SWB model simulated fractional interception and harvestable dry mass for drought stress treatments reasonably well. The calibrated model was then used to predict the grain yield for three sites of Limpopo over a period of nine years. The scenario modelling results indicated that the model can, apart from its use as irrigation scheduling tool, also be successfully used to estimate yields of dry beans at other localities.

Keywords: Leaf area index, total dry mass, fractional interception, scenario modelling, water management, yield forecast

8.1 INTRODUCTION

In Limpopo and North West provinces dry bean production is done under irrigation due to the fact that their planting starts after the rainy season has passed. Irrigation water management is necessary for structural, economic and environmental reasons. Population growth is expected to double food demand by 2050. In order to meet the food security there is a need for a change in agricultural water management (Mueller *et al*., 2012). Irrigated agriculture as the largest water user is subjected to water allocation cuts due to rapid growth in water demand from non-agricultural sectors (e.g. domestic, industrial and environmental use) (Levidow *et al*., 2014). There is a need for a highly efficient agricultural water management strategy to reduce water loss through runoff. This can be achieved through irrigation scheduling. Irrigation scheduling is important for both water savings and improved crop yields (Phocaides, 2007). Irrigation scheduling is a systematic method by which the farmer or producer decides when to irrigate and how much water to apply (Van der Gulik, 2006). Irrigation scheduling can lead to increased profit without compromising the environment by increasing productive water use, reducing water loss through runoff, deep percolation beyond the crop root zone (which also results in nutrient leaching), and soil evaporation (Reinders, 2010).

The interest in scheduling irrigation with crop growth models is rapidly increasing (Annandale *et al*., 1999). Simulation models mathematically describe the processes of soil water balance, plant growth and yield expression to determine their evolution during the simulation period (Abazi *et al*., 2013). A number of models have been developed to manage irrigation, for example SWB (Annandale *et al*., 1999), BUDGET (Raes *et al*., 2006), OSIRI (Chopart *et al*., 2007), SWAT (Luo *et al*., 2008), SWAP (Vazifedoust *et al*., 2008), PILOTE (Khaledian *et al*., 2009), AquaCrop (Steduto *et al*., 2009), RIDECO (Zapata *et al*., 2012) and DIDAS (Friedman *et al*., 2016).

The Soil Water Balance (SWB) computer model was identified by the Water Research Commission (South Africa) as a potential technology that could be adopted for real time irrigation scheduling country-wide (Annandale *et al*., 2002). The

SWB model was developed by the University of Pretoria (Department of Plant Production and Soil Science) in 1999 (Annandale *et al*., 1999) as a real-time, user-friendly, irrigation scheduling tool (Benadè *et al*., 1997). It is based on the improved generic crop version of the New Soil Water Balance model described by Campbell and Diaz (1988). According to Campos *et al*. (2016), such soil water balance models can be powerful tools to predict crop responses under different climatic and management scenarios.

Since SWB is a generic crop growth model, parameters specific for each crop have to be determined. In previous studies, a database of crop-specific growth parameters was generated for annual crops and pasture species (Barnard *et al*., 1998), winter vegetables (Jovanovic *et al*., 1999), summer vegetables (Jovanovic and Annandale, 2000) and sunflower (Jovanovic *et al*., 2000). Therefore, the objective of this study was to calibrate and validate the SWB generic crop model for dry beans (cv. DBS 360) to enable accurate irrigation scheduling under well-watered conditions. The model can then also be used to run scenarios to predict crop response to water supply under both irrigation and dryland conditions, which is useful for irrigation scheduling and planning purposes.

8.2 MODEL DESCRIPTION

The SWB model gives a detailed description of the soil-plant-atmosphere system, making use of weather, soil and crop data bases which are used to calculate the water balance and crop growth. The functioning of the SWB model is briefly described below. A more detailed description of the model can be found in Annandale *et al*. (1999).

The purpose of the weather unit of Soil Water Balance is to calculate the potential evapotranspiration from available meteorological input data (Allen *et al*., 1998; Smith, 1992; Smith *et al*., 1996). Daily Penman-Monteith grass reference evapotranspiration (ET_o) and crop potential evapotranspiration (PET) are calculated and used by the soil unit to compute actual crop transpiration (T) and soil evaporation (E).

The purpose of the soil unit of SWB is to simulate the dynamics of water movement in the soil profile to determine E and T. The SWB model has a multilayer soil component and water contents and potentials of the various layers are calculated on a daily time step. Cascading water movement is simulated once canopy water interception and surface runoff have been accounted for (Jovanovic *et al*., 2000). Potential evapotranspiration (PET) is divided into potential evaporation and potential transpiration by calculating canopy radiant interception from simulated leaf area (Ritchie, 1972).

In the crop unit, SWB calculates crop dry matter accumulation in direct proportion to transpiration (corrected for vapour pressure deficit) of the environment (Tanner & Sinclair, 1983). The model calculates radiation limited growth (Monteith, 1977). This dry matter is partitioned into roots, stems, leaves and grain or fruits. Partitioning depends on the phenology, which is calculated using thermal time and modified by water stress.

8.3 MATERIALS AND METHODS

8.3.1 Experimental site and treatments

A field experiment was conducted at the Hatfield Experimental Farm of the University of Pretoria, Pretoria, South Africa (25°45’0’’S, 28°16’0’’E and an altitude of 1327 m.a.s.l.) in 2013. The trial consisted of eight plots under sprinkler irrigation. The plots were 5 x 9 m^2 each. The trial was irrigated every week, according to measured soil deficits. Nitrogen top dressing was done 28 days after planting (DAP) using limestone ammonium nitrate (LAN-28%N) at the rate of 30 kg/ha. Destructive plant samples for growth analyses were collected at 30, 37, 43, 58, 72, 86 and 99 DAP. The model validation was done using data from the trial discussed in Chapter 6.

Drought stress treatments used to validate the model were as follows:

1. Irrigated to field capacity on a weekly basis and withholding irrigation from 36 days after planting (DAP) for 24 days (S1), whereafter it was weekly irrigated to field capacity until the end of the growing season.
2. Irrigated to field capacity on a weekly basis and withholding irrigation from 49 DAP for 24 days (S2), whereafter it was weekly irrigated to field capacity until the end of the growing season.

3. Initially irrigated to field capacity on a weekly basis, whereafter it was irrigated to field capacity on a fortnightly basis from 36 DAP (S3) until the end of the growing season.

8.3.2 Data collection

Soil water content was monitored using a 503DR CPN hydro probe neutron water meter (Campbell Pacific Nuclear, California) which was calibrated for the experimental site. Readings were taken twice a week, at 0.2 m increments to a depth of 1.0 m, from aluminum access tubes installed in the middle of each plot and positioned between the rows. An overhead sprinkler irrigation system was used to irrigate the trial.

Weather data were collected from an automated weather station close to the experimental site. Daily solar radiation, maximum and minimum relative humidity, maximum and minimum temperatures, average wind speed and rainfall were collected.

Dry bean growth analysis was carried out by harvesting plants from 1 m^2 per plot every one to two weeks from 30 DAP. The samples were divided into leaves, stems and pods. The leaf area was measured using a LI 3100 belt-driven leaf area meter (Li Cor, Lincoln, Nebraska, USA) and leaf area index (LAI) was calculated using equation 8.1. Thereafter the samples were oven-dried for 72 hours at 65 ^oC to determine dry matter yield (DM) of the different plant components. The total above-ground dry matter yield was determined by adding together the dry mass of the leaves, stems and pods. Crop height was measured weekly.

Fractional interception of photosynthetically active radiation was measured weekly with a Decagon sunfleck ceptometer (Decagon, Pullman, Washington, USA). Readings were taken between 9:00 and 10:00 on cloudless days. A series of measurements consisted of one reference reading above and ten readings beneath the canopy, which were then averaged.

8.3.3 Crop specific growth parameters

The weather and dry bean growth analysis data were used to determine crop-specific model parameters. The following parameters were determined: Canopy extinction coefficient for Photosynthetically active radiation (PAR) (K_{PAR}), specific leaf area (SLA), leaf-stem partitioning parameter (PART), vapour pressure deficit-corrected dry matter/water ratio and thermal time requirements for the different developmental stages.

The canopy extinction coefficient for solar radiation was calculated using Beer-Bouguer's law (Campbell and Van Evert, 1994):

$$FI = 1 - e^{(-K_{PAR}LAI)} \qquad 8.1$$

Where K_{PAR} is the canopy extinction coefficient for PAR. Where FI is expressed as a function of LAI. Measured data of FI and LAI were used to determine the K_{PAR} (Figure 8.1). Guidelines for determining KPAR in the field are given by Jovanovic and Annandale (1998).

K_{PAR} can be used to calculate phptpsynthesis as a function of intercepted PAR. The canopy extinction coefficient for solar radiation (K_s) is required by SWB to predict radiation limited dry matter production (Monteith, 1977) and for partitioning evapotranspiration into evaporation from the soil surface and crop transpiration (Ritchie, 1972). The procedure recommended by Campbell and Van Evert (1994) was used to convert K_{PAR} into K_s:

$$K_s = \mathrm{K}_{bd}\sqrt{\mathrm{a}_s} \qquad 8.2$$

$$K_{bd} = \mathrm{K}_{PAR}/\sqrt{\mathrm{a}_P} \qquad 8.3$$

$$\mathrm{a}_s = \mathrm{a}_p\mathrm{a}_n \qquad 8.4$$

Where K_{bd} is canopy radiation extinction coefficient for black leaves, and diffuse radiation a_s is the leaf absorptances of solar radiation, a_p is the generic mean of the absorptance of PAR, a_n is leaf absorptance of near infrared radiation (NIR, 0.7-3 m). The value of a_p was assumed to be 0.8, whilst a_n was assumed to be 0.2

(Goudriaan, 1977). The term a_s is the geometric mean of the absorptances in the PAR and NIR spectrums.

Radiation conversion efficiency (E_c) is a crop-specific parameter used to calculate dry matter production under conditions of radiation-limited growth (Monteith, 1977) as follows:

$$DM = E_c FIR_s \tag{8.5}$$

Where DM is dry matter production (g m^{-2}), E_c is radiation conversion efficiency (g MJ^{-1}), FI is expressed as a function of LAI and R_s is daily total incident solar radiation (MJ m^{-2})

SWB calculates daily increments of DM as being either transpiration-limited or radiation-limited processes; with water stress affecting the partitioning of assimilates to the different plant organs.

Specific leaf area (SLA) and PART must be known in order to calculate dry matter (DM) partitioning with SWB. The leaf-stem partitioning parameter was determined as a function of SLA, LAI and CDM, by combining equations 8.7 through 8.9 (Jovanovic *et al*., 1999). The slope of the regression line represents the leaf-stem partitioning parameter in m^2 kg^{-1}. The SWB calculates leaf (LDM) and stem dry matter (SDM) as follows:

$$LDM = CDM/(1 + pCDM) \tag{8.6}$$

$$SDM = CDM - LDM \tag{8.7}$$

LDM is used to calculate LAI as follows:

$$LAI = SLA\, LDM \tag{8.8}$$

Where LDM is leaf dry matter yield (kg m^{-2}), CDM is canopy dry matter yield (kg m^{-2}), SDM is stem dry matter yield (kg m^{-2}), LAI is leaf area index (m^2 m^{-2}) and SLA is the specific leaf area in m^2 kg^{-1}.

Vapour pressure deficit-corrected dry matter/water ratio (DWR) of dry beans was calculated according to Tanner and Sinclair (1983):

$$DWR = (DM\, VPD)/ET \tag{8.9}$$

Where DM (kg m^{-2}) is above-ground biomass yield, and was measured at harvest, whilst VPD represents the seasonal average vapour pressure deficit. Both VPD andDWR are in Pascal (Pa). ET is the seasonal total evapotranspiration (ET) in mm. Evaporation from the soil surface should not actually be included in the calculation of DWR, as unlike transpiration, it is not tightly linked to photosynthesis and therefore dry matter production. Root dry matter was also not measured and was therefore also not included in the calculation of DWR. The SWB model calculates transpiration limited DM production as follows:

$$DM = DWR\,Tr\ /\ VPD \qquad 8.10$$

Where : Tr – Crop transpiration (mm)

ET was obtained using the following equation for weekly time intervals:

$$ET = P + I - R - Dr - \Delta Q \qquad 8.11$$

Where R is runoff, D is drainage and ∆Q represents the soil-water storage for 1 m soil depth, expressed in mm. The term R was assumed to be negligible as no high intensity rain occurred and the irrigation system application rate did not exceed the soil infiltration rate. SWB was used to calculate Dr. A positive sign for ∆Q indicates a gain in soil water storage. ∆Q was calculated from soil water content measurements with the neutron water meter.

Daily VPD was calculated from measurements of T_w and T_d, adopting the following procedure recommended by the Food and Agriculture Organization (FAO) of the United Nations (Smith, 1992):

$$VPD = \left[\frac{e_{sTmax} \ + e_{sTmin}}{2}\right] - e_a \qquad 8.12$$

Where e_{sTmax} is saturated vapour pressure at maximum air temperature (kPa), e_{sTmin} is saturated vapour pressure at minimum air temperature (kPa) and e_a is actual vapour pressure (kPa). Saturated vapour pressure (e_s) at maximum (T_{max}) and minimum air temperature (T_{min}) was calculated by replacing T with T_{max} and T_{min} (ºC) in the following equation (Allen *et al*., 1998):

$$e_s \ = 0.611\, exp\left[\frac{17.27T}{T+237.3}\right] \qquad 8.13$$

e_a was calculated from the measured daily Ta_{max}, Ta_{min}, RH_{max} and RH_{min}, using the following equation (Allen *et al*., 1998):

$$e_a = \frac{e_s\ (T_{min})\frac{RH_{max}}{100} + e_s\ (T_{max})\frac{RH_{min}}{100}}{2} \qquad 8.14$$

Growing day degrees (GDD) (d ºC) were determined from daily average air temperature (T_{avg}), according to Monteith (1977):

$$GDD = (\ T_{avg} - T_b\ )\Delta t \qquad 8.15$$

Where Tb is the base temperature for beans in ºC and Δt is one day. A T_b value of 10, as recommended by Hoogenboom *et al*. (1994), was used in this study.

The statistical parameters in SWB were used to perform statistical comparisons between measured and simulated data. The following statistical parameters were calculated: coefficient of determination (r^2), Willmott's (1982) index of agreement (D), root mean square error (RMSE) and mean absolute error (MAE, expressed as a % of the average measured value). These parameters were recommended by De Jager (1994) to assess model accuracy. De Jager (1994) also recommended as model prediction reliability criteria that r^2 and D should be >0.8, whilst MAE should be < 20%.

8.4 RESULTS AND DISCUSSION

8.4.1 Model calibration

Table 8.1 displays a list of crop growth specific parameters determined for dry bean under well-irrigated conditions.

The canopy radiation extinction coefficient fond in the study was 0.84 which was different from 0.7 by Marrou *et al*. (2014) in lingot beans. The specific leaf area of 20.98 $m^2\ kg^{-1}$ which was also different 15 $m^2\ kg^{-1}$ Marrou *et al*. (2014) in lingot bean.

Table 8.1 Crop-specific model parameters for dry bean (indeterminate cv. DBS 360)

Crop parameter	Value
Canopy radiation extinction coefficient (K_{PAR})******	0.84
Dry matter/transpiration ratio corrected for vapour pressure deficit (DWR) (Pa)*	2.6
Specific Leaf Area (SLA) (m^2 kg^{-1})*	20.98
Leaf-Stem Partition parameter PART (m^2 kg^{-1})*	3.873
Root Growth Rate RGR (m^2 $kg^{-0.5}$)***	3.0
Fraction of Total Dry Matter Translocated to Roots ***	0.20
Leaf water potential at maximum transpiration rate (J kg^{-1})***	-1500
Maximum root depth (m)*	0.5
Maximum crop height (m)*****	0.5
Maximum transpiration rate (mm d^{-1})***	7.0
Base temperature (ºC)**	10
Optimum temperature (ºC)**	24
Cut-off temperature (ºC)**	35
Emergence day degrees (ºC d)*	92
Flowering day degrees (ºC d)*	400
Maturity day degrees (ºC d)****	730
Transition day degrees (ºC d)****	400
Total dry matter yield at emergence (kg m^{-2})***	0.009
Radiation use efficiency (E_c)(kg MJ^{-1})*	0.00122
Stress index***	0.95

*	Calculated according to Jovanovic *et al*., 1999
**	Hoogenboom *et al*., 1994
***	Adopted from Annandale *et al*., 1999
****	Estimated by calibration against measurement of growth, phenology, yield and water use
*****	Measured
******	Calculated according to Jovanovic and Annandale, 1998

Figure 8.1 represents FI of PAR measured with the ceptometer as a function of LAI of dry bean. The calculated value of K_{PAR} was 0.84, and the coefficient of determination (r^2) of the exponetial function was 0.99. The calculated value of K_{PAR} falls within the range of 0.4 – 1.15, as was reported by Allen *et al*. (1998).

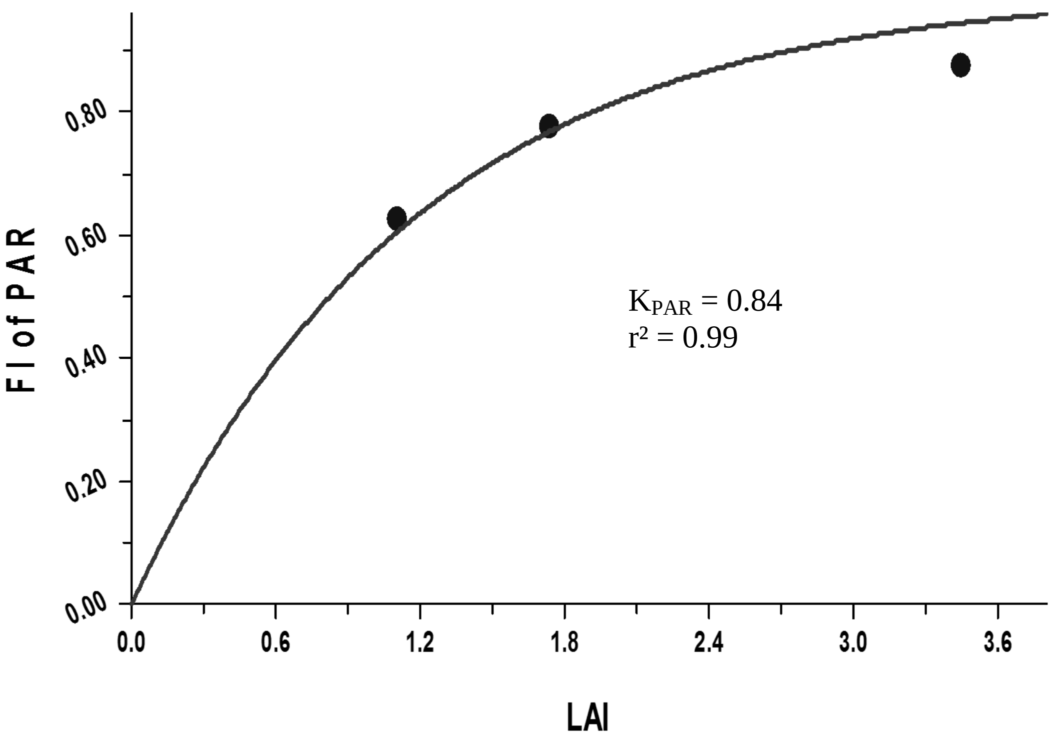


Figure 8.1 Fractional interception of photosynthetically active radiation (FI_{PAR}) as a function of leaf area index

The SWB model was calibrated for dry bean cultivar DBS 360 using the parameters that were developed from the calibration data set. Calibration was based on field measured values of LAI, photosynthetically active radiation, biomass produced, calculated soil water deficits, crop water used and grain yield. Root depth measurements were not done but estimated. The leaf area index, harvestable dry matter yield, top dry matter yield and the soil water deficits were predicted with reasonable accuracy by the model for the well-irrigated treatment (Figures 8.2 A-C). The overestimation of LAI during the early stages of growth resulted from overestimation of soil water deficits. The underestimation of HDM late in the the season might have resulted to changes in the climatic conditions which changed to cold towards the end of the growing season.

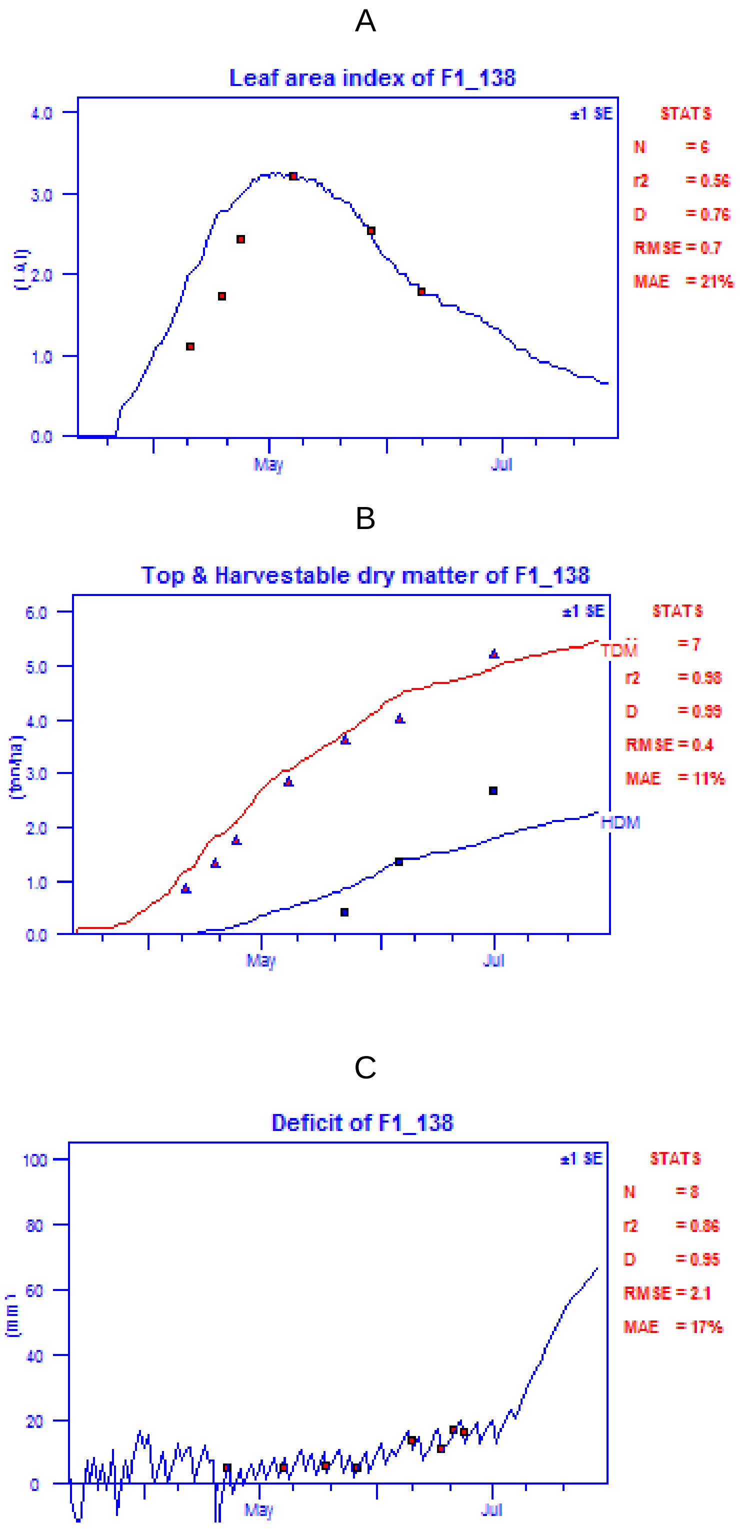


Figure 8.2 Simulated (solid lines) and measured values (points) of leaf area index (LAI) (A), top dry matter (TDM) yield and harvestable dry matter (HDM) yield (B) and soil water deficits (C) for well-irrigated dry bean (Calibration data set).

8.4.2 Model validation

The top dry matter and harvestable dry matter yields, leaf area index, and soil water deficits were predicted with reasonable accuracy by the model for plants that were stressed during reproductive stages (S1) (Figures 8.3 A-C) and plants irrigated only once in two weeks (S2) (Figure 8.4 A-C), although the latter treatment was simulated with less accuracy. The model underestimated HDM during early and late growth stages. The earlier underestimation is due to overestimation of soil water deficits at the same time but the model late in the season expect the crop to be going through stress whereas for dry bean towards the end of the growing season the amount of irrigation water is reduced to avoid too much moisture on the pods leading to decay.

The results indicated that the model was able to simulate both the crop growth, water use and yield of dry beans under different water supply conditions. It is therefore sufficient to indicate that the model can be used for scenario simulations of the growth and yield of DBS 360 under different climatic conditions for planning purposes.

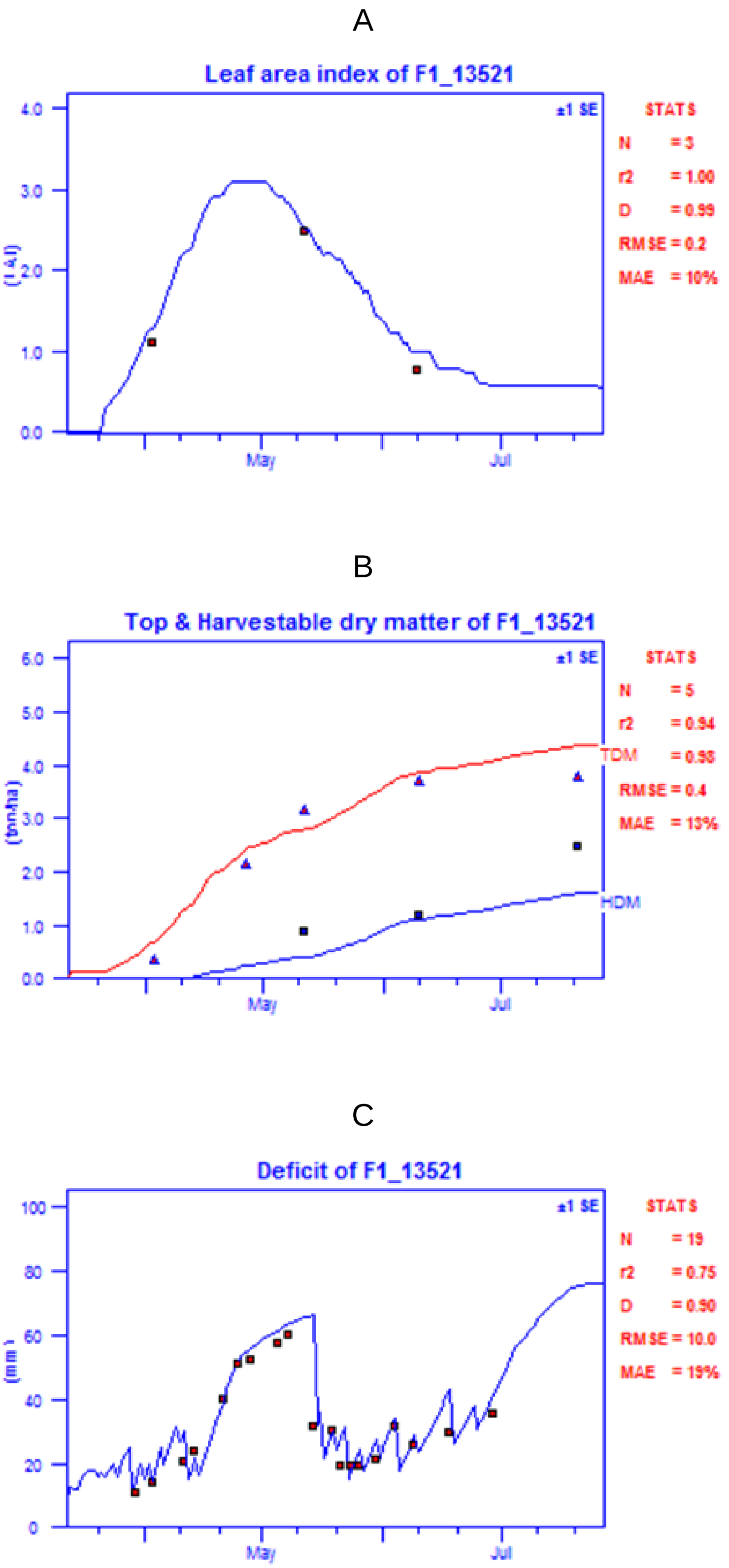


Figure 8.3 Simulated (solid lines) and measured values (points) of leaf area index (LAI) (A), top dry matter (TDM), harvestable dry matter (HDM) (B) and soil water deficits (C) for treatment S1 (irrigation withheld for 24 days from 49 DAP).

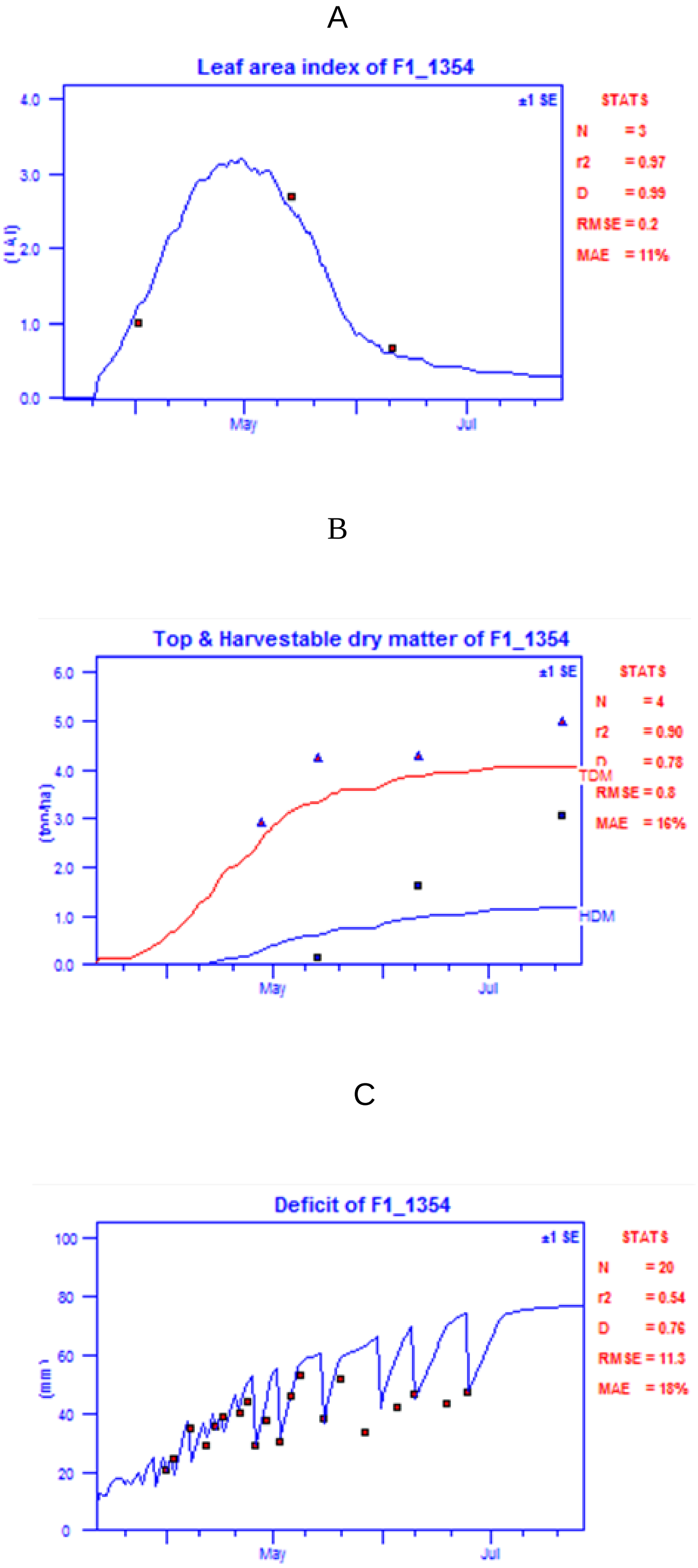


Figure 8.4 Simulated (solid lines) and measured values (points) of leaf area index (LAI) (A), Top dry matter (TDM) , harvestable dry matter (HDM) (B) and soil water deficits for treatment (C) S2 (Irrigated to field capacity on a fortnightly basis from 36 DAP (S3) until the end of the growing season).

8.4.3 Scenario modelling

Table 8.2 presents the simulated potential grain yield of dry beans under irrigation for nine years at two districts, Mopani (Trichardtsdal) and Vhembe (Dzindi and Tshiombo), of Limpopo Province. The rainfall received is also indicated in Table 8.2. The three areas selected are important dry bean production areas where farmers are producing certified seed for the province. The weather data used for the simulations was obtained from the Limpopo Department of Agriculture, Crop Production Directorate. The Limpopo Department of Agriculture together with ARC-Soil Climate and Water has established weather stations in the different farming communities. The scenario simulations were run in order to determine the dry bean yield which the farmers can expect to harvest with good crop management in order to assist in the future planning. The complete scenario simulation results for the period 2007 to 2015 are shown in the Annexures. Simulation results of nine years showed that grain yields of dry beans varied substantially from year to year and area to area. The simulations also indicated that for cultivar DBS 360 highest yields were achieved at Dzindi (2007 and 2012) and Trichardtsdal (2008). The results in Chapter 3 also indicated that DBS 360 was one of the best performing genotypes at Dzindi 2010 and Trichardtsdal 2010.

Table 8.2 Simulated dry bean grain yield (cv DBS 360) for three sites in Limpopo province

	Dzindi		**Trichardtsdal**		**Tshiombo**	
Year	Yield (t ha$^{-1)}$	Rainfall (mm)	Yield (t ha$^{-1)}$	Rainfall (mm)	Yield (t ha$^{-1)}$	Rainfall (mm)
2007	2.7	121	-	-	2.2	159
2008	2.2	235	2.7	184	2.2	239
2009	2.5	126	2.2	86	2.4	130
2010	2.4	307	2.2	310	2.3	328
2011	-	-	2.0	482	2.0	140
2012	2.7	91	1.3	179	1.7	17
2013	2.5	282	2.6	231	1.8	168
2014	2.3	285	-	339	2.3	-
2015	1.9	113	2.4	129	1.9	129

8.5 CONCLUSIONS

A database of crop-specific model parameters was generated for dry bean cultivar DBS 360. The SWB model was successfully calibrated and validated with accuracy that is sufficient for irrigation scheduling and also for long-term scenario modelling for planning purpose. The SWB model was able to simulate the grain yield well for Limpopo conditions. The use SWB was useful in predicting dry bean grain yield for the nine years. The model can now be used to simulate yields for other dry bean production areas to give an indication of yields that can be expected under those conditions.

It is therefore recommended that to make SWB model more useful, crop parameters should be determined for other cultivars as well.

CHAPTER 9

SUMMARY , CONLUSION AND RECOMMENDATION

9.1 SUMMARY AND CONCLUSION

Dry bean is a very important crop for its high protein content. The fact that dry bean production in South Africa is lower than the consumption creates a need to maximize dry bean production in the country. The aim of this study was to maximize dry bean production through selected agronomic practices. To achieve this goal field experiments were conducted in Limpopo province and also at Hartfield Experimental Farm. The agronomic practices that were addressed in this thesis in order to maximize dry bean production were variety, plant population and the effect of deficit irrigation and drought stress on growth and yield.

Variety evaluation is very crucial in maximizing dry bean production since variety performance is highly influenced by climatic factors. Kranskop is the variety which small scale farmers have been planting. In order to improve dry bean production there is a need to get the variety which will replace Kranskop as Kranskop is an old variety and is being faced out and that was done through genotype by stability analysis. Dry bean genotypes where exposed to different environments of Limpopo province. The combined ANOVA indicated that environment had the highest influence on dry bean yield. GGE biplot analysis identified OPS-RS1 as the best and stable genotype. Dry bean production can be done in any of the tested environments but Tshiombo was identified as the ideal environment for dry bean production so farmers at Tshiombo should invest on improving their dry bean production.

Plant population density is very important in crop production since it determines the harvest. There was no significant effect of plant populations on number of seeds per pod, shelling %, plant height and 100 seed weight. The plant height and 100 seed weight were, however, influenced by genetic (variety) factors. The lower plant population density of 70 000 plants ha^{-1} resulted in significantly higher grain yield per plant and number of pods per plant but lower grain yield ha^{-1} as compared to 150 000 plants ha^{-1}.

The positive relationship between dry bean varieties and plant population significantly influenced grain yield, grain yield per plant, chlorophyll content and plant height. Plant population density of 150 000 plants per ha^{-1} was the best for both determinate and indeterminate growth forms with all the other plant population resulting in significant grain yield reductions.

Irrigation water availability is a challenge in South Africa. Dry bean is sensitive to drought stress but it was necessary to evaluate the effect of deficit irrigation in dry bean production. Deficit irrigation has been used in many crops to improve water use efficiency in crop production. A dry bean variety (DBS 360) was exposed to four levels of deficit irrigation. Deficit irrigation proposed in this study negatively affected plant height, number of seeds per plant, number of pods per plant and grain yield. The reduction in grain yield resulted from the reduced number of pods per plant and number of seeds per plant due to flower abscission. The results confirm that deficit irrigation during late flowering and pod filling stages can cause severe losses. The results indicate that the deficit irrigation levels used in this study were too harsh for successful implementation in dry bean production. The result of this was the exposure of the dry bean cultivar to different levels and durations of drough stress to further explore the effect of water stress on dry bean production.

From both deficit irrigation and water stress trials, it was clear that water stress should be kept to a minimum during flowering, while reduced irrigation during the pod development and growth stages could lead to non-significant decreases in yield and an increase in water use efficiency.

Drought stress effects on photosynthetic rate were highly significant. The reduction was up to 45%. The reduction of photosynthesis at 63 and 105 DAP was greatly due to stomatal conductance. Drought stress resulted in a reduction in intercellular carbon dioxide concentration, stomatal conductance and transpiration. Chlorophyll fluorescence was also affected by drought stress. The minimal chlorophyll fluorescence (F_0) was increased by drought stress accompanied by a reduction in the maximal chlorophyll fluorescence (F_m) and F_v/F_m. Drought stress can have serious effects on leaf gaseous exchange rate and chlorophyll fluorescence depending on the stage of the plant and the duration of drought stress. Treatments

S2 and S3 could not recover after alleviation of drought and that this was reflected in the lower values of maximal chlorophyll fluorescence(F_m). This poor recovery ability when stressed at S2 and S3 could therefore explain the poor yields associated with these two treatment.

The SWB model was calibrated and validated and the results indicated that it is a useful tool for irrigation scheduling and can also be used to predict grain yield production. It predicted the growth and yield of dry bean with high degree of accuracy. However there is a need to explore with other varieties.

A calibration and validation of the SWB model for dry bean growth was done with varying degrees of success. For simulation of grain yield for dry bean (cv DBS 360) the model performed well both under irrigation and water stressed conditions.

In conclusion, the results indicated that dry bean yield can be improved with the appropriate variety suitable for the environmental condition, proper planting population, good understanding of the water requirements and sensitive growth stages and proper irrigation modeling.

9.2 RECOMMENDATIONS

- It is recommended that OPS-RS1 be the variety to replace Kranskop for planting in Limpopo since it was the most stable across localities.
- Tshiombo irrigation scheme invest in dry bean production as one of the major crops for that area.
- Deficit irrigation be practiced in dry bean production with the consideration of the crop growth stage, avoiding late flowering and poding stages and the deficit treatment adjusted to irrigate 50 or 60% of measured field capacity.
- The good simulations with the SWB model for cultivar DBS 360 has proof this model to be useful for predicting growth and yield of dry bean under different levels of water availability. We do recommend that cultivar specific crop parameters for other dry bean cultivars should be determined to increase the usefulness of the SWB model in irrigation scheduling for dry beans.

REFERENCES

ABAZI, U., LORITE, I.J., CÁRCELES, B., MARTÍNEZ RAYA, A., DURÁN, V.H., FRANCIA, J.R. & GÓMEZ, J.A., 2013. WABOL: A conceptual water balance model for analyzing rainfall water use in olive orchards under different soil and cover crop management strategies. *Comp. Elec. Agric.* 91, 35-48.

ABDEL-AZIZ, E.L., EL-SET. A. & SHALABY, F.H., 1999. Physiological studies on response of new released faba bean varieties to different plant populations. *Zagazig J. Agric. Res*. 26, 1229-1244.

ABUBAKER, S. 2008. Effect of plant density on flowering date, yield and quality attribute of bush beans (*Phaseolus vulgaris* L.) under centre pivot irrigation systems. *Am. J. Agric. Biol. Sci*. 3, 666-668.

ACOSTA-GALLEGOS, J.A. & ADAMS, M.W., 1991. Plant traits and yield stability of dry bean (*Phaseolus vulgaris L*.) cultivars under drought stress. *J. Agric. Sci.* 117, 213-219.

ACOSTA-GALLEGOS, J.A. & SHIBATA, J.K., 1989. Effect of water stress on growth and yield of indeterminate dry-bean *(Phaseolus vulgaris)* cultivars. *Field Crops Res.* 20, 81-93.

ACOSTA-GALLEGOS, J.A., 1988. Selection of common bean (*Phaseolus vulgaris* L.) genotypes with enhanced drought tolerance and biological nitrogen fixation. PhD Diss., Michigan State University, East Lansing.

AKYEAMPONG, E., 1986. Some responses of cowpea to drought stress. In: Haque, I., Jutzi, S. & Neate, P.J.H. (Eds). Potentials of forage legumes in farming systems of sub-Saharan Africa – Proceedings of a workshop held at ILCA, Addis Ababa, Ethiopia.

AKINTOYE, H.A., KINTOMO, A.A. & ADEKUNLE, A.A., 2009. Yield and fruit quality of watermelon in response to plant population. *Int. J. Vegetable Sci.* 15, 369-380.

ALLEN, R.G., PEREIRA, L.S., RAES, D. & SMITH. M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56. FAO, Rome. Italy.

AMINIFAR, J., MOHSENABADI, G.H., BIGLOUEI, M.H. & SAMIEZADEH, H., 2012. Effect of deficit irrigation on yield, yield components and phenology of soybean cultivars in Rasht region. *Int. J. of Agri Sci.* 2,185-191.

AMINIFARD, M.H., AROIEE, H., KARIMPOUR, S. & NEMATI, H., 2010. Growth and yield characteristics of paprika pepper (*Capsicum annum* L.) in response to plant density. *Asian J. Plant Sci*. 9, 276-280.

ANNANDALE, J.G., BENADE, N., JOVANOVIC, N.Z., STEYN, J.M. & DU SAUTOY N., 1999. Facilitating irrigation scheduling by means of the Soil Water Balance model. Water Research Commission Rep. No. 753/1/99, Pretoria, South Africa.

ANNANDALE, J.G., CAMPBELL, G.S., OLIVIER, F.C. & JOVANOVIC, N.Z., 2000. Predicting crop water uptake under full and deficit irrigation. An example using pea (*Pisum sativum* cv. Puget). *Irrigation Sci*, 19:65-72.

ANNANDALE, J.G. JOVANOVIC, N.Z. STEYN, J.M. SOUNDY, P. BACKEBERG, G.R. 2002. Technology transfer of the Soil water balance (swb) Model for irrigation Scheduling. Irrigation Advisory Services and Participatory Extension in Irrigation Management. Workshop organised by FAO – ICID TECHNOLOGY, 24 July 2002, Montreal, Canada

ANNANDALE, J.G., STIRZAKER, R.J., SINGELS, A., VAN DER LAAN, M. & LAKER, M.C., 2011. Irrigation scheduling research: South African experiences and future prospects. *Water SA,* 37, 751–762.

ANNICCHIARICO, P., 2002. Genotype x Environment Interactions – Challenges and opportunities for plant breeding and cultivar recommendations. FAO Plant Production and Protection paper – 174. Food and Agriculture Organization of the United Nations, Rome. www.fao.org/DOCREP/005/Y4391e00.htm Accessed on the 05/11/2009.

APARICIO-TEJO, P.M. & BOYER, J.S., 1983. Significance of accelerated leaf senescence at low water potentials for water loss and grain yield in maize. *Crop Sci*. 23, 1198-1201.

ARO, E.M. & VIRGIN, I., 1993. Photo inhibition of photosystem II. Inactivation, protein damage and turnover. *Biochem. Biophys Acta*. 1143, 113-134.

AROCA, R., FERRANTE, A., VERNIERI, P. & CHRISPEELS, M. J., 2006. Drought, abscisic acid and transpiration rate effects on the regulation of pip aquaporin gene expression and abundance in *Phaseolus vulgaris* plants. *Ann. Bot*. 98, 1301–1310.

ASHLEY, D.A. & ETHRIDGE, R.A., 1978. Irrigation effects on vegetative and reproductive development of three soybean cultivars. *Agron. J*. 70, 467-471.

BAKER, R.J., 1988. Differential response to environmental stress. In: WEIR, B.S., EISEN, E.J., GOODMAN, M. M. & NAMKOONG, G., (Eds.). Proceedings of the second International Conference on Quantitative Genetics. Sinauer, Sunderland. pp 492 -504.

BARNARD, R.O., RETHMAN, N.F.G., ANNANDALE, J.G., MENTZ, W. & JOVANOVIC, N.Z., 1998. The Screening of Crop, Pasture and Wetland Species for Tolerance of Polluted Water Originating in Coal Mines. Water Research Commission Report No. K5/582.

BECKER, H.C., 1981. Correlations among some statistical measures of phenotypic stability. *Euphytica,* 30, 835-840.

BENADĖ, N., ANNANDALE, J.G. & VAN ZIJL, H., 1997. The development of a computerized management system for irrigation schemes. Water Research Commission Rep. No. 513/1/95, Pretoria, South Africa

BENNET, J.P., ADAMS, M.W. & CLIFFORD, P.E., 1977. Pod yield component variation and interrelation in *Phaseolus vulgaris* L. as affected by planting density. *Crop Sci*.17, 73-75.

BHATT, M. & CHANDA, S.V., 2003. Prediction of leaf area in *Phaseolus vulgaris* by non-destructive method. *Bulg. J. Plant Physiol. 29, 96-100*.

BOARD, J. & HARVILLE, A., 1998. Late planted soya bean yield response to reproductive source/sink stress. *Crop Sci*. 38, 763-771.

BOOTE, K.J., JONES, J.W. & HOOGEBOOM, G., 1988. Research and management application of the Peanutgro crop growth model. *Proc. Am. Peanut Res. Edu. Soc*. 20, 57.

BOURGAULT, M., MADRAMOOTOO, C.A., WEBBER, H.A., DUTILLEUL, P., STULINA, G., HORST, M.G. & SMITH, D.L., 2013. Legume production and irrigation strategies in the Aral Sea basin: Yield, yield components, water relations and crop development of common bean (*Phaseolus vulgaris* L.) and Mungbean (*Vigna radiata* (L.) Wilczek). *J. Agro. Crop Sci.* 199, 241–252.

BOURGAULT, M., MADRAMOOTOO, C.A., WEBBER, H.A., STULINA, G., HORST, M.G. & SMITH, D.L., 2010. Effects of deficit irrigation and salinity stress on common bean (*Phaseolus vulgaris* L.) and Mungbean (*Vigna radiata* (L.) Wilczek) grown in a controlled environment. *J. Agron. Crop Sci*. 196, 262–272.

BOUTRAA, T. & SANDERS, F.E., 2001a. Influence of water stress on grain yield and vegetative growth of two cultivars of bean (*Phaseolus vulgaris* L.). *J. Agron. Crop Sci*., 187, 251-257.

BOUTRAA, T. & SANDERS, F.E., 2001b. Effects of interactions of moisture regime and nutrient addition on nodulation and carbon partitioning in two cultivars of bean (*Phaseolus vulgaris* L.). *J. Agron. Crop Sci*. 186, 229-237.

BOYER, J.S. & MCPHERSON, H.G., 1975. Physiology of water deficits in cereal crops. *Advances Agronomy*, 27**,** 1-27.

BRADU, D. & GABRIEL, K.R., 1978. The biplot as a diagnostic tool for models of two-way tables. *Technometrics,* 20:47-68

BRAY, E.A., 1997. Plant responses to water deficit. Trends *Plant Sci.* 2, 48-54.

BREVEDAN, R.E. & EGLI, D.B., 2003. Short periods of water stress during seed filling, leaf senescence, and yield of soybean. *Crop Sci*. 75, 2083-2088.

CALVACHE, M., REICHARDT, K., BACCHP, O.O.S. & DOURADO-NETO, D., 1997. Deficit irrigation at different growth stages of the common bean *(Phaseolus vulgaris* L., cv. Imbabello). *Sci. Agric. Piricicaba*, 54, 1-16.

CAMPBELL, G.S. & DIAZ, R., 1988. Simplified soil-water balance models to predict crop transpiration. In: F.R. Bidinger & c. Johansen (eds.). Drought Research Priorities for the Dryland Tropics. ICRISAT, India, 15-26.

CAMPBELL, G.S. & VAN EVERT, F.K., 1994. Light interception by plant canopies: Efficiency and architecture. In: Monteith JL, Scott RK and Unsworth MH (eds.) *Resource Capture by Crops.* Nottingham Univ. Press. 35-52.

CAMPOS, I., BALBONTÍN, C., GONZÁLEZ-PIQUERAS, J., GONZÁLEZ-DUGO, M.P., NEALE, C. M.U. & CALERA, A., 2016. Combining a water balance model with evapotranspiration measurements to estimate total available soil water in irrigated and rain-fed vineyards. *Agric. Water Manage*. 165,141–152.

CARVALHO, L.C.B., SILVA, K.J.D., ROCHA, M.M. & OLIVEIRA, G.C.X., 2016. Evolution of methodology for the study of adaptability and stability in cultivated species. *Afr. J. Agric. Res.* 11, 990-1000.

CASTELLANOS, J.Z., PENA-CABRIALES, J.J. & ACOSTA-GALLEGOS, J.A., 1996. 15 N-determined dinitrogen fixation capacity of common bean (*Phaseolus vulgaris* L.) cultivars under water stress. *J. Agric. Sci.* 126, 327-333.

CECCARELLI, S., 1996. Positive interpretation of genotypes by environment interaction in relation to sustainability and biodiversity. In Cooper, M. & Hammer, G.L. (Eds.). Plant adaptation and crop improvement. Wallingford, UK, CABI. pp 467 - 486.

CHAVES, M.M., 1991. Effects of water deficits on carbon assimilation. *J. Exp. Bot.*42, 1-16.

CHAVES, M.M., FLEXAS, J. & PINHEIRO, C., 2009. Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell. *Ann. Bot.*, 103, 551–560.

CHAVES, M.M., PEREIRA, J.S., MAROCO, J., RODRIGUES, M.L., RICARDO, C.P.P., CARVALHO, I., FARIA, T. & PINHEIRO, C., 2002. How plants cope with water stress in the field. Photosynthesis and growth. *Ann. Bot.*, 89, 907-916.

CHIULELE, R.M., MWANGI, G., TONGOONA, P., EHLERS, J.D. & NDEVE, A.D., 2011. Assessment of cowpea genotypes for variability to drought tolerance. *ACSS Conference Proceedings*, 10, 531 – 537.

CHOPART, J.L., MEZINO, M., AURE, F., LE MEZO, L., METE, M. & VAUCLIN, M., 2007. OSIRI: a simple decision-making tool for monitoring irrigation of small farms in heterogeneous environments. *Agric. Water Manage*. 87, 128–138.

CHUTIA, J. & BORAH, S.P., 2012. Water Stress Effects on Leaf Growth and Chlorophyll Content but Not the Grain Yield in Traditional Rice (*Oryza sativa* Linn.) Genotypes of Assam, India II. Protein and Proline Status in Seedlings under PEG Induced Water Stress. *Am. J. Plant Sci.*, 971-980.

CICOGNA, A., DIETRICH, S., GANI, M., GIOVANARDI, R. & SANDRA, M., 2005. Use of meteorological radar to estimate leaf wetness as data input for application of territorial epidemiological model (downy mildew – *Plasmopara viticola*): Agrometeorology. *Phys. Chem. Earth*, 30, 201–207.

COMSTOCK, R. E., & MOLL, R. H. 1963. Genotype environment Interactions. *In* Statistical Genetics and Plant Breeding. NAS-NRC No. 982, pp. 164-196.

COOPER, M. & HAMMER, G. L., 1996. Plant adaptation and crop improvement. CAB International, Wallingford, UK, ICRISAT, Patancheru, India, and IRRI, Manila, Philippines.

CORNIC, G. & MASSACCI, A., 1996. Leaf photosynthesis under drought stress. In: Baker, N.R., (Ed.). Photosynthesis and the environment. The Netherlands, Kluwer Academic publishers.

CROSBY, C.T., 1996. SAPWAT 1.0 – A computer program for estimating irrigation requirements in Southern Africa. Water Research Commission Report No. 379/1/96, Pretoria, South Africa.

CROSSA, J., 1990. Statistical analysis of multi-location trials. *Adv. Agron.* 44, 55-86.

CROSSA, J., FOX, P.N., PFEIFFER, W.H., RAJARAM S. & GAUCH, H.G. (Jr), 1991. AMMI adjustment for statistical analysis of an international wheat yield trial. *Theor Appl Genet.* 81, 27- 37.

CROTHERS, S. & WESTERMANN, D., 1976. Plant population effects on the seed yield of *Phaseolus vulgaris* L. *Agron. J.*, 68, 958-960. http://agron.scijournals.org/cgi/content/abstract/68/6/958.

DAHMARDEH, M., RAMROODI, M. & VALIZADEH, J., 2010. Effect of plant density and cultivars on growth, yield and yield components of faba bean (*Vicia faba* L.). *Afri. J. Biotechnol.* 9, 8643 - 8647.

DAPAAH, H.K., MCKENZIE, B.A. & HILL, G.D., 2000. Influence of sowing date and irrigation on the yield of pinto beans (*Phaseolus vulgaris*) in a sub-humid tropical environment. *J. Agric. Sci.* 134, 33–43.

DAVIES, S., TURNER, N.C., SIDDIQUE, K.H.M., LEPORT, L. & PLUNNER, J., 1999. Seed growth of desi and kabuli chickpea (*Cicer arietinum*) in a short season Mediterranean-type environment. *Aust. J. Exp. Agric*. 39, 181-188.

DE COSTA, W.A.J.M. & LIYANAGE, L.P., 1997. Effects of potassium and water availability on water use efficiency of common beans (Phaseolus vulgaris L.). *J. Natn. Sci. Coun. Sri Lanka* 25, 241-254.

DE JAGER, J.M., 1994. Accuracy of vegetation evaporation ratio formulae for estimating final wheat yield. *Water SA* 20, 307-315.

DE LANGE, A.F. & LABUSCHAGNE, M.T., 1999. Genotype × environment interaction and principal factor analysis of seed characteristics related to canning quality of small white beans (*Phaseolus vulgaris* L.) in South Africa. *S. Afr. J. Plant and Soil,* 16, 192-196.

DEPARTMENT OF AGRICULTURE, FORESTRY & FISHERIES, 2012. Dry bean market value chain profile. Arcadia, South Africa. http://www.nda.agric.za/doaDev/sideMenu/Marketing/Annual%20Publications/Commodity%20Profiles/field%20crops/Dry%20Bean%20Market%20Value%20Chain%20Profiles%202012.pdf Accessed on the 07/09/2013.

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAAF), 2016. Trends in the Agricultural sector. www.econostatistics.co.za/**Trends**inSA**Agriculture**13.pdf Accessed on the 05/08/2017

DING, M., TIER, B. & YAN, W., 2007. Application of GGE biplot analysis to evaluate genotype (G), environment (E) and GxE interaction on *P. radiata*: A case study. Paper presented to Australasian Forest Genetics Conference Breeding for Wood Quality, 11¬14 April 2007, Hobart, Tasmania, Australia.

DOSS, B.D., PEARSON, R.W.& ROGERS, H.T., 1974. Effect of soil water stress at various growth stages on soybean yield. *Agron. J.* 66, 297-299.

DUBETZ, S., & MAHALLE, P., 1969. Effect of soil water stress on bush beans (*Phaseolus vulgaris L.*) at three stages of growth. *J. Am. Soc. Hort. Sci*. 94, 479-481.

EBDON, J.S. & GAUCH, H.G. (Jr), 2002. Additive mean effect and multiplicative interaction analysis of national turfgrass performance trials. 1. Interpretation of genotype x environmental interaction. *Crop Sci.* 42, 489-496.

EBERHART, S.A. & RUSSELL, W.A., 1966. Stability parameters for comparing varieties. *Crop Sci*. 6, 36-40.

ECK, H.V., MATHERS, A.C. & MUSICK, J.T. 1987. Plant water stress at various growth stages and growth and yield of soybean. *Field Crop Res.* 17: 1-16.

EGLI, D.B., MECKEL, L., PHILLIPS, R.E., RADCLIFFE, D. & LEGGETT, J.E., 1983. Moisture stress and N redistribution in soybean. *Agron. J*. 75, 1027-1031.

EL-FIESHAWY, M.A. & FAYED, E.H., 1990. Seed yield and seed yield components of faba bean as influenced by plant spacing and phosphorus fertilizer. *Zagazig J. Agric. Res*. 17, 227-233.

EL-NAIM, A.M. & JABERELDAR, A., 2010. Effect of plant density and cultivar on growth and yield of Cowpea (*Vigna unguiculata* L. Walp). *Aust. J. Basic & Appl. Sci*. 4, 3148-3153.

ENOCH, H.Z. & HURD, R.G., 1979. The effect of elevated CO_2 concatenation in atmosphere on plant transpiration and water use efficiency: A study with potted carnation plants. *Int. J. Biometer. 23, 345-351*.

FAGERIA, N.K. & SANTOS, A.B., 2008. Yield physiology of dry bean. *J. Plant Nutri*. 31, 983-1004.

FAN, X.M., KANG, M.S., CHEN, H., ZHANG, Y., TAN, J., XU, C., 2007. Yield stability of maize hybrids evaluated in multi-environment trials in Yunnan, China. *Agron J*. 99, 220-228.

FARSHADFAR, E., 2008. Incorporation of AMMI stability value and grain yield in a single non-parametric index (GSI) in bread wheat. *Pak. J. Biol. Sci*. 11, 1791-1796.

FARSHADFAR, E., MAHTABI, E. & JOWKAR, M.M., 2013a. Assessment of parametric stability statistics for selecting stable chick pea genotypes. *Intl. J. Agric. Crop Sci.* 5, 2568-2575.

FARSHADFAR, E., MOHAMMADI, R., AGHAEE, M. & VAISI, Z., 2012. GGE biplot analysis of genotype × environment interaction in wheat-barley disomic addition lines. *AJCS*, 6, 1074-1079.

FARSHADFAR, E., RASHIDI, M., JOWKAR, M.M. & HASSAN ZALI, H., 2013b. GGE- Biplot analysis of genotype × environment interaction in chickpea genotypes. *Euro. J. Exp. Bio. 3,* 417-423*.*

FERERES, E. & SORIANO, M.A., 2007. Deficit irrigation for reducing agricultural water use. Special issue on 'Integrated approaches to sustain and improve plant production under drought stress' *J. Exp. Bot.* 58, 147–159.

FERNANDEZ-JARAMILLO, A.A., DUARTE-GALVAN, C., CONTRERAS-MEDINA, L.M., TORRES-PACHECO, I., ROMERO-TRONCOSO, R.J., GUEVARA-GONZALEZ, R.G. & MILLAN-ALMARAZ, J.R., 2012. Instrumentation in developing chlorophyll fluorescence bio-sensing: A Review. *Sensors*, *12*, 11853-11869.

FIELD, R.J. & NKUMBULA, S., 1986. Green beans (*Phaseolus vulgaris* cv. Gallatin 50): Effects of plant population density on yield and quality. *New Zeal. J. Exp. Agr*. 14, 435-442.

FIKERE, M., BING, D.J., TADESSE, T. & AYANA, A., 2014. Comparison of biometrical methods to describe yield stability in field pea (*Pisum sativum* L.). under south eastern Ethiopian conditions. *Afr. J. Agric. Res.* 9, 2574-2583.

FINLAY, K.W. & WILKINSON, G.N., 1963. The analysis of adaptation in a plant-breeding programme. *Aust. J. Agric. Res.*14, 742-754.

FLEXAS, J. & MEDRANO, H., 2002. Drought-inhibition of photosynthesis in C_3 plants: Stomatal and non-stomatal limitations revisited. *Ann Bot.* 89, 183-189.

FOSTER, E.F., PAJARITO, A.J.A. & ACOSTA, G. 1995: Moisture stress impact on N partitioning, N remobilization and N-use efficiency in beans (*Phaseolus vulgaris L*.). *J. Agric. Sci. Camb*. 124, 27-37.

FOTOVAT, R., VALIZADEH, M. & TOOREHI, M., 2007. Association between water-use-efficiency components and total chlorophyll content (SPAD) in wheat (*Triticum aestivum* L.) under well-watered and drought stress conditions. *J. Food. Agric. Environ*. 5, 225-227.

FOYER, C.H., DESCOURVIERES, P. & KUNERT, K.J., 1994. Photo oxidative stress in plants. *Plant. Physiol*. 92, 696-717.

FRAHM, M.A., ROSAS, J.C., MAYEK-PEREZ, N., LOPEZ-SALINA, S.E., ACOSTA-GALLEGOS, J.A. & KELLY, J.D., 2004. Breeding beans for resistance to terminal drought in the Lowland tropics. *Euphytica*, 136, 223-232.

FRIEDMAN, S.P., COMMUNAR, G. & GAMLIEL, A., 2016. DIDAS – User-friendly software package for assisting drip irrigation design and scheduling. *Comput. Elect. Agric.* 120, 36–52.

GABRIEL, K.R. 1971.The biplot graphic display of matrices with application to principal component analysis. *Biometrika,* 58, 453-467.

GAN, S. & AMASIMO, R.M., 1997. Making sense of senescence: molecular genetic regulation and manipulation of leaf senescence. *Plant Physiol*. 113, 313-319.

GARDNER, F.P., PEARCE, R.B. & MITCHELL, R.L., 1985. Physiology of crop plants. Iowa State University Press, Ames, USA.

GAUCH, H.G., 1988. Model selection and validation for yield trials with interaction. *Biometrics*, 44, 705-715.

GAUCH, H.G., 1992. Statistical analysis of regional yield trials: AMMI analysis of factorial designs. Elsevier, Amsterdam, Netherlands.

GAUCH, H.G. & ZOBEL, R.W., 1997. Identifying mega-environments and targeting genotypes. Crop Sci. 37, 311-326.

GEERTS, S. & RAES, D., 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agr. Water Manage. 96,* 1275-1284*.*

GEERTS, S., RAES, D., GARCIA, M., VACHER, J., MAMANI, R., MENDOZA, J., HUANCA, R., MORALES, B., MIRANDA, R., CUSICANQUI, J. & TABOADA, C., 2008. Introducing deficit irrigation to stabilize yields of quinoa (*Chenopodium quinoa* Wild.). *Eur. J. Agron*. 28, 427–436.

GHASSEMI-GOLEZANI, K. & MARDFAR, R.A., 2008. Effects of limited irrigation on growth and yield of common bean. *J. Plant Sci*. 3(2) 230-235.

GOHARI, A.A., 2013. Effects of water infiltration of soil on yield and water use efficiency of common bean (*Phaseolus vulgaris* L.) *Intl. J. Agron. Plant Prod.* 4, 459-463.

GOUDRIAAN, J., 1977. *Crop Meteorology: A Simulation Study.* Pudoc, Wageningen.

GOWDA, C.L.L., UPADHYAYA, H.D., DRONAVALLI, N. & SINGH, S., 2011. Identification of large seeded high yielding stable Kabuli chick pea germ plasm lines for use in crop improvement. *Crop Science*, 51, 198-209.

GRAFTON, K.F., SCHNEITER, A.A. & NAGLE, B.J., 1988. Row spacing plant population and genotype x row spacing interaction effects on yield and yield components of dry bean. *Agron. J.* 80,631-634.

GUNTON, J.L. & EVENSON, J.P., 1980. Moisture stress in navy beans. I. Effect of withholding irrigation at different phonological stages on growth and yield. *Irri. Sci*. 2, 49-58.

HALL, A. E. & SCHULZE E. D., 1980. Drought effects on transpiration and leaf water status of cowpea in controlled environments. *Aust. J. Plant Physiol., 7,* 141-147.

HAMMER, G.L., 1998. Crop modelling: Current status and opportunities to advance. *Acta Hort*. 456, 27 – 36.

HATERLEIN, A.J., 1983. Bean. In: Tearce, T.P., Peet, M.M. Jr (Eds.), Crop Water Relations. Wiley, New York, pp. 157– 185.

HOOGENBOOM, G., WHITE, J.M., JONES, J.W., BOOTE, K.J., BOWEN, W.T., PICKERING, N.B. & BATCHELOR, W.D., 1994. CROPGRO – Dry bean. In: TSUJI, G.Y.; UEHARA, G.; BALAS, S. (Ed.) Crop models. DSSAT version 3. Honolulu: University of Hawaii, 1994, p.95-281.

HOPKINS, W.G. & HÜNER, N.P.A., 2004. Introduction to plant physiology. 3rd Edn. John Wiley and Sons, Inc. United States of America. pp 462.

HOSSEINI, N.M., ELLIS, R. H. & YAZDI-SAMADI, B., 2001. Effects of plant population density on yield and yield components of eight isolines of cv. Clark (*Glycine max* L.) *J. Agric. Sci. Technol. 3, 131-139*

HSIAO, T., STEDUTO, P. & FERERES, E., 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. *Irrig. Sci*. 25, 209-231.

HSIAO, T.C., 1973. Plant responses to water stress. *Ann. Rev. Plant Physiol*. 24, 519-570.

HUGH, G. & GAUCH, H.G., 2006. Statistical analysis of yield trials by AMMI and GGE. *Crop Sci.* 46, 1488-1500.

IMRIE, B.C. & HACKER, J. B., 1993. Focused plant improvement: towards responsible and sustainable agriculture. Proceedings 10th Australian plant breeding conference. Volume I. Organizing committee, Australian Convention and Travel Service, Canberra, Australia.

INAKI-ITURBE, O., ESCUREDO, P.R., ARRESE-IGOR, C. & BECANA, M., 1998. Oxidative damage in pea plants exposed to water deficits or paraquat. *Plant Physiol*. 116, 173-181.

ISAAC, W.A.P., HILL, G.D., MCKENZIE, B.A., FRAMPTON, C. & BOURDOT, G.W., 2000. Effect of crop morphology and density on crop and weed productivity. *Agron. N.Z*. 30, 161-168.

ISTANBULLUOGLU, A., ARSLAN, B, GOCMEN, E., GEZER, E. & C. PASA, C., 2010. Effects of deficit irrigation regimes on the yield and growth of oilseed rape (*Brassica napus* L.). *Biosyst. Eng.*, 105, 388-394.

JAMAATI-E-SOMARIN, S., HASSANZADEH, M., PEYGHAMI, F. & ZABIHI-E-MAHMOODABAD, R., 2009. Response of durum wheat growth and chlorophyll content to nitrogen rates and plant populations. *Res. J. Biol. Sci*. 4, 1135-1141.

JOHNSON, G.A., HOVERSTAD, T.R. & GREENWALD, R.E., 1998. Integrated weed management using narrow corn row spacing, herbicides and cultivation. *Agron. J*. 77, 40 - 46.

JOVANOVIC, N.Z. & ANNANDALE, J.G., 1999. An FAO type crop factor modification to SWB for inclusion of crops with limited data: Examples for vegetable crops. *Water SA,* 25 , 181-189.

JOVANOVIC, N.Z. & ANNANDALE, J.G., 2000. Crop growth model parameters of 19 summer vegetable cultivars for use in mechanistic irrigation scheduling models. *Water SA ,* 26, 67-76.

JOVANOVIC, N.Z., ANNANDALE, J.G. & BENNIE A.T.P., 2002. Calibration and validation of the SWB irrigation scheduling model for soybean [Glycine max. (L.) Merr., indeterminate cv. Wayne], *S. A. J. Plant*, 19, 165-172.

JOVANOVIC, N.Z., ANNANDALE, J.G. & HAMMES, P.S., 2000. Teaching crop physiology with the soil water balance (SWB) model. *J. Nat. Resour. Life Sci. Educ.* 29**,** 23-30.

JOVANOVIC, N.Z., ANNANDALE, J.G. & MHLAULI, N.C., 1999. Field water balance and SWB parameter determination of six winter vegetable species. *Water SA* 25, 191-196.

JOVANOVIC, N.Z. & ANNANDALE, J.G., 998. Measurement of radiant interception of crop canopies with the LAI-2000 plant canopy analyzer. *S. Afr. J. Plant and Soil* 15, 6-13.

KALAJI, H. M. & GUO*,* P., 2008. Chlorophyll fluorescence: a useful tool in barley plant breeding programs. In: Sánchez A. & Gutierrez, S. J. (Eds.). Photochemistry Research Progress. Nova Science Publishers, Inc.

KAMUTANDO, C.N., MUUNGANI, D., MASVODZA, D.R. & GASURA, G., 2013. Exploiting genotype x environment interaction in maize breeding in Zimbabwe. *Afr. J. Agric. Res.* 8, 4058-4066.

KANG, M. S. & GAUCH, H. J., 1996. Genotype-by-environment interaction. CRC Press, Boca Raton, FL.

KANG, M. S., 1990. Genotype-by-environment interaction and plant breeding. Louisiana State University Agricultural Center, Baton Rouge, LA.

KANG, M. S., 2003. Quantitative genetics, genomics, and plant breeding. CAB International, Wallingford, UK.

KANG, M.S., 1998. Using genotype-by-environment interaction for crop cultivar development. *Adv. Agron*. 62, 199-252.

KANG, M.S., 2002. Genotype x environment interaction: progress and prospects. In: Kang, M.S. (Ed.) Quantitative Genetics, Genomics and Plant Breeding. Wallingford, UK, CABI. pp. 221−243

KANG, M.S., AGGARWAL, V.D. & CHIRWA, R.M., 2006. Adaptability and stability of bean cultivars as determined via yield-stability static and GGE bi-plot analysis. J. *Crop Improve.* 15, 97-120.

KARAM, F., KABALAN, R., BREIDI, J., ROUPHAEL, Y. & OWEIS, T., 2009. Yield and water production functions of two durum wheat cultivars grown under different irrigation and nitrogen regimes. *Agr. Water Manage*. 96, 603–615.

KARAM, F., LAHOUD, R. MASAAD, R. KABALAN, R., J. BREIDI, J., CHALITA,C. & ROUPHAEL, Y., 2007: Evapotranspiration, seed yield and water use efficiency of drip irrigated sunflower under full and deficit irrigation conditions. *Agr. Water Manage*. 90, 213-223.

KEMPTON, R. A., 1984. The use of biplot in interpreting variety by environment interactions. *J. Agric. Sci*. 103, 123-135.

KHALEDIAN, M.R., MAILHOL, J.C., RUELLE, P., ROSIQUE, P., 2009. Adapting PILOTE model for water and yield management under direct seeding system: the case of corn and durum wheat in a Mediterranean context. *Agric. Water Manage*. 96, 757–770.

KHALIL, S.A., DISSOUKY, R.F., AMER, M.I., EL-HADY, M.M.& HASSAN, M.W.A., 1993. Performance of yield and yield components of two faba bean (*Vicia faba* L.) cultivars as affected by two plant densities and foliar disease control in the new reclaimed land. *J. Agric. Sci. Mansoura Univ*. 18, 1306-1314.

KIRDA, C., 2000. Deficit Irrigation Scheduling Based on Plant Growth Stages Showing Water Streets Tolerance. In: Food and Agricultural Organization of the United Nations (FAO) (ed.). *Deficit Irrigation Practices*. Viale delle Terme di Caracalla, Rome, Italy, p3-10.

KIRDA, C. & KANBER, R. 1999. Water, no longer a plentiful resource, should be used sparingly in irrigated agriculture. *In:* Kirda, C., Moutonnet, P., Hera, C. & Nielsen, D.R. (Eds.) *Crop yield response to deficit irrigation*, Dordrecht, The Netherlands, Kluwer Academic Publishers.

KORTE, L.L., SPECHT, J.E., WILLIAMS, J.H. & SORENSEN, R.C., 1983a. Irrigation of soybean genotypes during reproductive ontogeny. II. Yield component responses. *Crop Sci*. 23, 528-533.

KORTE, L.L., WILLIAMS, J.H. & SORENCEN, R.C. 1983b. Irrigation of soybean genotypes during reproductive ontogeny. I. Agronomic responses. *Crop Sci.* 23, 521-527.

KROONENBERG, P.M., 1995. Introduction to biplots for G×E tables. Department of Mathematics, Research Report #51, University of Queensland, 22.

LAUBSCHER, M.C., ROUX, C.Z. & GEERTHSEN, J.M.P., 2000. An explanation of genotype by environment interaction for maize in South Africa. *S. Afr. J. Plant Soil,* 16, 192-196.

LAWLOR, D.W., 1995. The effects of water deficits on photosynthesis. In: Smirnoff, N., (Ed.). *Environment and plant metabolism. Flexibility and acclimation*. Oxford, BIOS Scientific publishers.

LEIB, B.G., HATTENDORF, M. & MATTHEWS, G., 2002. Adoption and adaptation of scientific irrigation scheduling: trends from Washington, USA as of 1998. *Agr. Water Manage*. 55, 105-120.

LEITH, J.H., REYNOLDS, J.P. & ROGERS, H.H., 1986. Estimation of leaf area of soybeans grown under elevated carbon dioxide levels. *Field Crops Res*. 13, 193-203.

LEVIDOW, L., ZACCARIA, D., MAIA, R., VIVAS, E., TODOROVIC, M. & SCARDIGNO, A., 2014. Improving water-efficient irrigation: prospects and difficulties of innovative practices. *Agric. Water Manage*. 146, 84–94.

LIEBENBERG A.J, VAN WYK C, TRENT C, SWANEPOEL S.C., MC DONALD A. & ELS I.J, 2002. Dry bean production manual. Agricultural Research Council Grain Crops Institute, Potchefstroom.

LIN, C.S. & BINNS, M.R., 1991. Genetic properties of four types of stability parameter. *Theor. Appl. Genet*., 82, 505 - 509.

LIN, C.S. & BINNS, M.R., 1994. Concepts and methods for analyzing regional trial data for cultivar and location selection. *Plant Breed Rev* .12, 271-297.

LIN, C.S., BINNS, M.R. & LEFKOVITCH, L.P., 1986. Stability analysis: Where do we stand? *Crop Sci*., 26, 894-900.

LIU, M., QI, H., ZHANG, Z.P., SONG, Z.W., KOU, T.J., ZHANG, W.J. & YU, J.L., 2012. Response of photosynthesis and chlorophyll fluorescence to drought stress in two maize cultivars. *Afr. J. Agric. Res*., 7, 4751-4760.

LOPEZ, F.B., JOHANSEN, C. & CHAUHAN, Y.S., 1996. Effect of timing of drought stress on phenology, yield and yield components of a short-duration pigeon pea. *J Agron Crop Sci.* 177,311-320.

LUO, Y., HE, C., SOPHOCLEOUS, M., YIN, Z., REN, H. & ZHU, O., 2008. Assessment of crop growth and soil water modules in SWAT2000 using extensive field experiment data in an irrigation district of the Yellow River Basin. *J. Hydrol.* 352, 139–156.

MA'ALI, S. H., 2008. Additive mean effects and multiplicative interaction analysis of maize yield trials in South Africa. *S. Afr. J. Plant Soil*, 25, 185-193.

MAFAKHERI, A., SIOSEMARDEH, A., BAHRAMNEJAD, B., STRUIK, P.C. & SOHRABI, Y., 2010. Effect of drought stress on yield, proline and chlorophyll contents in three chickpea cultivars. *AJCS*, 4, 580-585.

MALEKI, A., NADERI, A., NASERI, R., FATHI, A., BAHAMIN, S. & MALEKI, R., 2013. Physiological performance of soybean cultivars under drought stress. *Bull. Env. Pharmacol. Life Sci*. 2, 38-44

MALIK, V.S., SWANTON, C.J. & MICHAELS, T.E., 1993. Interaction of white bean (*Phaseolus vulgaris* L.) cultivars, row spacing and seeding density with annual weeds. *Weed Sci.* 41, 62-68.

MANJERU, P., MADANZI, T., MAKEREDZA, B., NCIIZAH, A. & SITHOLE, M., 2007. Effects of water stress at different growth stages on components and grain yield of common bean (*Phaseolus vulgaris* L.). In: *African Crop Science Conference Proceedings*, 8, 299-303.

MARROU, H., SINCLAIRA, T.R. & METRALBA, R., 2014. Assessment of irrigation scenarios to improve performances of Lingot bean (*Phaseolus vulgaris*) in southwest France. *Europ. J. Agronomy*, 59, 22–28

MAXWELL, K. & JOHNSON G.N., 2000. Chlorophyll fluorescence—a practical guide. *J. Exp. Bot.* 51, 659-668.

MAYNARD, E.T. & SCOTT, W.D., 1998. Plant spacing affects yield of superstar muskmelon. *J. Hort. Sci*. 33, 52-54.

MEDRANO, H., ESCALONA, J.M., BOTA, J., GULIAS, J. & FLEXAS, J., 2002. Regulation of photosynthesis of C_3 plants in response to progressive drought: stomatal conductance as a reference parameter. *Ann Bot.*, 89, 895-905.

MILLER, D.E. & BURKE, D.W., 1983. Response of dry beans to daily deficit sprinkler irrigation. *Agron. J*. 75, 775-778.

MIRNOFF, N., 1993. The role of active oxygen in the response of plants to water deficit and desiccation. *New Phytol*. 125, 27-58.

MOHAMMADKHANI, N. & HEIDARI, R., 2007. Effects of water stress on respiration, photosynthetic pigments and water content in two maize cultivars. *Pak. J. Biol. Sci*. 10, 4022-4028.

MONIRUZZAMAN, M., HALIM, G.M. & FIROZ, Z.A., 2009. Performances of French bean as influenced by plant density and nitrogen application. *Bangladesh J. Agril. Res. 34, 105-111*.

MONTAGU, K.D. & WOO, K.C., 1999. Recovery of tree photosynthetic capacity from seasonal drought in the wet-dry tropics: The role of phyllode and canopy processes in *Acacia auriculiformis*. *Aust. J. Plant Physiol*. 26, 135-145.

MONTEITH, J.L., 1977. Climate and efficiency of crop production in Britain. Philos. Trans. R. Soc. London, Ser. B. 281, 277-294.

MORGADE, L. & WILLEY, R., 2003. Effect of plant population and nitrogen fertilizer on yield and efficiency of maize/bean intercropping. *Pesq. Agropec. Bras. Brasilia*, 38, 1257-1264.

MUELLER, N.D., GERBER, J.S., JOHNSTON, M., RAY, D.K., RAMANKUTTY, N. & FOLEY, J.A., 2012.Closing yield gaps through nutrient and water management. *Nature* 490, 254–257.

MWANAMWENGE, J., LOSS, S.P., SIDDIQUE, K.H.M. & COCKS, P.S, 1999. Effect of water stress during floral initiation, flowering and podding on the growth and yield of faba bean (*Vicia faba* L.). *Eur. J. Agron*.11, 1-11.

MZEZEWA, J., MISI, T. & VAN RENSBURG, L.D., 2010. Characterisation of rainfall at a semi-arid ecoptope in the Limpopo Province (South Africa) and its implications for sustainable crop production. *Water SA*, 36, 19-26.

NANDAN R. & PRASAD, U.K., 1998. Effect of irrigation and nitrogen on growth, yield, nitrogen uptake and water – use efficiency of French bean *(Phaseolus vulgaris). Indian J. Agric. Sci*. 68, 75–80.

NEL, A.A., LOUBSER, H.L. & HAMMES, P.S., 2000. The effect of environment and cultivar on sunflower seed. I. Yield, hullability and physical seed characteristics. *S. Afr. J. Plant Soil*, 10, 28-34.

NIELSEN, D.V., & NELSEN, N.O., 1998. Black bean sensitivity to water stress at various growth stages. *Crop Sci*. 38, 422-427.

NIELSON, D. V., & NELSON, N. O., 1998. Black bean sensitivity to water stress at various growth stages. *Crop Sci*. 38, 422-427.

NIENHUIS, J. & SINGH, S.P., 1985. Effects of location and plant density on yield and architectural traits in dry beans. *Crop Sci*. 25,579-584.

NIKOLAEVA, M.K., MAEVSKAYA, S.N., SHUGAEV, A.G. & BUKHOV, N.G., 2010. Effect of drought on chlorophyll content and antioxidant enzyme activities in leaves of three wheat cultivars varying in productivity. *Russ. J. Plant Physiol*. 57, 94-102.

NILSEN, E.T. & ORCUTT, D, M., 1996. Physiology of plants under stress, Abiotic factors. 2nd edn., John Wiley and Sons Inc., New York, pp, 689.

OKOYE, M.N., OKWUAGWU, C.O. & UGURU, M.I., 2008. Genotype and genotype by environment (GGE) biplot analysis of fresh fruit bunch yield and yield components of oil palm (*Elaeis guineensis* Jacq.). *J. Appl. Biosci.,* 8, 288 - 303.

OMMEN, O.E., DONNELLY, A., VANHOUTVIN, S., VAN OIJEN,M. & MANDERSCHEID, R., 1999. Chlorophyll content of spring wheat flag leaves grown under elevated CO2 concentrations and other environmental stresses within the ESPACE-wheat project. *Eur. J. Agron*. 10, 197-203.

OSORIO, J., OSORIO, M.L., CHAVES, M.M. & PEREIRA, J.S., 1998. Effects of water deficit on ^{13}C discrimination and transpiration efficiency of *Eucalyptus globulus* clones. *Austr. J. Plant Physiol*. 25, 645-251.

PANDA, R.K., BEHERA, S.K. & KASHYAP, P.S., 2003. Effective management of irrigation water for wheat under stressed conditions. *Agr. Water Manage.* 63, 37–56.

PANDEY, R.K., HERERA, W.A.T. & PENDLETON, J.W., 1984. Drought response of grain legumes under irrigation gradient. I: Yield components. *Agron. J.*, 76, 549-553.

PANDEY, R.K., MARANVILLE, J.W. & CHETIMA, M.M., 2000. Deficit irrigation and nitrogen effects on maize in a Sahelian environment. II. Shoot growth, nitrogen uptake and water extraction. *Agr. Water Manage,* 46, 15-27.

PARVIZI, S., AMIRNIA, R., BERNOOSI, I., GORTTAPEH, A.H., FEGHNABI, F., SABER-REZAIE, M., ASBAG, F.T., EIZADKHAH, M. & RAHIM, S., 2009. Evaluation of different plant densities effect on grain filling rate and duration, yield and its components in Pinto bean varieties. *Res. J. Biol. Sci.* 4, 499-502.

PEREIRA, L.S., OWEIS, T. & ZAIRI, A., 2002. Irrigation management under water scarcity. *Agric. Water Manage*. 57, 175–206.

PERKINS, J.M. & JINKS, J.L., 1968. Environmental and genotype-environmental components of variability. III. Multiple lines and crosses. In: Annicchiarico, P. (ed.) Genotype x Environment Interactions – Challenges and opportunities for plant breeding and cultivar recommendations. FAO Plant Production and Protection paper – 174. Food and Agriculture Organization of the United

Nations, Rome. www.fao.org/DOCREP/005/Y4391e00.htm Accessed on the 05/11/2008.

PHOCAIDES, A., 2007. Handbook on pressurized irrigation techniques. 2nd ed. Food and Agriculture Organization of the United Nations, Rome. pp 6.1.

PURCHASE, J.L., HATTING, H. & VAN DEVENTER, C.S., 2000. Genotype x environment interaction of winter wheat (*Triticum aestivum* L.) in South Africa: 1. AMMI analysis of yield performances. *S. Afr. J. Plant Soil,* 17, 95-100.

RAD, N.M.R., KADIR, M. A., RAFII, M.Y., HAWA, JAAFAR, Z.E., NAGHAVI, M.R. & AHMADI, F., 2013. Genotype × environment interaction by AMMI and GGE biplot analysis in three consecutive generations of wheat (*Triticum aestivum*) under normal and drought stress conditions. AJCS 7, 956-961.

RAES, D., GEERTS, S., KIPKORIR, E., WELLENS, J. & SAHLI, A., 2006. Simulation of yield decline as a result of water stress with a robust soil water balance model. *Agric. Water Manage*. 81, 335–357.

RAHMAN, M.U., GUL, S. & AHMAD, I., 2004. Effects of water stress on growth and photosynthetic pigments of corn (*Zea mays* L.) cultivars. *Int. J. Agric. Biol*. 4, 652-655.

RAMAGOSA, I., FOX, P.N., GARCIA DEL MORAL, L.F., RAMOS, J.M., GARCIA DEL MORAL, B., ROCA DE TOGORES, F. & MOLINA-CANO, J.L., 1993. Integration of statistical and physiological analyses of adaptation of near-isogenic barley lines. *Theor. Appl. Genet*. 86, 822-826.

RAMBURAN, S., ZHOU, M. & LABUSCHAGNE, M., 2011. Interpretation of genotype x environment interactions of sugarcane: Identifying significant environmental factors. *Field Crop Res*. 124, 392-399.

RAMIREZ-VALLEJO, P. & KELLY, J.M., 1998. Traits related to drought resistance in common bean. *Euphytica*, 99, 127-136.

RASHIDI, M. & SEYFI, K., 2007. Effect of water stress on crop yield and yield components of cantaloupe. *Int. J. Agric. Biol*., 9, 271-273.

REINDERS, F.B., 2010. Standards and guidelines for improved efficiency of irrigation use from dam wall release to root zone application. Water Research Commission Report No. TT465/10, Pretoria, South Africa.

REYNOLDS, M. & TUBEROSA, R., 2008. Translational research impacting on crop productivity in drought-prone environments. *Curr. Opin. Plant Biol.* 11, 171–179.

RITCHIE, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res*. 8, 1204-1213.

SAMONTE, S.O.P.B., WILSON, L.T., MCCLUNG, A.M. & MEDLEY, J.C., 2005. Targeting cultivars onto rice growing environments using AMMI and SREG GGE biplot analyses. *Crop Sci*. 45, 2414-2424.

SANCHEZ, P., SWAMINATHAN, M.S., DOBIE, P. & YUKSEL, N., 2005. Halving hunger: it can be done. UN Millennium Project – Task Force on Hunger. Earth scan, London.

SARKAR S. & KAR, S., 1995. Simulation of evapotranspiration from groundnut under wet and dry conditions. *Agric. Water Manage*. 27, 299–307.

SATHE, S.K., DESHPANDE, S.S., SALUNKHE, D.K. & RACKIS, J.J., 1984. Dry beans of *Phaseolus*. A review. Part 1: Chemical composition Proteins. *Crit. Rev. food Sci. Nutr,* 20, 1-46.

SCHAPENDONK, A.H.C.M., SPITTERS, C.J.T. & GROOT, P.J., 1989. Effects of water stress on photosynthesis and chlorophyll fluorescence of five potato cultivars. *Potato Research,* 32, 17-32.

SCHREIBER, U, SCHLIWA, U. & BILGER, W., 1986. Continuous recording of photochemical and non-photochemical chlorophyll fluorescence quenching with a new type of modulation fluorometer. *Photosynth. Res*. 10, 51–62.

SHARKEY, T.D., 1990. Water stress effects on photosynthesis. *Photosynthetica*, 24, 651

SHARKEY, T.D. & SEEMANN, J.R., 1989. Mild water stress effects on carbon-reduction-cycle intermediates, ribulose bisphosphate carboxylase activity, and spatial homogeneity of photosynthesis in intact leaves. *Plant Physiol*. 89, 1060-1065.

SHENKUT, A.A. & BRICK, M.A., 2003. Trait associated with dry edible bean (*Phaseolus vulgaris* L.) productivity under diverse soil moisture environments. *Euphytica*, 133, 339-347.

SHIRTLIFFE, S.J. & JOHNSTON, A.M., 2002. Yield density relationships and optimum plant populations in two cultivars of solid-seeded dry bean (*Phaseolus vulgaris* L.) grown in Saskatchewan. *Can. J. Plant Sci*. 82, 521-529.

SIDDIQUE, M.R.B., HAMID, A. & ISLAM, M.S., 1999. Drought stress effects on photosynthetic rate and leaf gas exchange of wheat. *Bot. Bull. Acad. Sin*. 40, 141-145.

SIMMONDS, N.W., 1991. Selection for local adaptation in a plant breeding programme. *Theor. Appl. Genet*., 82, 363-367.

SINGELS, A. & DE JAGER, J.M., 1991. Refinement and validation of PUTU wheat crop growth model. 1. Phenology. *S. Afr. J. Plant Soil*, 8, 59-66.

SINGELS, A., ANNANDALE, J.G., DE JAGER, J.M., SCHULZE, R.E., INMAN-BAMBER, N.G., DURAND,W., VAN RENSBURG, L.D., VAN HEERDEN, P.S., CROSBY, C.T., GREEN, G.C. & STEYN, J.M., 2010. Modelling crop growth and crop water relations in South Africa: Past achievements and lessons for the future. *S.Afr. J. Plant Soil*, 27, 49-65.

SINGH, S.P., 1995. Selection for water-stress tolerance in interracial populations of common bean. *Crop Sci*. 35, 118-124.

SINGH, S.P. & GUTIÈRREZ, J.A., 1990. Effect of plant density on selection for seed yield in two population types of *Phaseolus vulgaris* L. *Euphytica* 51, 173-178.

SINGH, S.P., SINGH, N.P. & PANDEY, R.K., 1992. Performance of faba bean varieties at different plant densities. *FABIS Newsletter,* 30, 29–31.

SINGH, S.P., TERAN, H., MUNOZ, C.G. & TAKEGAMI, J.C., 1999. Two cycles of recurrent selection for seed yield in common bean. *Crop Sci*. 39, 391-397.

SINHA, N.K. & HUI, Y.H., 2011. *Handbook of vegetables and vegetables processing.* Wiley-Blackwell. Iowa, USA. pp. 545.

SIONIT, N. & KRAMER, P.J., 1977. Effects of water stress during different stages of growth of soybeans. *Agron. J*. 69, 274-278.

SMIRNOFF, N., 1995. Antioxidant systems and plant response to the environment. In: Smirnoff, V. (Ed.), Environment and Plant Metabolism: Flexibility and Acclimation, BIOS. Scientific Publishers, Oxford, UK.

SMITH, M., 1992. CROPWAT. A computer program for irrigation planning and management. F AO Irrigation and Drainage Paper No. 46. FAO, Rome, Italy.

SMITH, M., ALLEN, R.G. & PEREIRA L.S., 1996. Revised FAO methodology for crop water requirements. p. 133.140. *In* Proc. of the Int. Conf. on Evapotranspiration and Irrigation Scheduling, San Antonio, TX. 3.6 Nov. 1996. ASAE, St. Joseph, MI.

SMITH, M.F & SMITH, A., 1992. CROPW A T. A computer program for irrigation planning and management. F AO Irrigation and Drainage Paper No. 46. FAO, Rome, Italy.

SPECK, J.E., ELMORE, R.W., EISENHAUER, D.E. & KLOCKE, N.W., 1989. Growth stage scheduling criteria for sprinkler-irrigated soybeans. *Irrigation Sci.* 10, 99-111.

STATISTICS SOUTH AFRICA, 2013. Millennium development goals, country report 2013. Beta2.statssa.gov.za/MDG/MDGR_2013pdf

STEDUTO, P. & ALBRIZIO, R., 2005. Resource use efficiency of field-grown sunflower, sorghum, wheat and chickpea. II. Water use efficiency and comparison with radiation use efficiency. *Agr. Forest Meteorol*. 130, 269–281.

STEDUTO, P., HSIAO, T.C. & FERERES, E., 2007. On the conservative behavior of biomass water productivity. *Irrig. Sci.* 25, 189–207.

STEDUTO, P., HSIAO, T.C., RAES, D., FERERES, E., 2009. AquaCrop – the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agron. J. 101, 426–437.

STEGMAN, E.C. 1982. Corn grain yield as influenced by timing of evapotranspiration. *Irrigation Sci.*3:75-87.

STEGMAN, E.C., SCHATZ, B.G. & GARDNER, J.C., 1990. Yield sensitivities of short season soybeans to irrigation management. *Irrigation Sci.* 11, 111-119.

STEVENS, J.B., DUVEL, G.H., STEYN, G.J. & MAROBANE, W., 2005. The range, distribution and implementation of irrigation scheduling models and methods in South Africa. WRC Report No. 1137. Pretoria, South Africa.

STEYN, P.J., VISSER, A.F., SMITH, M.F. & SCHOEMAN, J.L., 1993. AMMI analysis of potato cultivar yield trials. *S. Afr. J. Plant Soil* 17, 133-137.

STIRBET, A. & GOVINDJEE, 2011. On the relation between the Kautsky effect (chlorophyll a fluorescence induction) and photosystem II: Basics and applications of the OJIP fluorescence transient. *J. Photochem. Photobiol. B: Biol. 104*, 236–257.

STOKER, R., 1974. Effect on dwarf beans of water stress at different phases of growth. *NZ J. Exp. Agric*. 2, 13-15.

SZILAGYI, L., 2003. Influence of drought on seed yield components in common bean. *Bulg. J. Plant Physiol*., Special Issue, 320-330.

TAIZ, L. & ZEIGER, E., 2006. Plant Physiology. 4th Edition. Sinauer Associates, Inc., Publishers, Sutherland, Massachusetts, USA. pp125.

TALEBI, R., 2011. Evaluation of chlorophyll content and canopy temperature as indicators for drought tolerance in durum wheat (Triticum durum Desf.). *Aust. J. Basic & Appl. Sci.* 5, 1457-1462.

TANG, A.C., KAWAMITSU, Y., KANECHI, M. & BOYER, J.S., 2002. Photosynthetic oxygen evolution at low water potential in leaf discs lacking an epidermis. *Ann. Bot*. 89, 861-870.

TANNER, C.B. & SINCLAIR, T.R., 1983. Efficient water use in crop production: research or re-search? In: H.M. Taylor, W.R. Jordan & T.R. Sinclair (Editors). Limitations to Efficient Water Use in Crop Production. ASA-CSSA-SSSA. 677 S. Segoe Rd . Madison. WI 53711, 1-27.

TERAN, H. & SINGH, S.P., 2002. Selection for drought resistance in early generations of common bean populations. *Canadian J. of Plant Sci.* 82,491-497.

TEZARA, W., MITCHELL, V.J., DRISCOLL, S.D. & LAWLOR, D.W., 1999. Water stress inhibits plant photosynthesis by decreasing coupling factor and ATP. *Nature*, 401, 914-917.

THOMAS, H. & STODDART, J.L., 1980. Leaf senescence. *Annu. Rev. Plant Physiol*. 31, 83-111.

THORNLEY, J.H.M. & FRANCE, J., 2007. Mathematical models in Agriculture: Quantitative methods for the plant, animal and ecological sciences. CABI, Wallingford, UK. pp. 7-8.

UCAR, Y., KADAYIFCI, A., YILMAZ, H.I., TUYLU, G.I. & YARDIMCI, N., 2009. The effect of deficit irrigation on the grain yield of dry bean. Span. J. Agric. Res. 7, 474-485.

ÜNLÜ, M., KANBER, R., SENYIGIT, U., ONARAN, H. & DIKER, K., 2006. Trickle and sprinkler irrigation of potato (*Solanum tuberosum* L.) in the middle Anatolian region in Turkey. *Agr. Water Manage*. 79, 43–71.

UPRETY, D.C. & BHATIS, R., 1989. Effect of water stress on the photosynthesis, productivity and water status of mungbean (*Vigna radiate* L. Wilczek) *J. Agron. Crop Sci.* 163, 115-123.

VAN DER GELUK, T., 2006. Water conservation fact sheet. Irrigation scheduling techniques. British Columbia Ministry of Agriculture and Lands. No. 577.100-1.

VAN KOOTEN, O. & SNEL, J.F.H., 1990. The use of chlorophyll fluorescence nomenclature in plant stress physiology. *Photosynth. Res.* 25, 147–150.

VARGA, M. & CROSSA, J., 2000. The AMMI analysis and graphing the biplot. Biometrics and Statistics Unit. CIMMYT.

VASSILEV, A. & MANOLOV, P., 1999. Chlorophyll fluorescence of barley (*H.vulgare* L.) seedlings grown in excess of Cd. *Bulg. J. Plant Physiol.* 25, 67-76.

VAZIFEDOUST, M., VAN DAM, J.C., FEDDES, R.A., FEIZI, M., 2008. Increasing water productivity of irrigated crops under limited water supply at field scale. *Agric. Water Manage*. 95, 89–102.

VERHOEVEN, A.S., DEMMIG-ADAMS, B. & ADAMS, B.B., 1997. Enhanced employment of the xanthophylls cycle and thermal energy dissipation in spinach exposed to high light and N stress. *Plant Physiol*. 113, 817-824.

WAHAB, M.N.J., DABBS, D.H. & BAKER, R.J., 1986. Effects of planting density and design on pod yield of bush snap bean (*Phaseolus vulgaris* L.). *Can. J. Plant Sci*. 669-675.

WAKRIM, R., WAHBI, S., TAHI, H., AGANCHICH, B., SERRAJ, R., 2005. Comparative effects of partial root drying (PRD) and regulated deficit irrigation (RDI) on water relations and water use efficiency in common bean (*Phaseolus vulgaris* L.). *Agr. Ecosyst. Environ*. 106, 275–287.

WALLACE, D.H., OZBUM, J.L. & MUNGER, H.M., 1972. Physiological genetics of crop yield. *Adv. Agron*. 24, 97-146.

WASKOM, R.M., 1994. Best irrigation management practices for irrigation management. Colorado State University Cooperative Extension. Bulletin No. XCM-173.

WEBBER, H. A., MADRAMOOTOO, C.A., BOURGAULT, M., HORST, M.G., STULINA, G. & SMITH, D.L., 2006. Water use efficiency of common bean and green gram grown using alternate furrow and deficit irrigation. *Agric. Water Manage*. 86, 259–268.

WEIN, H.C., SANDSTED, R.F. & WALLACE, D.H., 1973. The influence of flower removal on growth and seed yield of *Phaseolus vulgaris* L. *J. Am. Soc. Hortic. Sci*. 98, 45-49.

WESTERMANN, D.T. & CROTHERS, S.E., 1977. Plant population effects on the seed yield components of beans. *Crop Sci.* 17, 493-496.

WHISLER, F.D., ACOCK, B., BAKER, D.N., FYE, R.E., HODGES, H.F., LAMBERT, J.R., LEMMON, H.E., MCKINION, J.M. & REDDY, V.R., 1986. Crop simulation models in agronomic systems. *Adv. Agron*. 40, 141-208.

WHITFIELD, D.M., CONNER, D.J. & HALL, A.J., 1989. Carbon dioxide balance of sunflower (*Helianthus annuus* L.) subjected to water stress during grain filling. *Field Crops Res*. 20, 65-80.

WILLMOTT, C.J., 1982. Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.* 64, 1309-1313.

YAN, W., 2001. GGE biplot–A Windows application for graphical analysis of multi-environment trial data and other types of two-way data. *Agron J.* 93, 1111-1118.

YAN, W., 2002. Singular value partitioning in biplot analysis of multi-environment trial data. *Agron J*. 94, 990-996.

YAN, W. & HUNT, L.A., 2001. Interpretation of genotype x environment interaction for winter wheat yield in Ontario. *Crop Sci*. 41, 19-25.

YAN, W., HUNT, L.A., SHENG, Q., SZLAVNICS, Z., 2000. Cultivar evaluation and mega environment investigation based on the GGE biplot. *Crop Sci*. 40, 597-605.

YAN, W. & KANG, M.S., 2003. GGE Biplot Analysis: A Graphical Tool for Breeders, Geneticists and Agronomists. 1st Edn. CRC Press LLC., Boca Roton, Florida. pp 271.

YAN, W. & RAJCAN, I. 2002. Biplot analysis of test sites and trait relations of soybean in Ontario. *Crop Sci*. 42, 11-20.

YAN. W. & TINKER, N.A., 2006. Biplot analysis of multi-environment trial data: Principles and applications. *Can. J. Plant Sci*. 86, 623-645.

YATES, F., & COCHRAN, W. G. 1938. The analysis of groups of experiments. J. Agric. Sci. 28, 556-580.

YAU, S.K., 1995. Regression and AMMI analysis of genotype x environment interactions: an empirical comparison. *Agron. J.* 80, 388-393.

YORDANOV, I., TSONEV, T., VELIKOVA, V., GEORGIEVA, K., INANOV, P., TSENOV, N. & PETROVA, T., 2001. Changes in CO_2 assimilation, transpiration and stomatal resistance of different wheat cultivars experiencing drought under field conditions. *Bulg. J. of Plant Physiol. 27,* 20-33*.*

YU, D.J., KIM, S.J. & LEE, H.J., 2009. Stomatal and non-stomatal limitations to photosynthesis in field-grown grapevine cultivars. *Biol. Plant*. 53, 133-137.

ZAPATA, N., CHALGAF, I., NERILLI, E., LATORRE, B., LOPEZ, C., MARTINEZ-COB, A., GIRONA, J. & PLAYAN, E., 2012. Software for on-farm irrigation scheduling of stone fruit orchards under water limitations. *Comput. Elect. Agric*. 88, 52–62.

ZHANG, V., VU, Q., LIU, C., JIANG, J. & ZHANG, X., 2004. Estimation of winter wheat evapo-transpiration under water stress with the semi empirical approaches. *Agron. J.* 96,159-168.

ZISKA, L.H. & HALL, A.E. 1983. Seed yields and water use of cowpeas (*Vigna unguiculata* L. Walp.) subjected to planned water deficit irrigation. *Irrigation Sci.* 3: 237-245.

ZLATEV, Z., & STOYANOV, Z., 2005. Effects of water stress on leaf water relations of young bean plants. *J. Central Eur. Agric.* 6, 5-14.

ZLATEV, Z.S., & YORDANOV, I.T., 2004. Effects of soil drought on photosynthesis and chlorophyll fluorescence in bean plants. *Bulg. J. of Plant Physiol*. 30, 3-18.

ZOBEL, R.W., WRIGHT, M.J. & GAUCH, H.G., 1988. Statistical analysis of yield trial. *Agron. J.* 80, 388-393.

ANNEXURES

ANNEXURE A: EVALUATION OF VARIETY X ENVIRONMENT INTERACTION USING GGE-BIPLOT ON DRY BEAN

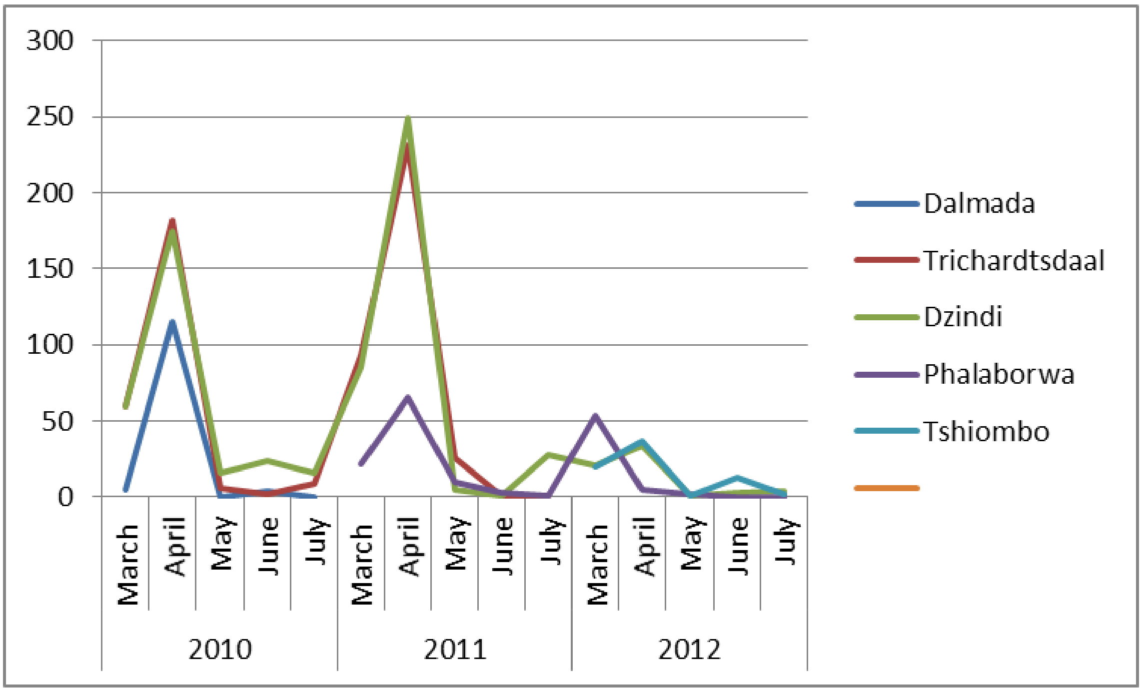


Figure 1 Rainfall data for all the locations from 2010-2012

Table 1 Irrigation data of all the locations

Location	**Irrigation**		
	2010	**2011**	**2012**
Dalmada	410	-	-
Dzindi Irrigation Scheme	360	400	420
Trichardtsdal	210	200	-
Phalaborwa	-	400	410
Tshiombo	-	-	405

ANNEXURE B: EFFECT OF PLANT POPULATION AND DRY BEAN VARIETIES ON DRY BEAN PRODUCTION

Experiment 1

Table 1 ANOVA table for number of pods plant^{-1}

Source	DF	SS	MS	F Value	Pr > F
Variety	2	0.12518519	0.06259259	0.05	0.9482
Plant population	2	16.7829629	8.39148148	7.15	0.0060
Replication	2	21.7918518	10.8959259	9.28	0.0021
Plant population*variety	4	0.33037037	0.08259259	0.07	0.9901
Error	16	18.7814814	1.17384259		
Corrected Total	26	57.8118518			

Table 2 ANOVA table for seeds per pod

Source	DF	SS	MS	F Value	Pr > F
Variety	2	0.51851852	0.25925926	1.37	0.2834
Plant population	2	0.07407407	0.03703704	0.20	0.8247
Replication	2	0.29629630	0.14814815	0.78	0.4749
Plant population*variety	4	0.14814815	0.03703704	0.20	0.9374
Error	16	3.03703704	0.18981481		
Corrected Total	26	4.07407407			

Table 3 ANOVA table for plant height

Source	DF	SS	MS	F Value	Pr > F
Variety	2	203.969629	101.984814	12.90	0.0005
Plant population	2	25.8696296	12.9348148	1.64	0.2256
Replication	2	2.4762963	1.2381481	0.16	0.8563
Plant population*variety	4	9.7481481	2.4370370	0.31	0.8682
Error	16	126.450370	7.9031481		
Corrected Total	26	368.514074			

Table 4 ANOVA table for shelling %

Source	DF	SS	MS	F Value	Pr > F
Variety	2	4.9629630	2.4814815	0.10	0.9009
Plant population	2	44.7407407	22.3703704	0.95	0.4088
Replication	2	3.8518519	1.9259259	0.08	0.9221
Plant population*variety	4	139.037037	34.7592593	1.47	0.2574
Error	16	378.148148	23.6342593		
Corrected Total	26	570.740740			

Table 5 ANOVA table for grain yield ha^{-1}

Source	DF	SS	MS	F Value	Pr > F
Replication	2	0.18918489	0.09459244	3.80	0.0527
Plant population	2	1.01168422	0.50584211	20.31	0.0001
Plant population *replication	4	0.35221022	0.08805256	3.54	0.0397
Variety	2	0.24976156	0.12488078	5.01	0.0261
Plant population*variety	4	0.18692689	0.04673172	1.88	0.1794
Error	12	0.29886822	0.02490569		
Corrected Total	26	2.28863600			

Table 6 ANOVA table for yield plant^{-1}

Source	DF	SS	MS	F Value	Pr > F
Replication	2	12.9062334	6.4531167	2.23	0.1498
Plant population	2	298.755969	149.377984	51.69	<.0001
Plant population*replication	4	34.9963641	8.7490910	3.03	0.0610
Variety	2	24.1443134	12.0721567	4.18	0.0420
Plant population*variety	4	15.8507741	3.9626935	1.37	0.3011
Error	12	34.6760811	2.8896734		
Corrected Total	26	421.329735			

Table 7 ANOVA table for 100 seed weight

Source	DF	SS	MS	F Value	Pr > F
Replication	1	0.055555	0.055555	0.00	0.9527
Plant population	2	206.777777	103.388888	7.13	0.0260
Plant population*replication	2	1.444444	0.722222	0.05	0.9518
Variety	2	40.111111	20.0555556	1.38	0.3206
Plant population*variety	4	9.555555	2.3888889	0.16	0.9487
Error	6	87.000000	14.500000		
Corrected Total	17	344.944444			

Experiment 2

Table 8 ANOVA table for yield per hectare

Source	DF	SS	MS	F Value	Pr > F
Replication	2	0.22202844	0.11101422	1.93	0.2253
Plant population	2	1.74831078	0.87415539	15.20	0.0045
Plant population *replication	4	0.13999356	0.03499839	0.61	0.6717
Variety	1	0.58248022	0.58248022	10.13	0.0190
Plant population*variety	2	0.61062544	0.30531272	5.31	0.0471
Error	6	0.34503933	0.05750656		
Corrected Total	17	3.64847778			

Table 9 ANOVA table for number of pods plant^{-1}

Source	DF	SS	MS	F Value	Pr > F
Replication	2	1.5613778	0.7806889	0.97	0.4309
Plant population	2	108.3547111	54.1773556	67.44	<.0001
Plant population *replication	4	0.3614222	0.0903556	0.11	0.9735
Variety	1	0.4293556	0.4293556	0.53	0.4923
Plant population*variety	2	3.6627111	1.8313556	2.28	0.1835
Error	6	4.8201333	0.8033556		
Corrected Total	17	119.1897111			

Table 10 ANOVA table for number of seeds plant^{-1}

Source	DF	SS	MS	F Value	Pr > F
Replication	2	37.367778	18.683889	1.86	0.2352
Plant population	2	1367.467778	683.733889	68.06	<.0001
Plant population *replication	4	31.902222	7.975556	0.79	0.5699
Variety	1	63.845000	63.845000	6.36	0.0452
Plant population*variety	2	5.143333	2.571667	0.26	0.7822
Error	6	60.276667	10.046111		
Corrected Total	17	1566.002778			

Table 11 ANOVA table for plant height at 30 DAP

Source	DF	SS	MS	F Value	Pr > F
Replication	2	12.96454444	6.48227222	0.49	0.6356
Plant population	2	28.98111111	14.4905555	1.09	0.3936
Plant population *replication	4	77.64995556	19.4124888	1.47	0.3213
Variety	1	4.80500000	4.80500000	0.36	0.5691
Plant population*variety	2	62.70333333	31.3516666	2.37	0.1747
Error	6	79.4911667	13.2485278		
Corrected Total	17	266.5951111			

Table 12 ANOVA table for plant height at 62 DAP

Source	DF	SS	MS	F Value	Pr > F
Replication	2	42.3996333	21.1998167	2.81	0.1378
Plant population	2	175.5833333	87.7916667	11.63	0.0086
Plant population *replication	4	173.1197333	43.2799333	5.73	0.0301
Variety	1	159.0138889	159.013888	21.07	0.0037
Plant population*variety	2	425.1944444	212.597222	28.17	0.0009
Error	6	45.289367	7.548228		
Corrected Total	17	1020.600400			

Table 13 ANOVA table for plant height at 98 DAP

Source	DF	SS	MS	F Value	Pr > F
Replication	2	39.956078	19.978039	0.99	0.4264
Plant population	2	2189.52778	1094.763889	54.01	0.0001
Plant population *replication	4	59.247422	14.811856	0.73	0.6028
Variety	1	174.222222	174.222222	8.60	0.0262
Plant population*variety	2	595.194444	297.597222	14.68	0.0049
Error	6	121.610833	20.268472		
Corrected Total	17	3179.75878			

Table 14 ANOVA table for chlorophyll content at 30 DAP

Source	DF	SS	MS	F Value	Pr > F
Replication	2	0.73107778	0.36553889	0.28	0.7623
Plant population	2	16.09734444	8.04867222	6.26	0.0341
Plant population *replication	4	4.29875556	1.07468889	0.84	0.5494
Variety	1	2.96055556	2.96055556	2.30	0.1801
Plant population*variety	2	10.84981111	5.42490556	4.22	0.0719
Error	6	7.72003333	1.28667222		
Corrected Total	17	42.65757778			

Table 15 ANOVA table for chlorophyll content at 62 DAP

Source	DF	SS	MS	F Value	Pr > F
Replication	2	6.4410778	3.2205389	0.51	0.6229
Plant population	2	223.409677	111.7048389	17.78	0.0030
Plant population *replication	4	15.7529556	3.9382389	0.63	0.6609
Variety	1	48.6426722	48.6426722	7.74	0.0319
Plant population*variety	2	315.281011	157.6405056	25.10	0.0012
Error	6	37.6893667	6.2815611		
Corrected Total	17	647.216761			

Table 16 ANOVA table for chlorophyll content at 98 DAP

Source	DF	SS	MS	F Value	Pr > F
Replication	1	0.38520833	0.38520833	0.13	0.7406
Plant population	2	26.92625000	13.4631250	4.61	0.1217

Plant population *replication	2	45.92791667	22.9639583	7.86	0.0641
Variety	1	80.34187500	80.3418750	27.50	0.0135
Plant population*variety	2	36.91625000	18.4581250	6.32	0.0840
Error	3	8.7631250	2.9210417		
Corrected Total	11	199.2606250			

Table 17 ANOVA table for 100 seed weight

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Replication	2	107.732811	53.866406	1.29	0.3417
Plant population	2	2705.93641	1352.968206	32.43	0.0006
Plant population *replication	4	1134.20826	283.552064	6.80	0.0204
Variety	1	1980.51200	1980.512006	47.47	0.0005
Plant population*variety	2	484.751944	242.375972	5.81	0.0395
Error	6	250.322400	41.720400		
Corrected Total	17	6663.46382			

Table 18 ANOVA table for yield plant^{-1}

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Replication	2	0.238900	0.119450	1.14	0.3814
Plant population	2	2712.39910	1356.199550	12906.6	<.0001
Plant population *replication	4	0.378100	0.094525	0.90	0.5190
Variety	1	72.000000	72.000000	685.21	<.0001
Plant population*variety	2	106.806233	53.403117	508.22	<.0001
Error	6	0.630467	0.105078		
Corrected Total	17	2892.45280			

Table 19 ANOVA table for dry matter at 30 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Replication	2	0.01634444	0.00817222	1.05	0.4063
Plant population	2	0.94289144	0.47144572	60.60	0.0001
Plant population *replication	4	0.04444556	0.01111139	1.43	0.3311
Variety	1	0.03493606	0.03493606	4.49	0.0784
Plant population*variety	2	0.27135478	0.13567739	17.44	0.0032
Error	6	0.04667467	0.00777911		
Corrected Total	17	1.35664694			

Table 20 ANOVA table for dry matter at 62 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Replication	2	0.49739233	0.24869617	5.01	0.0526
Plant population	2	14.18079633	7.09039817	142.76	<.0001

Plant population *replication	4	0.41769733	0.10442433	2.10	0.1986
Variety	1	0.75809089	0.75809089	15.26	0.0079
Plant population*variety	2	2.03175411	1.01587706	20.45	0.0021
Error	6	0.29799500	0.04966583		
Corrected Total	17	18.18372600			

Table 21 ANOVA table for dry matter at 98 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Replication	2	0.51156578	0.25578289	2.96	0.1277
Plant population	2	17.16235244	8.58117622	99.23	<.0001
Plant population *replication	4	0.43770956	0.10942739	1.27	0.3787
Variety	1	2.46198050	2.46198050	28.47	0.0018
Plant population*variety	2	1.23382800	0.61691400	7.13	0.0259
Error	6	0.51887400	0.08647900		
Corrected Total	17	22.32631028			

ANNEXURE C: EFFECT OF DEFICIT IRRIGATION

Table 1 ANOVA table for plant height

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	2	1.7150000	0.8575000	0.55	0.6032
Stress levels	3	155.3425000	51.7808333	33.25	0.0004
Error	6	9.3450000	1.5575000		
Corrected Total	11	166.4025000			

Table 2ANOVA table for number of seeds per plant

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	2	123.62	61.81	8.77	0.0166
Stress levels	3	2955.39	985.13	139.71	<.0001
Error	6	42.30	7.05		
Corrected Total	11	3121.32			

Table 3 ANOVA table for number of pods per plant

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	2	9.78	4.89	9.85	0.0127
Stress levels	3	199.30	66.43	133.76	<.0001
Error	6	2.98	0.497		
Corrected Total	11	212.06			

Table 4 ANOVA table for 100 seed weight

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	2	26.64	13.32	0.43	0.6686
Stress levels	3	229.91	76.63	2.48	0.1586
Error	6	185.52	30.92		
Corrected Total	11	442.08			

Table 5 ANOVA table for shelling %

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	2	24.67	12.33	0.50	0.6297
Stress levels	3	72.25	24.08	0.98	0.4637
Error	6	148.00	24.67		
Corrected Total	11	244.91			

Table 6 ANOVA table for grain yield

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	2	0.195	0.098	1.21	0.3608
Stress levels	3	5.313	1.771	22.01	0.0012
Error	6	0.482	0.080		
Corrected Total	11	5.992			

Table 7 ANOVA table for irrigation amount

Source	DF	SS	MS	F Value	Pr > F
Block	2	126.15	63.07	2.12	0.2008
Stress levels	3	4524.18	1508.06	50.77	0.0001
Error	6	178.23	29.70		
Corrected Total	11	4828.57			

ANNEXTURE D: EFFECT OF DROUGHT STRESS

Table 1 ANOVA table for leaf dry matter at 48 DAP

Source	DF	SS	MS	F Value	Pr > F
Block	5	0.04855975	0.00971195	1.23	0.4124

Stress levels	1	0.55513008	0.55513008	70.39	0.0004
Error	5	0.03943042	0.00788608		
Corrected Total	11	0.64312025			

Table 2 ANOVA table for stem dry matter at 48 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.06889067	0.01377813	2.34	0.1862
Stress levels	1	0.35914800	0.35914800	60.98	0.0006
Error	5	0.02944600	0.00588920		
Corrected Total	11	0.45748467			

Table 3 ANOVA table for total dry matter at 48 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.18099542	0.03619908	2.05	0.2255
Stress levels	1	1.80730408	1.80730408	102.12	0.0002
Error	5	0.08848942	0.01769788		
Corrected Total	11	2.07678892			

Table 4 ANOVA table for leaf dry matter at 64 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.09168938	0.01833788	2.10	0.1216
Stress levels	3	0.73237113	0.24412371	28.00	<.0001
Error	15	0.13080013	0.00872001		
Corrected Total	23	0.95486063			

Table 5 ANOVA table for stem dry matter at 64 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.08287971	0.01657594	2.12	0.1193
Stress levels	3	0.46662013	0.15554004	19.89	<.0001
Error	15	0.11730413	0.00782028		
Corrected Total	23	0.66680396			

Table 6 ANOVA table for total dry matter at 64 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.09408837	0.01881767	1.61	0.2169
Stress levels	3	2.35332246	0.78444082	67.20	<.0001
Error	15	0.17508679	0.01167245		
Corrected Total	23	2.62249762			

Table 7 ANOVA table for leaf dry matter at 92 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.07941550	0.01588310	4.50	0.0066
Stress levels	4	2.64864187	0.66216047	187.54	<.0001
Error	20	0.07061533	0.00353077		
Corrected Total	29	2.79867270			

Table 8 ANOVA table for stem dy matter at 92 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.03698320	0.00739664	1.11	0.3883

Stress levels	4	2.01814353	0.50453588	75.44	<.0001
Error	20	0.13375447	0.00668772		
Corrected Total	29	2.18888120			

Table 9 ANOVA table for pods dry matter at 92 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.00466750	0.00093350	1.02	0.4346
Stress levels	4	0.99174500	0.24793625	269.72	<.0001
Error	20	0.01838500	0.00091925		
Corrected Total	29	1.01479750			

Table 10 ANOVA table for total dry matter at 92 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.14871630	0.02974326	2.50	0.0653
Stress levels	4	15.70725013	3.92681253	329.42	<.0001
Error	20	0.23840587	0.01192029		
Corrected Total	29	16.09437230			

Table 11 ANOVA table for leaf area index at 48 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.83186142	0.16637228	0.48	0.7796
Stress levels	1	5.58831008	5.58831008	16.15	0.0101
Error	5	1.72974742	0.34594948		
Corrected Total	11	8.14991892			

Table 12 ANOVA table for leaf area index at 64 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.08016171	0.01603234	1.51	0.2451
Stress levels	3	3.60666312	1.20222104	113.25	<.0001
Error	15	0.15923613	0.01061574		
Corrected Total	23	3.84606096			

Table 13 ANOVA table for leaf area index 92 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	0.02550750	0.00510150	0.35	0.8742
Stress levels	4	1.65862847	0.41465712	28.70	<.0001
Error	20	0.28894633	0.01444732		
Corrected Total	29	1.97308230			

Table 14 ANOVA table for number of pods per plant

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Block	5	8.54966667	1.70993333	2.98	0.0363
Stress levels	4	19.02866667	4.75716667	8.28	0.0004
Error	20	11.49533333	0.57476667		
Corrected Total	29	39.07366667			

Table 15 ANOVA table for number of seeds per plant

Source	DF	SS	MS	F Value	Pr > F
Block	5	118.7200000	23.7440000	2.47	0.0678
Stress levels	4	235.9866667	58.9966667	6.13	0.0022
Error	20	192.5933333	9.6296667		
Corrected Total	29	547.3000000			

Table 16 ANOVA table for 100 seed weight

Source	DF	SS	MS	F Value	Pr > F
Block	5	44.3744267	8.8748853	1.33	0.2926
Stress levels	4	231.2321467	57.8080367	8.65	0.0003
Error	20	133.6453733	6.6822687		
Corrected Total	29	409.2519467			

Table 17 ANOVA table for shelling %

Source	DF	SS	MS	F Value	Pr > F
Block	5	925.4666667	185.0933333	1.14	0.3702
Stress levels	4	848.2000000	212.0500000	1.31	0.3000
Error	20	3236.200000	161.810000		
Corrected Total	29	5009.866667			

Table 18 ANOVA table for seed yield hectare^{-1}

Source	DF	SS	MS	F Value	Pr > F
Block	5	0.47106857	0.09421371	0.59	0.7094
Stress levels	4	7.15946033	1.78986508	11.16	<.0001
Error	20	3.20638327	0.16031916		
Corrected Total	29	10.83691217			

Table 19 ANOVA table for water use

Source	DF	SS	MS	F Value	Pr > F
Block	5	427.2147	85.4429	0.57	0.7237
Stress levels	4	120299.6964	30074.9241	199.86	<.0001
Error	20	3009.5613	150.4781		
Corrected Total	29	123736.4725			

Table 20 ANOVA table for water use efficiency

Source	DF	SS	MS	F Value	Pr > F
Block	5	6.2601246	1.2520249	0.79	0.5693
Stress levels	4	165.7440035	41.4360009	26.14	<.0001
Error	20	31.7048533	1.5852427		
Corrected Total	29	203.7089814			

ANNEXURE E: EFFECT OF DROUGHT STRESS ON DRY BEAN PHYSIOLOGY

Table 1 ANOVA table for chlorophyll content at 48 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	1	6.81013333	6.81013333	119.62	0.0001
Block	5	1.41826667	0.28365333	4.98	0.0513
Error	5	0.28466667	0.05693333		

Corrected Total	11	8.51306667			

Table 2 ANOVA table for chlorophyll content at 53 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Stress levels	1	3.56409000	3.56409000	23.09	0.0086
Block	4	0.68596000	0.17149000	1.11	0.4606
Error	4	0.61736000	0.15434000		
Corrected Total	9	4.86741000			

Table 3 ANOVA table for chlorophyll content at 61 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Stress levels	3	18.54951875	6.18317292	16.30	0.0006
Block	3	0.09886875	0.03295625	0.09	0.9655
Error	9	3.41450625	0.37938958		
Corrected Total	15	22.06289375			

Table 4 ANOVA table for chlorophyll content at 77 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Stress levels	3	139.7049333	46.5683111	132.46	<.0001
Block	5	1.5139333	0.3027867	0.86	0.5290
Error	15	5.2734667	0.3515644		
Corrected Total	23	146.4923333			

Table 5 ANOVA table for chlorophyll content at 80 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Stress levels	3	84.07725000	28.02575000	34.09	<.0001
Block	5	1.68548333	0.33709667	0.41	0.8345
Error	15	12.33225000	0.82215000		
Corrected Total	23	98.09498333			

Table 6 ANOVA table for chlorophyll content at 89 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Stress levels	4	304.3144533	76.0786133	74.50	<.0001
Block	5	4.0555867	0.8111173	0.79	0.5664
Error	20	20.4247467	1.0212373		
Corrected Total	29	328.7947867			

Table 7 ANOVA table for chlorophyll content at 104 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Stress levels	4	206.6572000	51.6643000	190.57	<.0001
Block	5	0.7244267	0.1448853	0.53	0.7478
Error	20	5.4220400	0.2711020		
Corrected Total	29	212.8036667			

Table 8 ANOVA table for photosynthesis at 63 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	213.4929271	71.1643090	45.32	<.0001
Block	5	31.2558922	6.2511784	3.98	0.0169
Error	15	23.5514809	1.5700987		
Corrected Total	23	268.3003002			

Table 9 ANOVA table for photosynthesis at 100 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	4	72.57876720	18.1446918	9.06	0.0002
Block	5	26.74614747	5.34922949	2.67	0.0524
Error	20	40.0360032	2.0018002		
Corrected Total	29	139.3609179			

Table 10 ANOVA table for photosynthesis at 105 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	2	42.39834444	21.1991722	115.66	<.0001
Block	5	3.27037778	0.65407556	3.57	0.0412
Error	10	1.83285556	0.18328556		
Corrected Total	17	47.50157778			

Table 11 ANOVA table for intercellular carbon dioxide concentration (Ci) at 63 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	3239.707746	1079.902582	8.28	0.0017
Block	5	1813.432335	362.686467	2.78	0.0570
Error	15	1957.029145	130.468610		
Corrected Total	23	7010.169226			

Table 12 ANOVA table for intercellular carbon dioxide concentration (Ci) at 100 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	4	7064.01868	1766.004672	5.11	0.0053
Block	5	4192.06370	838.412741	2.43	0.0711
Error	20	6908.7415	345.43708		
Corrected Total	29	18164.8239			

Table 13 ANOVA table for intercellular carbon dioxide concentration (Ci) at 105 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	2	732.296844	366.1484222	20.08	0.0003
Block	5	24.723894	4.9447789	0.27	0.9187
Error	10	182.309488	18.2309489		
Corrected Total	17	939.330227			

Table 14 ANOVA table for stomatal conductance (g_s) at 63 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	0.22997562	0.07665854	11.81	0.0003
Block	5	0.09830373	0.01966075	3.03	0.0436
Error	15	0.09733790	0.00648919		
Corrected Total	23	0.42561724			

Table 15 ANOVA table for stomatal conductance (g_s) at 100 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	4	0.02104313	0.00526078	3.85	0.0177
Block	5	0.01800377	0.00360075	2.64	0.0549
Error	20	0.02732407	0.00136620		
Corrected Total	29	0.06637097			

Table 16 ANOVA table for stomatal conductance (g_s) at 105 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	2	0.00907433	0.00453717	7.09	0.0121
Block	5	0.00073117	0.00014623	0.23	0.9415
Error	10	0.00639500	0.00063950		
Corrected Total	17	0.01620050			

Table 17 ANOVA table for transpiration at 63 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	12.87393251	4.29131084	10.50	0.0006
Block	5	6.54521712	1.30904342	3.20	0.0364
Error	15	6.12837866	0.40855858		
Corrected Total	23	25.54752828			

Table 18 ANOVA table for transpiration at 100 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	4	3.36869087	0.84217272	5.09	0.0054
Block	5	0.84384800	0.16876960	1.02	0.4322
Error	20	3.30901233	0.16545062		
Corrected Total	29	7.52155120			

Table 19 ANOVA table for transpiration at 105 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	2	0.96045733	0.48022867	3.57	0.0676
Block	5	0.52182250	0.10436450	0.78	0.5886
Error	10	1.34497867	0.13449787		
Corrected Total	17	2.82725850			

Table 20 ANOVA table for minimal chlorophyll fluorescence (f_0) at 52 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	1009.621419	336.540473	59.24	<.0001
Block	3	14.567619	4.855873	0.85	0.4986
Error	9	51.125206	5.680578		
Corrected Total	15	1075.314244			

Table 21 ANOVA table for minimal chlorophyll fluorescence (f_0) at 93 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	533.066818	177.688939	4.75	0.0299
Block	3	372.782468	124.260822	3.32	0.0706
Error	9	336.841356	37.426817		
Corrected Total	15	1242.69064			

Table 22 ANOVA table for minimal chlorophyll fluorescence (f_0) at 100 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	829.8023188	276.600772	33.84	<.0001
Block	3	9.5433687	3.1811229	0.39	0.7637
Error	9	73.5690063	8.1743340		
Corrected Total	15	912.9146938			

Table 23 ANOVA table for maximal chlorophyll fluorescence (f_m) at 52 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	147351.1593	49117.0531	563.65	<.0001
Block	3	153.7160	51.2387	0.59	0.6380
Error	9	784.2669	87.1408		
Corrected Total	15	148289.1421			

Table 24 ANOVA table for maximal chlorophyll fluorescence (f_m) at 93 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	46181.2849	15393.761	4.94	0.0269
Block	3	9285.55282	3095.1842	0.99	0.4389
Error	9	28042.4679	3115.8297		
Corrected Total	15	83509.3056			

Table 25 ANOVA table for maximal chlorophyll fluorescence (f_m) at 100 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	75327.10822	25109.03607	6375.44	<.0001
Block	3	82.72277	27.57426	7.00	0.0100
Error	9	35.44561	3.93840		
Corrected Total	15	75445.27659			

Table 26 ANOVA table for minimal chlorophyll fluorescence (F_v/F_m) at 52 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	0.09253419	0.03084473	14.06	0.0010
Block	3	0.00491869	0.00163956	0.75	0.5506
Error	9	0.01974106	0.00219345		
Corrected Total	15	0.11719394			

Table 27 ANOVA table for minimal chlorophyll fluorescence (F_v/F_m) at 93 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	0.08962625	0.02987542	121.93	<.0001
Block	3	0.00014225	0.00004742	0.19	0.8982
Error	9	0.00220525	0.00024503		
Corrected Total	15	0.09197375			

Table 28 ANOVA table for minimal chlorophyll fluorescence (F_v/F_m) at 100 DAP

Source	DF	SS	MS	F Value	Pr > F
Stress levels	3	0.05420919	0.01806973	11.25	0.0021
Block	3	0.01608919	0.00536306	3.34	0.0697
Error	9	0.01445256	0.00160584		
Corrected Total	15	0.08475094			

Table 31 ANOVA table for coefficient of photochemical quenching (Q_p) at 93 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Stress levels	3	0.00436419	0.00145473	2.49	0.1268
Block	3	0.00348569	0.00116190	1.99	0.1868
Error	9	0.00526656	0.00058517		
Corrected Total	15	0.01311644			

Table 32 ANOVA table for coefficient of photochemical quenching (Q_p) at 100 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Stress levels	3	0.00300225	0.00100075	9.22	0.0042
Block	3	0.00064475	0.00021492	1.98	0.1875
Error	9	0.00097675	0.00010853		
Corrected Total	15	0.00462375			

Table 33 ANOVA table for coefficient of non-photochemical quenching (Q_n) at 93 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Stress levels	3	0.04702319	0.01567440	37.76	<.0001
Block	3	0.00390769	0.00130256	3.14	0.0798
Error	9	0.00373606	0.00041512		
Corrected Total	15	0.05466694			

Table 34 ANOVA table for coefficient of non-photochemical quenching (Q_n) at 100 DAP

Source	**DF**	**SS**	**MS**	**F Value**	**Pr > F**
Stress levels	3	7.19999069	2.39999690	13.94	0.0010
Block	3	2.02143369	0.67381123	3.91	0.0485
Error	9	1.54978906	0.17219878		
Corrected Total	15	10.77121344			

ANNEXURE F: WEATHER DATA FOR GXE SITES

DALMADA					Mar-10							
DATE	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/03/2010	60	28.97	19.97	62.51	1.09	0	27.46	11.63	96.4	28.19	5.63	9.97
02/03/2010	61	25.17	23.65	55.96	2.09	0	32.68	10.92	97.8	21.03	5.63	13.65
03/03/2010	62	23.13	21.68	65.11	2.48	0	26.76	17.51	84.3	42.61	4.79	11.68
04/03/2010	63	15.76	19.78	77.35	1.42	0.25	24.44	16.36	96.2	54.69	3.14	9.78
05/03/2010	64	11.37	18.9	77.79	1.12	0	23.85	14	96.2	56.6	2.38	8.9
06/03/2010	65	25.21	20.37	63.66	1.88	0	25.48	14.32	95.2	40.67	4.81	10.37
07/03/2010	66	25.59	19.85	62.86	2.21	0	25.93	13.18	86.1	35.53	5.03	9.85
08/03/2010	67	17.93	19.76	61.42	1.11	0	27.38	12.49	91.8	31.37	3.69	9.76
09/03/2010	68	20.08	21.39	60.95	0.71	0	30.68	12.9	94.6	22.84	4.13	11.39
10/03/2010	69	23.05	23.41	57.31	1.01	0	32.58	12.83	96.8	19.06	4.89	13.41
11/03/2010	70	22.35	24.01	59.22	0.95	0	32.45	14.75	95.5	24.34	4.69	14.01
12/03/2010	71	24.34	26.18	55.74	1.05	0	35.42	17.02	93.7	22.13	5.35	16.18
13/03/2010	72	23.61	25.34	60.11	1.63	0	33.37	17.23	94.3	24.57	5.25	15.34
14/03/2010	73	20.52	23.04	67.87	1.92	0	29.53	18.61	89.1	41.22	4.5	13.04
15/03/2010	74	11.35	20.17	72.42	1.79	0	25.29	15.11	88.2	48.73	2.54	10.17
16/03/2010	75	18.46	21.58	65.99	0.83	0	29.26	13.66	97	33.87	3.8	11.58
17/03/2010	76	17.23	22.03	68.11	0.86	0	29.76	14.41	92.3	35.58	3.54	12.03
18/03/2010	77	23.19	20.76	76.15	1.77	1.52	25.37	17.2	94.7	55.79	4.37	10.76
19/03/2010	78	17.57	19.46	84.17	0.93	2.54	26.03	16.13	97.3	55.72	3.4	9.46
20/03/2010	79	15.62	22.09	70	0.92	0.25	28.81	15.79	97.5	38.02	3.26	12.09
21/03/2010	80	11.16	19.19	78.71	1.25	0	25.21	14.68	92.9	57.07	2.34	9.19
22/03/2010	81	10.42	19.23	78.51	0.39	0	24.83	13.41	97.7	55.13	2.13	9.23
23/03/2010	82	18.68	23.6	64.78	0.84	0	30.66	13.99	97.5	30.32	3.94	13.6
24/03/2010	83	15.45	20.77	74.08	1.01	0	26.66	16.5	96.4	47.79	3.19	10.77
25/03/2010	84	19.62	22.88	67.83	0.5	0.51	31.46	15.19	94.2	35.37	4.11	12.88

26/03/2010	85	20.71	24.53	61.31	1.24	0	31.18	15.6	96	30.83	4.61	14.53
27/03/2010	86	21.26	24.22	62.86	0.64	0	31.78	15.81	94	34.3	4.57	14.22
28/03/2010	87	12.26	22.7	72.33	1.3	0	30.12	17.24	93.1	40.4	2.91	12.7
29/03/2010	88	17.4	20.91	72.9	1.22	0	27.97	15.21	96.4	41.64	3.46	10.91
30/03/2010	89	16.71	23.16	62.61	0.59	0	30.92	12.79	97.9	30.66	3.59	13.16
31/03/2010	90	22.26	22.22	67.72	1.94	0	27.2	16.98	88.2	49.06	4.61	12.22
					Apr-10							
DATE	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/04/2010	91	10.61	21.45	73.76	1.22	0	25.54	17.32	91.3	55.15	2.46	11.45
02/04/2010	92	11.15	21.34	76.81	1.27	38.36	24.77	17.5	97.1	57.97	2.49	11.34
03/04/2010	93	8.93	20.16	83.63	0.58	3.81	23.9	16.91	97.3	64.03	1.85	10.16
04/04/2010	94	4.9	19.37	87.84	0.85	0.76	22.58	16.47	97.6	72.6	1.02	9.37
05/04/2010	95	10.53	19.66	83.04	0.78	7.37	24.44	17.8	96.9	53.75	2.13	9.66
06/04/2010	96	8.7	19.83	88.44	1.02	23.88	23.66	17.95	96.9	65.43	1.71	9.83
07/04/2010	97	16.96	22.54	69.93	0.81	0	28.16	17.1	96.5	45.62	3.43	12.54
08/04/2010	98	15.64	20.92	80.18	1.41	0	25.85	17.4	96.2	60.4	3.03	10.92
09/04/2010	99	13.18	21.84	77.36	0.99	0	25.17	17.66	95.7	54.92	2.66	11.84
10/04/2010	100	19.83	23.42	65.02	1.63	0	29.88	16.77	97.5	26.45	4.03	13.42
11/04/2010	101	14.32	17.49	78.95	2.2	0	21.47	15.02	92.4	60.86	2.61	7.49
12/04/2010	102	15.83	19.63	76.2	0.64	0	26.78	14.36	97.3	46.09	3.18	9.63
13/04/2010	103	14.72	17.14	79.74	0.97	0	22.92	11.13	97.5	59.65	2.75	7.14
14/04/2010	104	19.89	16.5	77.31	0.66	0	24.85	9.06	98.3	48.01	3.65	6.5
15/04/2010	105	17	19.76	65.56	0.49	0	27.76	8.78	98.2	26.66	3.29	9.76
16/04/2010	106	19.02	19.41	69.26	0.65	0	29.53	10.78	97.9	23.91	3.84	9.41
17/04/2010	107	17.93	19.51	76.13	0.89	0	26.9	12.63	97.5	39.4	3.49	9.51
18/04/2010	108	18.5	22.69	62.87	0.93	0	28.74	15.37	90	33.34	3.84	12.69
19/04/2010	109	9.31	18.89	83.12	0.69	22.35	25.42	15.35	97.5	56.5	1.79	8.89
20/04/2010	110	12.11	18.35	83.21	0.91	7.87	26.2	14.29	98	49.5	2.43	8.35
21/04/2010	111	15.23	15.59	83.63	1.26	0.51	20.1	12.02	97.4	60.99	2.58	5.59

22/04/2010	112	9.67	16.05	84.04	0.76	0	22.91	10.29	98.3	58.14	1.78	6.05
23/04/2010	113	16.68	15.93	79.31	2.44	0	20.59	11.32	98.5	62.31	2.79	5.93
24/04/2010	114	8.72	13.41	83.78	1.87	8.13	16.55	11.7	95.3	69.08	1.5	3.41
25/04/2010	115	3.58	13.23	89.4	0.72	1.78	14.14	12.54	93.5	84.2	0.7	3.23
26/04/2010	116	4.53	13.81	86.5	1.15	0.25	15.59	12.11	95.6	76	0.89	3.81
27/04/2010	117	5.57	14.84	86.01	1.19	0	16.48	13.04	91.3	80.2	1.02	4.84
28/04/2010	118	8.01	18.32	79.12	0.41	0	23.49	12.4	97.4	56.24	1.54	8.32
29/04/2010	119	17.48	20.03	60.51	0.91	0	26.37	12.3	98	26.02	3.48	10.03
30/04/2010	120	13.88	16.71	81.78	0.85	0	23.18	9.73	98.4	54.73	2.58	6.71
					May-10							
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/05/2010	121	14.32	18.76	73.75	0.58	0	26.03	11.4	98.8	39.61	2.79	8.76
02/05/2010	122	10.33	16.55	84.01	0.95	0	21.26	11.16	98.3	63.3	1.96	6.55
03/05/2010	123	15.77	17.48	77.67	0.57	0	25.34	9.38	98.7	45.62	2.97	7.48
04/05/2010	124	15.15	17.57	80.22	1.58	3.56	24.57	12.03	97.4	50.48	2.91	7.57
05/05/2010	125	16.44	17.77	73.09	0.95	0	26.35	10.19	98.4	31.47	3.47	7.77
06/05/2010	126	15.44	19.22	64.33	0.75	0	28.47	9.21	97.8	23.44	3.15	9.22
07/05/2010	127	9.11	18.68	73.53	0.42	0	26.62	13.46	93.4	36.06	1.91	8.68
08/05/2010	128	13.95	16.54	83.16	1.05	0	22.35	11.98	98.1	61.73	2.5	6.54
09/05/2010	129	15.08	20.26	68.63	1.11	0	26.89	10.58	98.3	42.68	3.09	10.26
10/05/2010	130	13.62	19.26	70.95	1.21	0	27.22	9.89	98.6	38.76	2.96	9.26
11/05/2010	131	16.84	19.15	61.65	1.28	0	27.25	10.17	97.5	28.83	3.68	9.15
12/05/2010	132	16.63	16.69	69.29	1.44	0	24.17	8.62	90.9	42.39	3.13	6.69
13/05/2010	133	8.55	14.9	86.56	1.02	0	18.73	9.24	98.5	72.3	1.5	4.9
14/05/2010	134	15.38	17.86	73.5	0.54	0	26.04	7.79	99.1	42.74	2.87	7.86
15/05/2010	135	12.48	17.89	72.17	1.82	0	26.38	7.34	99.1	35.23	2.51	7.89
16/05/2010	136	8.78	15.11	82.54	1.59	0	19.06	11.49	95.6	68.51	1.53	5.11
17/05/2010	137	12.41	14.03	76.5	1.58	0	18.2	7.07	98.6	56.49	2.21	4.03

18/05/2010	138	16.75	13.26	74.14	0.38	0	23.34	4.12	99.1	34.39	2.93	3.26
19/05/2010	139	13.44	14.67	71.9	0.77	0	24.47	3.82	99.4	31.51	2.51	4.67
20/05/2010	140	14.68	15.05	71.4	0.84	0	22.8	6.07	98.4	37.54	2.62	5.05
21/05/2010	141	12.68	16.03	74.74	1.21	0	21.24	10.53	96.5	53.77	2.32	6.03
22/05/2010	142	12.67	15.59	73.11	0.71	0	22.79	10.84	96.9	35.46	2.36	5.59
23/05/2010	143	15.92	13.24	67.83	0.39	0	23.23	4.99	98.7	27.13	2.8	3.24
24/05/2010	144	15.24	15.08	60.04	0.34	0	26.14	2.62	98.2	19.4	2.7	5.08
25/05/2010	145	13.46	15.9	63.85	0.43	0	26.9	3.5	98.2	18.29	2.5	5.9
					Jun-10							
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
02/06/2010	153	12.32	12.55	63.83	0.52	0	21.63	3.87	97.3	25.16	2.2	2.55
03/06/2010	154	12.46	9.79	74.59	0.51	0	20.22	0.11	99.4	34.49	4.36	-0.21
04/06/2010	155	14.78	10.93	68.47	0.57	0	21.61	1.1	99.3	30.78	2.56	0.93
05/06/2010	156	14.72	12.64	59.62	1	0	23.87	2.83	96.4	17.33	2.95	2.64
06/06/2010	157	16.1	14.83	58.85	0.71	0	25.68	0.92	98.8	15.66	2.91	4.83
07/06/2010	158	16.09	13.86	64.31	0.41	0	27.03	3.12	98.9	21.27	2.9	3.86
08/06/2010	159	11.19	14.05	59.43	0.68	0	27.68	2.37	99.4	13.28	2.29	4.05
09/06/2010	160	14.47	14.31	65.68	0.73	0	26.12	2.25	96.9	15.95	2.86	4.31
10/06/2010	161	15.85	13.43	78.46	1.81	0	18.64	6.95	97.7	53.58	2.59	3.43
11/06/2010	162	10.79	11.31	82.23	1.17	0	17.76	4.56	98.5	54.62	1.83	1.31
12/06/2010	163	14.38	12.27	76.15	0.74	0	21.57	4.5	98.6	41.42	2.52	2.27
13/06/2010	164	15.7	12.93	69.07	0.84	0	24.63	3.32	100	24.72	3.03	2.93
14/06/2010	165	15.98	12.5	63.95	1.32	0	25.15	2.8	98.6	20.67	3.51	2.5
15/06/2010	166	16.13	10.73	45.03	2.17	0	18.84	4.07	90.4	23.76	3.07	0.73
16/06/2010	167	16.65	5.77	51.74	0.67	0	16.47	-4.59	91.6	19.58	2.48	-4.23
17/06/2010	168	15.45	6.27	61.73	0.95	0	15.08	-3.17	97	32.87	2.42	-3.73
18/06/2010	169	16.38	8.83	60.31	1.21	0	16.21	-4.01	97.7	30.13	2.54	-1.17
19/06/2010	170	15.65	7.87	71.7	0.64	0	17.43	-1.12	98.5	36.54	2.47	-2.13
20/06/2010	171	14.59	11.64	55.05	0.87	0	20.02	-0.84	98.1	27.7	2.49	1.64

21/06/2010	172	15.22	8.62	63.5	0.7	0	20.62	-2.43	97.5	26.2	2.52	-1.38
22/06/2010	173	15.82	11.08	53.42	0.66	0	22.71	-1.8	99.7	12.58	2.8	1.08
23/06/2010	174	14.23	11.2	60.35	0.46	0	23.03	-1.13	98	20.91	2.55	1.2
24/06/2010	175	15.45	10.7	67.55	0.5	0	21.18	0.81	96.8	31.48	2.52	0.7
25/06/2010	176	15.01	12.67	52.02	0.84	0	23.81	0	98.8	15.26	2.87	2.67
26/06/2010	177	14.71	14.55	45.92	0.32	0	26.33	-1.12	98	13.25	2.54	4.55
27/06/2010	178	15.56	10.49	67.3	2.16	0	18.48	-0.65	90.3	44.85	2.69	0.49
28/06/2010	179	6.45	13.5	75.13	1.66	0	17.33	11.94	82.4	59.91	1.29	3.5
29/06/2010	180	8.19	13.34	80.02	1	0	16.49	11.06	90.7	62.95	1.43	3.34
30/06/2010	181	10.23	12.51	69.36	0.73	0	20.15	5.08	95.6	31.68	2.06	2.51
DATES						Jul-10						
01/07/2010	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
02/07/2010	182	12.35	13.94	65.23	2.01	0	19.9	7.32	86.5	39.16	2.35	3.94
03/07/2010	183	4.45	11.48	88.03	1.13	0	14.04	6.53	98.2	71.4	0.86	1.48
04/07/2010	184	14.08	10.95	73.27	0.66	0	20.79	2.63	99.6	29.94	2.39	0.95
05/07/2010	185	9.94	13.65	68.63	1.63	0	18.57	7.85	86.1	46.95	1.95	3.65
06/07/2010	186	15.63	13.32	72.49	1.16	0	19.49	6.43	97	45.47	2.67	3.32
07/07/2010	187	16.32	12.21	69.91	0.58	0	22.43	3.25	98.6	30.21	2.76	2.21
08/07/2010	188	13.98	11.17	73.53	1.25	0	21	2.06	98.2	38.95	2.49	1.17
09/07/2010	189	10.05	11.92	75.92	1.31	0	17.23	3.99	97.9	51.57	1.86	1.92
10/07/2010	190	16.41	10.06	72.91	0.49	0	20.47	1.1	99.6	34.37	2.72	0.06
11/07/2010	191	16.62	9.7	68.06	0.79	0	21.75	-0.08	99.6	28.3	2.99	-0.3
12/07/2010	192	16.67	11.16	58.08	1.31	0	22.68	1.31	95.4	20.74	3.38	1.16
13/07/2010	193	16.79	10.86	44.89	1.38	0	18.4	2.76	87.5	19.88	2.94	0.86
14/07/2010	194	16.32	8.57	66.84	1.19	0	15.76	0.19	99.2	36.02	2.55	-1.43
15/07/2010	195	16.37	8.15	75.78	0.97	0	17.78	-1.81	100	41.1	2.52	-1.85
16/07/2010	196	15.23	11.08	70.04	0.91	0	22.73	1.49	98.1	28.47	2.89	1.08
17/07/2010	197	17.68	9.47	41.01	2.04	0	17.23	-0.17	86.7	13.59	3.17	-0.53
18/07/2010	198	17.32	7.82	54.33	0.51	0	20.35	-4.71	96.6	12.58	2.79	-2.18

19/07/2010	199	17.25	9.01	57.33	1.24	0	19.67	-2.57	90.8	24.19	3.15	-0.99
20/07/2010	200	11.73	9.04	68.96	0.73	0	18.37	0.03	93.4	34.53	2.02	-0.96
21/07/2010	201	16.06	8.96	68.93	0.7	0	18.82	0.14	96.8	35.1	2.68	-1.04
22/07/2010	202	13.33	11.17	68.34	0.96	0	19.95	0.3	98.4	35.47	2.42	1.17
23/07/2010	203	15.58	12.68	77.24	1.13	0	19.62	5.55	97.3	42.76	2.6	2.68
24/07/2010	204	17.52	14.03	67.69	0.73	0	23.27	4.62	98.6	29.04	3.14	4.03
25/07/2010	205	14.8	13.37	63.35	0.67	0	22.48	4.08	98.5	28.2	2.74	3.37
26/07/2010	206	13.61	13.42	60.09	0.52	0	23.25	3.79	94.7	28.94	2.53	3.42
27/07/2010	207	11.05	13.26	67.46	1.02	0	19.87	4.78	95.9	33.8	2.15	3.26
28/07/2010	208	16.24	13.1	62.36	0.65	0	24.08	3.16	97.9	20.81	3.08	3.1
29/07/2010	209	17.39	13.16	53.52	0.9	0	22.69	4.62	91.4	18	3.35	3.16
30/07/2010	210	17.22	12.57	62.41	1.82	0	21.1	2.41	93.2	24.49	3.17	2.57
31/07/2010	211	15.97	11.37	74.9	1.96	0	16.01	3.33	95.3	57.16	2.36	1.37
2010/07/31	212	15.24	10.28	74.29	0.55	0	21.26	1.77	98.4	34.63	2.61	0.28

DZINDI IRRIGATION SCHEME					Mar-10							
DATES	**DOY**	**Rn**	T	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/03/2010	60	26	21.43	71.48	1.08	0	26.34	17.15	87.64	53.14	4.79	11.74
02/03/2010	61	28.69	25.48	58.15	0.96	0	31.93	18.87	79.58	29.18	6.04	15.4
03/03/2010	62	20.79	23.15	75.86	1.88	1.02	27.56	19.95	92.9	54.48	4.2	13.75
04/03/2010	63	12.18	21.25	86.03	1.41	16.51	24.59	19.49	95.76	70.24	2.32	12.04
05/03/2010	64	34.51	22.17	75.88	0.94	0.25	25.59	19.3	92.9	59.18	6.06	12.45
06/03/2010	65	54.65	22.12	69.46	1.18	0	26.05	18.77	88.96	50.78	8.97	12.41
07/03/2010	66	46.35	21.7	72.97	1.67	0	26.69	18.05	90.48	50.63	7.66	12.37
08/03/2010	67	30.38	22.33	64.94	1.43	0	27.11	18.41	91.81	36.13	5.41	12.76
09/03/2010	68	31.28	23.59	67.24	0.79	0	28.61	19.47	88.31	42.92	5.61	14.04
10/03/2010	69	45.93	25.43	65.19	0.59	0	30.8	21.05	86.42	41.46	8.33	15.92
11/03/2010	70	68.71	25.89	63.82	0.53	0	31.52	20.56	81.5	44	12.17	16.04

12/03/2010	71	65.45	27.11	62.39	0.66	0	32.83	22	79.98	45.23	12.25	17
13/03/2010	72	62.2	25.87	66.67	1.19	0	29.86	22.71	84.12	49.75	11.41	16.28
14/03/2010	73	59.44	24.34	72.8	1.75	0.51	29.21	21.36	87.3	50.99	10.37	15.29
15/03/2010	74	50.25	21.85	82.99	1.77	5.08	25.59	19.45	95.53	65.17	8.03	12.52
16/03/2010	75	63.14	23.23	72.65	0.84	0	28.22	19.54	91.29	52.02	10.96	13.88
17/03/2010	76	68.47	25.72	61.15	0.86	0	32.27	21.08	78.93	31.33	12.47	16.54
18/03/2010	77	55.63	22.36	80.59	1.03	3.3	25.93	19.28	93.91	61.76	9.32	12.61
19/03/2010	78	59.71	22.66	75.24	0.71	0	25.7	20.44	85.03	63.99	10.23	13.07
20/03/2010	79	65.18	24.04	68.78	0.73	0	29.98	20.33	85.03	44.31	11.59	15.16
21/03/2010	80	49.83	20.56	88.2	0.64	18.8	23.18	18.95	94.12	79.05	8.18	11.06
22/03/2010	81	59.17	21.56	79.77	0.65	0.25	25.18	18.97	94.64	62.99	9.91	12.07
23/03/2010	82	68.96	23.34	69.39	0.64	0	27.71	18.39	87.29	53.42	11.97	13.05
24/03/2010	83	62.19	23.88	73.26	0.83	1.27	27.91	20.48	94.07	52.43	10.83	14.19
25/03/2010	84	66.54	26.15	62.09	0.55	0	30.94	21.54	78.51	41.92	12.18	16.24
26/03/2010	85	67.97	27.45	57.85	0.57	0	31.95	22.9	72.12	40.76	12.62	17.43
27/03/2010	86	68.95	27.37	58.97	0.63	0	32.25	22.87	75.52	39.96	13.21	17.44
28/03/2010	87	67.49	25.98	66.2	1.64	0	31.33	21.14	84.78	48.15	12.52	16.24
29/03/2010	88	64.1	21.34	86.84	0.91	2.54	24.74	19.42	95.04	71.9	10.94	12.08
30/03/2010	89	48.94	25.36	65.33	0.54	0	31.47	19.94	87.42	36.59	9.06	15.7
31/03/2010	90	12.97	24.03	76.13	1.07	17.78	27.3	21.66	90.16	66.06	2.65	14.48
						Apr-10						
DATES	**DOY**	**Rn**		**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/04/2010	91	17.72	23.61	79.29	0.66	0.76	27.78	20.73	93.16	59.29	3.52	14.25
02/04/2010	92	19.47	24.39	74.94	0.62	0	28.64	21.31	88.51	52.78	3.87	14.98
03/04/2010	93	10.38	21.73	86.01	0.65	18.03	24.37	19.42	94.43	74.64	2.02	11.89
04/04/2010	94	14.13	23.66	77.64	0.52	2.29	27.84	21.24	87.94	61.49	2.77	14.54
05/04/2010	95	12.6	22.14	87.76	0.99	13.72	24.59	20.53	94.8	75.64	2.42	12.56
06/04/2010	96	19.21	23.37	81.91	0.78	29.97	29.04	20.05	95.42	57.99	3.78	14.54
07/04/2010	97	22.4	24.87	71.91	0.78	4.83	29.52	20.45	92.53	51.18	4.37	14.98

08/04/2010	98	11.36	22.37	89.44	1.2	22.35	24.67	20.54	94.28	80.26	2.19	12.61
09/04/2010	99	10.87	22.91	86.41	0.57	4.06	26.27	20.89	94.56	70.89	2.15	13.58
10/04/2010	100	20.12	25.08	73.34	1.43	1.27	30.78	19.69	90.5	50.94	4.3	15.23
11/04/2010	101	5.78	18.23	88.92	1.59	1.27	19.84	16.91	94.89	79.78	1.14	8.37
12/04/2010	102	20.05	20.6	77.1	0.59	0	24.96	17.68	90.59	60.16	3.67	11.32
13/04/2010	103	16.8	19.74	71.6	0.71	0	23.53	16.89	86.02	56.1	3.03	10.21
14/04/2010	104	18.46	19.76	71.89	0.5	0	23.72	16.29	87.58	55.43	3.25	10
15/04/2010	105	23.3	22.46	59.58	0.61	1.02	27.53	17.26	76.25	45.92	4.39	12.39
16/04/2010	106	22.44	24.23	55.44	0.57	0	29.07	20.1	65.21	38.71	4.31	14.58
17/04/2010	107	12.98	22.49	78.88	0.59	0	25.61	20.12	91.86	65.29	2.55	12.87
18/04/2010	108	21.99	25.43	62.51	0.58	0	31.86	20.13	87.72	34.05	4.34	15.99
19/04/2010	109	13.16	20.96	82.31	0.79	19.3	24.26	18.42	92.11	63.72	2.38	11.34
20/04/2010	110	11.15	21.74	79.63	1.34	3.05	26.48	18.91	93.4	56.79	2.4	12.7
21/04/2010	111	6.02	17.81	87.84	0.92	3.56	19.72	16.15	95.18	79.62	1.16	7.94
22/04/2010	112	13.84	20.31	77.5	0.58	0	25.5	16.57	90.92	57.95	2.6	11.04
23/04/2010	113	2.92	18.22	79.89	1.52	0	20.32	16.4	94.73	59.71	0.78	8.36
24/04/2010	114	2.37	14.49	92.09	1.09	9.4	16.16	13.54	95.83	79.37	0.53	4.85
25/04/2010	115	3.96	14.87	95.39	0.97	10.67	16.04	13.62	96.48	93.85	0.75	4.83
26/04/2010	116	9.46	16.69	87	0.63	5.84	19.6	14.89	96.06	67.98	1.64	7.24
27/04/2010	117	6.24	17.59	86.89	0.33	0	19.93	15.85	91.24	78.55	1.19	7.89
28/04/2010	118	17.75	20.65	77.69	0.44	0	25.5	16.04	90.72	61.83	3.18	10.77
29/04/2010	119	20.95	22.86	66.29	0.61	0	27.23	19.49	81.72	46.81	3.85	13.36
30/04/2010	120	10.1	19.84	83.32	0.82	18.03	22.83	17.85	94.88	68.94	1.85	10.34
					May-10							
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/05/2010	121	18.29	21.72	72.91	0.44	0	27.03	17.43	86.15	53.23	3.33	12.23
02/05/2010	122	8.15	19.54	84.04	0.53	0	22.6	18.18	92.55	71.59	1.52	10.39
03/05/2010	123	18.36	21	69.53	0.76	0	25.93	16.86	88.27	47.96	3.4	11.4

04/05/2010	124	18.99	23.05	57.91	1.43	0	28.21	17.93	72.38	42.47	4.06	13.07
05/05/2010	125	19.27	24.47	55.23	0.76	0	31.09	19.73	74.97	29.52	3.99	15.41
06/05/2010	126	19.87	24.34	50.95	0.54	0	29.17	18.76	66.11	37.99	3.71	13.97
07/05/2010	127	14.88	24.69	50.61	0.38	0	30.82	20.98	67.36	29.33	2.94	15.9
08/05/2010	128	11.81	20.51	79.81	0.75	0	23.79	18.31	92.21	57.71	2.2	11.05
09/05/2010	129	18.94	23.2	65.58	0.79	0	29.08	17.91	86.27	45.12	3.74	13.5
10/05/2010	130	19.08	26.16	44.81	1.14	0	31.54	21.65	56.19	30.76	4.24	16.6
11/05/2010	131	18.54	26.33	42.88	0.94	0	31.83	21.13	61.66	22.6	4.01	16.48
12/05/2010	132	17.67	20.42	71.59	0.74	0	23.32	16.79	86.99	58.31	3.83	10.05
13/05/2010	133	20.91	19.56	79.78	0.6	0	21.99	17.95	89.45	67.88	4.14	9.97
14/05/2010	134	5.36	21.09	73.65	0.68	0	25.95	17.04	88.23	57.51	1.54	11.49
15/05/2010	135	0	21.15	73.94	1.22	0.25	25.73	18.05	89.8	55.59	0.75	11.89
16/05/2010	136	70.66	17.81	91.31	1	1.02	18.52	17.07	94.41	88.09	11.06	7.8
17/05/2010	137	34.65	17.54	82.15	1.32	0	20.23	15.92	94.74	64.6	5.12	8.07
18/05/2010	138	25.53	18.11	74.21	0.53	0	22.08	14.79	92.54	54.81	4.89	8.44
19/05/2010	139	0	18.37	68.69	0.46	0	23	13.86	85.04	49	0.53	8.43
20/05/2010	140	20.5	18.25	76.71	0.83	0	21.61	15.38	93.12	58.59	2.75	8.49
21/05/2010	141	78.04	17.79	91.6	0.88	11.18	18.87	17.06	95.04	83.71	10.97	7.97
22/05/2010	142	49.05	17.72	87.68	0.54	1.78	19.24	16.55	95.01	79.01	7.54	7.9
23/05/2010	143	39.58	18.12	74.5	0.7	0	21.29	15.8	94.42	53.02	6.48	8.55
24/05/2010	144	0	18.35	61.82	0.43	0	23.94	14.09	75.51	37.37	0.54	9.01
25/05/2010	145	0	18.58	61.46	0.48	0	23.34	14.45	71.73	46.56	0.56	8.9
26/05/2010	146	5.39	20.05	56.92	0.49	0.76	25.18	15.54	70.76	37.92	1.34	10.36
27/05/2010	147	17.76	20.25	53.01	0.69	0	26.19	15.39	72.23	35.31	3.28	10.79
28/05/2010	148	17.99	22.65	36.18	1.78	0	28.15	17.36	48.61	25.47	4.38	12.75
29/05/2010	149	4.42	17.28	70.52	1.21	0	20.23	15.98	85.24	41.16	1.07	8.11
30/05/2010	150	3.12	14.05	84.86	0.87	1.52	15.79	13.15	93.7	79.31	0.71	4.47
31/05/2010	151	10.15	15.23	72.61	0.81	0	18.56	13.21	80.59	59.78	1.71	5.88
					Jun-10							

DATES	DOY	Rn	T	RH	WS	Rain	Tx	Tn	RHx	RHn	Evap	HU
01/06/2010	152	16.68	15.91	68.27	0.53	0	20.26	12.1	87.34	49.32	2.54	6.18
02/06/2010	153	17.35	16.91	61.51	0.57	0	22.28	13.03	85.7	33.99	2.79	7.65
03/06/2010	154	16.27	16.03	60.39	0.6	0	20.31	12.78	79.3	41.02	2.53	6.54
04/06/2010	155	17.05	17.59	50.85	0.84	0	22.79	13.14	62.68	37.18	2.97	7.97
05/06/2010	156	17.36	20.36	39.14	0.9	0	26.65	15.1	56.01	22.94	3.24	10.87
06/06/2010	157	16.65	17.5	64.67	0.51	0	22.55	13.67	76.04	45.78	2.64	8.11
07/06/2010	158	17.4	19.84	50.85	0.74	0	26.67	15.09	69.57	26.19	3.07	10.88
08/06/2010	159	17.46	20.22	46.04	0.68	0	27.23	14.64	65.3	25.5	3.13	10.94
09/06/2010	160	16.97	20.13	51.73	0.99	0	23.05	17.36	83.9	35.68	3.01	10.2
10/06/2010	161	9.11	17.34	81.06	1.65	0.51	20.32	15.87	92.36	65.23	1.63	8.1
11/06/2010	162	6.11	16.36	84.81	0.57	1.02	19.01	14.62	94.9	71.96	1.12	6.82
12/06/2010	163	13.16	18.02	74.31	0.59	0	22.76	13.82	89.72	57.99	2.26	8.29
13/06/2010	164	16.98	21.67	49.85	1.75	0	27.55	17.15	74.49	28.43	3.69	12.35
14/06/2010	165	17.01	24.09	26.43	2.27	0	28.66	21.06	31.4	20.43	4.86	14.86
15/06/2010	166	16.92	20.69	27.19	2.55	0	26.57	10.9	36.44	18.07	4.79	8.74
16/06/2010	167	17.56	12.22	37.69	0.7	0	16.49	7.84	55.42	29.1	2.55	2.16
17/06/2010	168	11.16	11.92	53.18	0.7	0	16.16	7.71	71.25	40.84	1.76	1.94
18/06/2010	169	16.92	13.11	55.29	1.2	0	17.64	7.74	69.1	42.56	2.62	2.69
19/06/2010	170	14.08	14.02	66.5	0.55	0	18.54	9.99	85.41	46.5	2.07	4.26
20/06/2010	171	17.43	15.63	46.75	0.5	0	20.39	11.52	58.45	30.49	2.65	5.95
21/06/2010	172	17.31	15.75	53.35	0.67	0	21.29	10.12	64.74	38.24	2.76	5.7
22/06/2010	173	17.33	17.58	44.52	1.08	0	22.7	13.74	58.71	23	3.04	8.22
23/06/2010	174	16.93	17.03	47.1	0.48	0	21.98	11.49	66.52	30.58	2.69	6.73
24/06/2010	175	13.97	15.49	64.67	0.49	0	20.59	10.97	89.51	46.04	2.23	5.78
25/06/2010	176	16.37	17.34	46.71	0.47	0	22.94	11.82	64.44	29.73	2.69	7.38
26/06/2010	177	17	18.72	43.54	0.64	0	25.01	13.64	59.03	28.17	2.89	9.33
27/06/2010	178	6.33	16.17	63.31	1.66	0	19.93	11.63	81.88	44	1.55	5.78
28/06/2010	179	4.42	15.57	90.27	0.96	5.59	17.1	14.79	94.87	79.8	0.81	5.94

29/06/2010	180	6.57	15.61	89.38	0.41	10.41	17.69	14.16	95.55	78.56	1.09	5.92
30/06/2010	181	10.07	17.59	76.15	0.35	0	20.82	14.76	92.48	61.08	1.72	7.79
						Jul-10						
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/07/2010	182	10.17	16.15	72.87	1.34	0	21.01	12.35	85.52	53.12	1.98	6.68
02/07/2010	183	3.09	14	91.6	0.95	4.32	14.93	13.26	95.62	88.07	0.59	4.1
03/07/2010	184	14.75	15.54	71.63	0.46	0.25	19.26	12.25	92.3	47.25	2.18	5.75
04/07/2010	185	6.6	15.59	82.12	0.32	2.03	17.78	13.67	93.7	59.64	1.1	5.72
05/07/2010	186	9.22	16.21	79.82	0.38	0	19.62	14.64	93.4	61.08	1.49	7.13
06/07/2010	187	17.34	16.73	64.07	0.42	0	21.67	11.91	86.2	41.29	2.7	6.79
07/07/2010	188	15.7	17.2	59.69	1.26	0	21.56	13.48	87.19	43.75	2.87	7.52
08/07/2010	189	9.52	16.14	76.89	1.21	0	18.92	14.07	92.83	60.39	1.67	6.49
09/07/2010	190	10.29	16.64	70.95	0.52	0	19.97	14.44	86.67	54.22	1.71	7.2
10/07/2010	191	17.72	18.63	47.4	1.31	0	24.03	14.48	60.82	31.91	3.39	9.25
11/07/2010	192	17.71	20.35	35.6	1.84	0	25.75	15.62	50.14	23.39	4.15	10.68
12/07/2010	193	17.03	19.53	40.06	1.27	0	24.81	14.28	77.41	22.7	3.27	9.55
13/07/2010	194	15.45	14	53.79	1.18	0	17.52	10.92	67.11	40.11	2.53	4.22
14/07/2010	195	14.57	14.39	69.22	0.58	0	19.83	10.9	87.66	44.79	2.28	5.36
15/07/2010	196	13.1	17.92	57.39	0.6	0	24.72	12.52	76.14	36.27	2.38	8.62
16/07/2010	197	17.82	17.47	37.01	1.05	0	22.66	11.61	65.4	12.83	3.25	7.13
17/07/2010	198	18.15	14.56	43.25	0.49	0	19.94	9.68	70.67	22.7	2.76	4.81
18/07/2010	199	17.14	14.8	51.78	0.63	0	19.64	10.54	71.59	32.86	2.57	5.09
19/07/2010	200	11.22	15.27	71.67	0.6	0.51	19.05	12.1	92.07	52.1	1.87	5.57
20/07/2010	201	11.33	16.11	66.43	0.54	0	20.19	12.82	77.96	52.61	1.92	6.5
21/07/2010	202	15.35	16.49	64.17	0.98	0	21.25	12.17	85.54	37.93	2.63	6.71
22/07/2010	203	8.14	15.43	86.54	1.04	1.78	18.31	13.92	95.09	71.42	1.38	6.11
23/07/2010	204	16.68	17.6	73.08	0.63	0	23.16	13.81	93.34	45.02	2.82	8.49
24/07/2010	205	16.04	19.06	53.82	0.56	0	24.33	14.65	76.32	31.69	2.83	9.49

25/07/2010	206	16.89	19.13	47.49	0.55	0	24.87	13.06	70.48	27.55	2.88	8.97
26/07/2010	207	14.95	17.78	62.53	0.71	0	22.07	14.84	89.5	42.45	2.55	8.46
27/07/2010	208	17.92	18.73	52.04	0.51	0	24.55	13.96	77.13	26.11	3.05	9.25
28/07/2010	209	18.19	19.05	42.92	0.58	0	24.25	15.35	56.07	23.74	3.15	9.8
29/07/2010	210	16.29	17.18	57.1	1.3	0	21.75	13.74	79.72	43.7	2.95	7.74
30/07/2010	211	3.13	13.38	88.8	1.4	12.45	15.01	12.02	95.9	79.41	0.59	3.52
31/07/2010	212	17.78	14.49	72.18	0.39	0.25	18.79	10.49	88.84	52.9	2.64	4.64
					Mar-12							
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/03/2012	61	10.44	22.65	74.28	1.23	0.51	25.94	20.13	83.97	62.94	2.31	13.04
02/03/2012	62	16.78	23.57	68.36	1.82	0	28.34	18.93	91.02	46.48	3.92	13.63
03/03/2012	63	25.2	25.5	55.76	0.9	0	32.57	18.55	87.03	28.7	5.29	15.27
04/03/2012	64	24.67	29.19	37.25	0.84	0	37.56	21.01	64.88	14.82	5.76	16.5
05/03/2012	65	21.56	26.46	58.8	1.84	0	32.34	22.69	78.37	37.66	5.27	17.35
06/03/2012	66	9.17	21.77	64.44	2.2	0	23.51	19.58	75.55	56.47	2.63	11.55
07/03/2012	67	15.73	21.54	62.89	1.09	0	26.33	18.02	79.94	42.08	3.34	12.17
08/03/2012	68	23.52	23.93	51.59	0.78	0	29.61	17.86	74.84	32.02	4.88	13.74
09/03/2012	69	18.7	23.5	59.34	0.61	0	29.44	19.06	81	35.94	3.84	14.25
10/03/2012	70	24.28	25.42	49.89	0.83	0	32.01	19.28	71.03	26.06	5.23	15.64
11/03/2012	71	18.04	24.58	58.93	1.89	0	29.89	20.76	84.64	34.46	4.39	15.32
12/03/2012	72	22.64	24.31	56.27	0.97	0	29.33	19.5	78.09	35.02	4.65	14.42
13/03/2012	73	20.61	25.95	56.78	0.85	0	33.73	20.19	84.26	29.86	4.67	16.09
14/03/2012	74	23.23	24.35	59.5	1.58	0	29.48	20.14	81.07	39.24	5.02	14.81
15/03/2012	75	14.8	22.68	66.52	0.72	0	26.84	19.15	88.49	47.92	3.01	12.99
16/03/2012	76	16.35	25.34	54.85	0.61	0	31.35	20.86	71.85	33.13	3.62	16.11
17/03/2012	77	17.56	26.94	52.96	0.8	0	32.64	21.87	78.12	30.36	3.9	16.94
18/03/2012	78	3.96	21.85	72.09	1.61	0	26.22	19.87	86.39	41.47	1.31	13.05
19/03/2012	79	14.85	22.1	73.26	0.65	2.03	27.02	18.45	93.58	50.36	2.95	12.74
20/03/2012	80	17.22	24.35	59.11	0.91	0	29.31	19.59	77.69	38.05	3.78	14.45

21/03/2012	81	18.18	23.62	61.31	0.96	0	28	20.33	87.57	34.22	3.73	14.16
22/03/2012	82	23.25	25.08	46.55	0.7	0	30.81	19.63	67.49	26.96	4.84	15.22
23/03/2012	83	18.34	23.63	56.8	1.05	0	29.03	19.33	82.77	31.8	3.96	14.18
24/03/2012	84	14.64	24.01	64.16	1.17	0.76	28.58	20.2	92.16	37.46	3.37	14.39
25/03/2012	85	14.42	22.67	68.63	1.34	0	27.11	19.43	84.72	49.71	3.01	13.27
26/03/2012	86	19.74	24.47	62.86	0.59	0.76	29.87	20.52	90.63	34.46	3.95	15.2
27/03/2012	87	22.31	25.64	48.65	0.57	0	31.39	20.05	74.22	24.2	4.55	15.72
28/03/2012	88	18.37	24.66	55.14	0.8	0	29.66	20.1	70.38	39.77	3.91	14.88
29/03/2012	89	15.98	25.78	62.84	0.71	7.62	31.59	21.59	84.91	37.48	3.42	16.59
30/03/2012	90	19.07	26.31	65.97	0.74	0.25	33.15	21.13	88.45	40.33	4.11	16.56
31/03/2012	91	17.94	24.48	69.59	1.55	7.87	30.95	19.7	93.74	41.14	4.04	15.33
					Apr-12							
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/04/2012	92	5.21	18.27	76.7	1.64	4.83	21.19	15.74	94.42	61.54	1.42	8.46
02/04/2012	93	20.04	19.26	59.04	1.96	0	24	15.62	76.03	36.72	4.06	9.81
03/04/2012	94	21.81	18.92	60.44	1.21	0	24.34	14.69	86.7	31.47	4.01	9.52
04/04/2012	95	22.23	19.94	54.88	0.76	0	26.15	13.97	86.25	28.93	4.13	10.06
05/04/2012	96	22.03	21.44	47.37	1.36	0	27.66	16	67.27	26.74	4.81	11.83
06/04/2012	97	16.92	20.14	62.1	1.17	0	24.66	16.1	88.92	37.3	3.3	10.38
07/04/2012	98	18.83	21.39	58.81	0.52	0	26.78	16.27	83.39	36.16	3.52	11.53
08/04/2012	99	19.14	24.09	44.57	0.59	0	30.56	18.33	60.74	27.31	3.86	14.44
09/04/2012	100	18.91	26.74	35.96	0.71	0	33.6	21.5	52.4	19.86	4.2	16.75
10/04/2012	101	10.75	20.94	62.03	1.02	0	24.83	18.27	81.63	35.54	2.18	11.55
11/04/2012	102	14.13	20.13	63.5	0.8	0	24.54	16.5	82.99	45.96	2.72	10.52
12/04/2012	103	11.22	19.6	64.24	1.14	4.32	23.68	16.46	77.57	47.21	2.41	10.07
13/04/2012	104	13.88	18.27	66.51	1.6	0.76	22.19	15.68	92.02	38.18	2.8	8.93
14/04/2012	105	16.89	18.36	59.7	0.7	0	23.16	13.68	84.72	37.39	3.01	8.42
15/04/2012	106	18.21	20.59	44.88	0.63	0	26.96	14.11	69.86	23.23	3.56	10.54
16/04/2012	107	20.05	22.23	39.81	0.88	0	27.31	18.15	59.8	25.78	4.06	12.73

17/04/2012	108	19.67	21.24	58.98	0.6	0	26.23	16.96	85.82	37.2	3.6	11.59
18/04/2012	109	18.67	21.88	49.94	0.96	0	27.92	16.7	69.23	27.27	3.96	12.31
19/04/2012	110	13.53	20.15	61.83	1.05	0	24.38	16.99	81.83	42.06	2.67	10.69
20/04/2012	111	12.68	19.04	71.9	0.6	1.02	23.92	15.98	90.8	51.87	2.33	9.95
21/04/2012	112	18.97	20.84	60.55	0.53	0	26.51	14.93	85	38.71	3.47	10.72
22/04/2012	113	17.44	23.69	46.84	0.72	0	30.07	16.48	74.62	27.58	3.62	13.27
23/04/2012	114	9.65	20.5	66.56	1.55	0	23.22	18.02	82.69	41.25	2.2	10.62
24/04/2012	115	3.16	15.25	93.22	1.39	17.02	18.05	13.97	95.29	82.83	0.64	6.01
25/04/2012	116	3.93	15.42	93.32	0.8	8.89	16.72	14.11	95.63	87.34	0.77	5.41
26/04/2012	117	10.48	17.48	75.97	0.46	0	21.28	14.69	89.88	57.51	1.92	7.99
27/04/2012	118	19.02	21.7	50.79	0.55	0	28.9	15.04	75.98	30.13	3.61	11.97
28/04/2012	119	18.78	25.11	35.18	0.47	0	32.24	19.45	47.96	20.36	3.7	15.73
29/04/2012	120	18.46	25.1	38.04	0.54	0	32.29	18.83	58.86	19.4	3.7	15.41
30/04/2012	121	18.57	26.26	29.9	0.69	0	32.41	20.91	41.91	19.22	3.93	16.45
						May-12						
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/05/2012	122	18.52	25.96	34.17	0.58	0	32.49	20.2	52.22	18.11	3.72	16.1
02/05/2012	123	14.31	21.68	57.87	0.9	0	26.58	17.52	84.88	32.73	2.87	12.05
03/05/2012	124	18.7	23.72	47.35	0.52	0	30.36	18.64	74.47	21.1	3.58	14.5
04/05/2012	125	18.46	25.9	31.81	0.47	0	32.49	19.37	46.73	14.7	3.54	15.69
05/05/2012	126	18.08	25.22	34.42	0.7	0	31.83	19.92	65.19	19.28	3.69	15.87
06/05/2012	127	10.54	20.86	71.87	1.26	0.25	24.45	18.68	93.31	50.71	2.15	11.56
07/05/2012	128	5.59	20.27	72.97	0.8	0	23.92	17.59	94.2	52.39	1.31	10.76
08/05/2012	129	12.04	20.44	67.79	0.99	0	24.78	17.33	89.65	46.05	2.43	11.06
09/05/2012	130	15.72	20.46	62.28	0.42	0	25.61	16.7	80.13	43.32	2.77	11.16
10/05/2012	131	17.47	20.46	51.82	0.42	0	26.23	15.23	74.72	29.32	3.07	10.73
11/05/2012	132	15.58	19.75	54.94	0.78	0	24.55	15.08	67.54	39.77	2.91	9.81
12/05/2012	133	14.51	18.72	60.03	0.44	0	23.48	13.76	81.72	36.95	2.47	8.62

13/05/2012	134	17.27	20.19	47.41	0.49	0	25.46	14.15	67.89	28.47	3.03	9.81
14/05/2012	135	15.67	22.31	39.96	0.6	0	27.55	16.34	60.96	23.8	3.02	11.94
15/05/2012	136	15.32	24.01	30.25	0.59	0	29.89	19.29	59.88	16.68	3.02	14.59
16/05/2012	137	9.5	18.4	70.84	0.91	0	21.75	16.31	83.49	55.87	1.8	9.03
17/05/2012	138	15.45	19.82	61.89	0.54	0	25.65	15.1	86.08	29.58	2.78	10.38
18/05/2012	139	16.4	22.42	36.18	0.8	0	28.42	16.66	59.88	19.13	3.35	12.54
19/05/2012	140	17.04	24.29	16.72	0.81	0	29.64	20.17	23.22	10.74	3.49	14.9
20/05/2012	141	14.65	19.2	54.9	0.61	0	24.93	13.41	81.09	20.79	2.59	9.17
21/05/2012	142	2.94	16.7	79.75	1.33	0.51	18.65	15.37	94.09	66.01	0.89	7.01
22/05/2012	143	8.31	16.51	68.25	0.84	0	20.07	14.05	88.51	48.92	1.5	7.06
23/05/2012	144	16.47	18.77	46.17	0.68	0	24.6	13.17	67.51	26.77	3	8.89
24/05/2012	145	16.11	22.03	28.14	0.79	0	27.88	16.06	47.11	15.66	3.15	11.97
25/05/2012	146	15.85	19.39	38.75	0.66	0	24.54	14.85	51.86	28.4	2.8	9.7
26/05/2012	147	15.85	18.22	53.17	0.48	0	23.39	13.06	71.06	34.64	2.65	8.22
27/05/2012	148	6.55	17.12	63.44	0.45	0	21.31	14.36	85.05	47.8	1.26	7.83
28/05/2012	149	9.85	17.66	65.76	0.49	0.51	22.45	14.81	88.2	44.15	1.79	8.63
29/05/2012	150	14.95	18.98	57.29	0.44	0	23.99	13.97	84.64	35	2.57	8.98
30/05/2012	151	14.78	20.88	36.8	0.43	0	26.29	15.57	56.91	22.35	2.64	10.93
31/05/2012	152	10.52	18.25	63.66	1.31	0	23.01	15.61	87.88	39.27	2.22	9.31
						Jun-12						
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/06/2012	153	14.92	18.19	57.98	0.44	0	23.67	14.05	83.18	31.74	2.49	8.86
02/06/2012	154	12.41	17.83	58.24	0.51	0	22.36	13.15	80.98	43.52	2.12	7.75
03/06/2012	155	14.61	17.63	57.89	0.99	0	22.4	13.06	77.07	37.3	2.7	7.73
04/06/2012	156	14.02	16.45	58.08	0.75	0	21.05	12.09	82.7	33.73	2.32	6.57
05/06/2012	157	15.72	16.96	49.02	0.44	0	23.06	11.88	66.72	30.44	2.57	7.47
06/06/2012	158	14.54	19.53	38.47	0.98	0	25.15	13.74	57.37	23.06	3.09	9.45
07/06/2012	159	14.88	20.8	29.46	0.97	0	26.37	15.16	50.55	15.29	3.09	10.76

08/06/2012	160	15.32	23.19	17.76	1.87	0	28.49	17.54	23.03	13.17	4.36	13.02
09/06/2012	161	15.52	18.91	23.89	2.06	0	24.1	14.22	36.17	15.32	4.15	9.16
10/06/2012	162	15.99	14.86	25.83	1.53	0	19.61	11.07	32.48	17.49	3.19	5.34
11/06/2012	163	15.41	14.4	40.18	0.83	0	19.34	9.97	60.65	26	2.5	4.66
12/06/2012	164	15.5	16.5	42.87	0.67	0	23.32	10.8	68.49	21.34	2.71	7.06
13/06/2012	165	15.11	17.37	33.14	0.89	0	22.08	13.98	48.6	23.06	2.74	8.03
14/06/2012	166	8.44	15.3	61.34	0.69	0	18.96	12.12	78.79	46.4	1.47	5.54
15/06/2012	167	8.72	16.45	62.63	0.45	0	20.88	13.09	78.14	43.25	1.55	6.99
16/06/2012	168	11.56	17.33	56.83	0.44	0	21.54	13.5	76.22	39.04	1.99	7.52
17/06/2012	169	14.7	17.75	51.51	0.51	0	23.4	12.23	69.39	33.27	2.48	7.81
18/06/2012	170	13.35	19.52	48.48	0.48	0	24.95	14.04	68.2	32.16	2.41	9.49
19/06/2012	171	6.47	17.08	67.89	0.54	0	20.41	13.66	81.5	52.26	1.23	7.04
20/06/2012	172	13.3	18.47	62.58	0.46	0.25	23.71	13.62	87.09	38.9	2.32	8.66
21/06/2012	173	1.69	15.71	80.22	0.49	10.16	17.63	13.48	90.34	59.18	0.47	5.55
22/06/2012	174	7.5	16.17	83.8	0.42	2.54	19.9	14.04	93.37	68.63	1.29	6.97
23/06/2012	175	14.12	19.94	60.52	0.63	0	28.19	14.6	86.25	29.06	2.65	11.4
24/06/2012	176	13.85	23.44	33.93	1.55	0	29.22	18.85	52.72	18.32	3.72	14.04
25/06/2012	177	15.57	18.76	23.71	0.88	0	25.11	12.35	35.97	13.83	3	8.73
26/06/2012	178	15.19	15.9	45.94	0.53	0	21.95	9.77	73.88	22.38	2.4	5.86
27/06/2012	179	15.48	19.41	34.89	0.57	0	26.79	13.51	55.38	15.2	2.78	10.15
28/06/2012	180	12.95	17.76	51.65	0.83	0	22.31	13.68	78.65	21.86	2.3	7.99
29/06/2012	181	15.03	19.09	51.99	0.4	0	25.44	13.44	73.69	33.5	2.56	9.44
30/06/2012	182	15.22	21.25	31.03	0.62	0	27.52	16.64	47.36	15.37	2.78	12.08
						Jul-12						
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/07/2012	183	15.07	19.82	34.2	0.6	0	24.85	16.08	44.24	25.1	2.69	10.47
02/07/2012	184	15.11	20.33	36.54	0.52	0	27.04	15.12	52.88	19.91	2.67	11.08
03/07/2012	185	15.03	18.74	38.48	0.6	0	23.61	15.3	51.36	28.5	2.6	9.46
04/07/2012	186	15.14	19.61	44.6	0.45	0	26.04	13.42	63.46	28.25	2.65	9.73

05/07/2012	187	2.52	16.34	64.13	1.03	0	18.8	12.38	81.89	36.87	0.81	5.59
06/07/2012	188	12.39	17.76	67.72	0.52	0	23.34	14.48	85.82	43.98	2.19	8.91
07/07/2012	189	15.06	19.54	48.28	0.52	0	26.29	13.82	78.12	23.87	2.71	10.05
08/07/2012	190	14.11	19.64	43.53	0.95	0	25.94	14.92	72.35	22.56	2.83	10.43
09/07/2012	191	7.99	17.06	77.33	0.9	0.51	20.66	14.64	94.09	56.71	1.51	7.65
10/07/2012	192	14.15	19.25	55.22	0.49	0	25.32	14.09	80.89	30.88	2.53	9.7
11/07/2012	193	13.93	20.63	42.68	0.63	0	26.35	15.92	61.22	23.74	2.61	11.13
12/07/2012	194	4.92	16.81	66.66	0.89	0	19.51	14.94	81.53	42.91	1.15	7.23
13/07/2012	195	8.66	16.71	72.12	0.41	0	21.01	12.89	88.43	52.04	1.6	6.95
14/07/2012	196	12.9	20.65	50.51	0.66	0	26.72	15.65	72.42	29.17	2.56	11.18
15/07/2012	197	16.03	17.82	24.1	1.29	0	22.65	13.19	36.37	17.02	3.32	7.92
16/07/2012	198	16.03	16.01	31.27	1.24	0	20.08	12.53	56.15	22.21	3.11	6.31
17/07/2012	199	15.56	15.18	44.92	0.69	0	21.31	8.97	66.32	25.55	2.71	5.14
18/07/2012	200	15.39	14.25	56.26	1.16	0	18.84	10.09	80.43	35.21	2.55	4.47
19/07/2012	201	15.91	15.09	52.68	0.52	0	21.9	9.3	79.67	26.96	2.56	5.6
20/07/2012	202	15.77	18.66	34.75	0.83	0	25.44	11.55	56.27	18.36	3.17	8.49
21/07/2012	203	16.4	21.2	18.69	0.94	0	27	14.98	29.04	10.44	3.42	10.99
22/07/2012	204	16.09	22.05	14.98	0.8	0	28.25	16.89	20.62	9.53	3.3	12.57
23/07/2012	205	9.09	17.3	53.3	1.17	0	20.58	12.53	78.4	14.14	1.85	6.56
24/07/2012	206	7.78	16.85	72.22	0.61	1.02	20.93	14.62	92.72	48.08	1.44	7.77
25/07/2012	207	14.39	17.81	59.13	0.7	0	22.41	14.03	71.62	42.76	2.57	8.22
26/07/2012	208	13.57	16.37	62.7	0.53	0	20.66	13.41	83.97	38.87	2.24	7.03
27/07/2012	209	15.79	19.74	34.14	0.78	0	26.6	14.28	52.32	13.52	3.06	10.44
28/07/2012	210	11.39	16.63	57.93	1.43	0	20.45	13.86	81.7	23.74	2.31	7.15
29/07/2012	211	8.28	15.32	69.81	0.67	0	19.84	13.11	88.41	45.47	1.49	6.47
30/07/2012	212	13.4	15.58	63.01	0.66	0	21.14	11.31	83.65	42.45	2.31	6.23
31/07/2012	213	13.96	18.09	47.55	0.6	0	23.86	12.12	71.22	26.82	2.55	7.99

TRICHATSDAL					Mar-10							
Dates	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/03/2010	60	24.1	24.06	54.92	0.72	0	30.91	17.21	84.29	27.48	4.91	14.06
02/03/2010	61	23.4	27.09	53	1.29	0	35.74	19.76	77.58	24.6	5.77	15.88
03/03/2010	62	13.6	24.13	70.2	1.03	0	29.29	21.65	81.14	49.81	3.12	15.47
04/03/2010	63	13.1	23.1	71.78	0.73	0.51	27.55	19.9	87.84	50.65	2.8	13.72
05/03/2010	64	12.25	23.9	68.46	0.67	0	27.95	20.9	86.21	47.86	2.69	14.42
06/03/2010	65	18.61	24.54	55.58	0.77	0	30.26	20.65	77.72	28.24	4.07	15.45
07/03/2010	66	18.14	23.69	59.87	0.86	0	29.45	17.87	82.32	35.93	4.01	13.66
08/03/2010	67	22.88	24.82	53.54	0.77	0	30.68	20.4	77.18	24.69	4.88	15.54
09/03/2010	68	24.63	26.44	55.59	0.86	0	32.9	20.01	84.98	26.75	5.33	16
10/03/2010	69	19.35	26.1	65.22	0.72	5.33	34.49	22.16	81.17	30.65	4.19	17.08
11/03/2010	70	21.64	27.59	58.92	0.75	0	34.54	22.28	82.03	33.06	4.77	17.14
12/03/2010	71	21.43	27.75	61.19	0.77	0.76	36	22.98	79.2	31.11	4.8	17.49
13/03/2010	72	20.88	27.69	59.43	0.86	0	33.32	23.5	77.72	36.18	4.69	17.75
14/03/2010	73	15.52	25.55	70.63	0.97	3.3	31.51	22.32	86.33	41.19	3.55	16.92
15/03/2010	74	12.35	24.35	68.34	0.6	0.51	28.7	21.19	87.78	43.43	2.58	14.95
16/03/2010	75	21.43	23.38	74.29	1.05	9.91	31.26	18.75	92.88	43.03	4.46	15.01
17/03/2010	76	17.56	24.67	69.43	0.8	0.76	31.66	20.49	85.85	43.17	3.79	16.08
18/03/2010	77	11.39	23.09	75.02	0.6	2.79	26.02	20.11	90.62	59.5	2.39	13.07
19/03/2010	78	12.22	23.13	76.37	0.62	1.78	26.14	19.77	90.24	61.39	2.56	12.96
20/03/2010	79	17.73	24.46	74.02	0.61	25.4	31.22	21.07	88.24	40.3	3.76	16.14
21/03/2010	80	6.99	21.62	83.45	0.5	8.64	24.8	19.91	90.77	65.89	1.48	12.35
22/03/2010	81	20.75	24.33	70.14	0.49	0	28.85	20.65	88.14	50.32	4.11	14.75
23/03/2010	82	22.06	25.39	65.87	0.58	0	30.67	20.38	86.04	46.37	4.5	15.53
24/03/2010	83	16.07	24.65	69.32	0.57	0	29.22	21.76	83.08	48.8	3.32	15.49
25/03/2010	84	21.84	26.32	63.24	0.66	0	32.54	20.86	81.02	39.92	4.62	16.43

26/03/2010	85	20.04	27.39	60.18	0.54	0	33.51	22.45	78.34	37.68	4.28	17.23
27/03/2010	86	20.23	28.19	63.22	0.74	0	33.55	24.29	81.67	44.84	4.43	18.15
28/03/2010	87	13.47	25.51	69.85	1.03	0	30.18	21.89	78.74	55.99	3.03	16.03
29/03/2010	88	15.56	24.01	67.72	0.73	0	28.36	21.27	80.1	51.42	3.2	14.81
30/03/2010	89	21.8	26.91	59.18	0.63	0	34.22	19.74	86.71	32.22	4.63	15.87
31/03/2010	90	11.92	25.21	67.9	0.77	0	29.07	23.2	77.28	55.66	2.71	16.13
						Apr-11						
DATES	**DOY**	**Rn**		**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/04/2010	91	8.18	23.3	80.84	0.47	1.78	26.74	22.23	88.05	64.28	1.68	14.48
02/04/2010	92	7.86	23.27	82.61	0.54	45.47	26.12	20.4	92.51	69.12	1.64	13.26
03/04/2010	93	9.65	22.2	84.07	0.48	11.68	25.66	19.82	93.56	70.07	1.96	12.74
04/04/2010	94	9.5	23.92	78.27	0.46	1.52	28.66	20.88	89.15	59.16	2.04	14.77
05/04/2010	95	4.87	22.07	88.38	0.48	48.26	23.44	20.77	93.4	81.95	1.06	12.11
06/04/2010	96	11.89	23.62	80.98	0.52	7.87	27.37	20.81	92.58	64.76	2.43	14.09
07/04/2010	97	20.32	25.39	72.21	0.48	32.26	31.53	20.82	91.69	45.38	4.12	16.17
08/04/2010	98	5.3	23.11	85.83	0.45	1.78	25.26	21.88	91.38	76.68	1.18	13.57
09/04/2010	99	13.67	23.81	80.57	0.59	0.51	28.31	21.6	91.37	62.2	2.81	14.96
10/04/2010	100	18.18	25.55	66.78	1.2	0.25	31.89	19.71	85.28	37.71	4.11	15.8
11/04/2010	101	7.95	20.25	78.69	0.7	0	22.51	18.5	85.61	67.74	1.6	10.51
12/04/2010	102	17.53	22.39	75.23	0.43	0.51	26.83	18.57	91.8	56.84	3.36	12.7
13/04/2010	103	15.88	21.42	69.59	0.48	0	25.35	18.86	81.44	53.07	3.03	12.11
14/04/2010	104	17.48	21.39	70.65	0.52	0	26.39	18.29	85.59	48.71	3.3	12.34
15/04/2010	105	21.13	22.78	66.17	0.6	0	29.6	17.17	83.15	43.88	4.09	13.39
16/04/2010	106	20.48	23.6	66.93	0.56	0	29.63	18.75	80.42	46.98	3.99	14.19
17/04/2010	107	18.69	24.29	72.66	0.6	0	28.36	20.91	89.22	53.06	3.69	14.64
18/04/2010	108	16.11	24.43	68.14	0.71	0	31.4	19.71	88.93	42.95	3.49	15.56
19/04/2010	109	7.85	21.68	81.69	0.46	6.1	24.89	19.8	90.85	70.69	1.54	12.34
20/04/2010	110	9.78	21.1	83.69	0.77	8.89	26.51	17.45	92.97	63.79	2.03	11.98
21/04/2010	111	11.03	19.1	80.47	0.54	0.25	22.76	15.47	92.27	62.78	2.03	9.12

22/04/2010	112	19.37	21.6	73.81	0.55	0	27.55	17.28	91.52	53.77	3.59	12.42
23/04/2010	113	5.58	18.9	75.71	0.77	0	20.9	17.25	84.29	67.8	1.23	9.07
24/04/2010	114	3.87	16.9	74.73	0.73	6.6	18.66	15.31	89.91	67.87	0.96	6.99
25/04/2010	115	3.32	16.23	89.86	0.38	2.54	16.74	15.39	93.03	86.12	0.71	6.06
26/04/2010	116	4.26	17.3	86.71	0.26	0.76	19.07	16.32	93.39	77.35	0.89	7.7
27/04/2010	117	6.9	18.31	80.83	0.34	0	21.33	16.14	90.42	66.66	1.39	8.73
28/04/2010	118	18.53	21.38	70.73	0.61	0	27.45	16.12	88.67	47.36	3.53	11.79
29/04/2010	119	19.13	23.15	63.91	0.73	4.06	29.58	17.08	87.06	29.18	3.77	13.33
30/04/2010	120	13.79	21.47	78.79	0.62	0.25	25.45	19.21	90.14	57.87	2.65	12.33
					May-10							
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/05/2010	121	18.19	22.44	70.8	0.5	0	29.39	17.32	88.43	43.68	3.48	13.36
02/05/2010	122	10.25	20.75	78.31	0.42	0	25.02	18.8	88.67	58.88	2	11.91
03/05/2010	123	17.59	21.7	74.49	0.62	0	27.06	16.86	90.82	54.1	3.35	11.96
04/05/2010	124	16.91	24.08	58.4	1.27	0	29.31	20.01	84.86	39.39	3.8	14.66
05/05/2010	125	19.06	24.08	54.9	0.78	0	30.74	18.32	83.17	25.48	3.93	14.53
06/05/2010	126	19.37	23.42	51.38	0.64	0	30.1	17.97	70.1	34.95	3.71	14.04
07/05/2010	127	15.8	24.35	61.87	0.6	0	31.07	20.07	78.83	36.53	3.29	15.57
08/05/2010	128	9.23	21.19	77.36	0.78	0	24.35	19.05	86.57	65.4	1.81	11.7
09/05/2010	129	17.73	22.94	68.93	0.63	0	30.32	16.17	88.71	43.22	3.47	13.24
10/05/2010	130	17.82	24.97	60.1	0.81	0	31.81	18.82	82.23	34.24	3.7	15.32
11/05/2010	131	19.35	26.05	34.41	1.68	0	29.96	23.12	53.36	22.44	4.74	16.54
12/05/2010	132	15.5	21.13	62.03	0.92	0.51	25.7	16.01	87.5	35.96	2.87	10.86
13/05/2010	133	8.22	20.22	76.94	0.59	0	23.48	17.8	87.42	61.25	1.66	10.64
14/05/2010	134	16.72	21.21	70.7	0.74	0	27.34	15.99	86.92	48.69	3.13	11.66
15/05/2010	135	12.38	21.2	71.75	0.89	0	26.45	17.07	87	50.86	2.57	11.76
16/05/2010	136	4.85	18.48	84.63	0.57	1.02	20.91	16.82	91.59	76.47	0.95	8.87
17/05/2010	137	10.35	19.01	75.98	0.57	0	23.22	16.09	91.87	52.49	1.92	9.65

18/05/2010	138	17.51	19.33	67.77	0.49	0	25.22	15.65	88.18	37.02	3.01	10.43
19/05/2010	139	17.84	18.71	68.52	0.53	0	25.22	13.43	83.97	46.1	3.04	9.32
20/05/2010	140	15.48	19.53	68.22	0.44	0	25.63	13.5	91.2	40.13	2.75	9.56
21/05/2010	141	12.63	20.06	70.81	0.57	0	24.98	15.64	87.66	50.23	2.38	10.31
22/05/2010	142	12.96	19.86	67.16	0.47	0	25.14	16.56	89.78	41.01	2.37	10.85
23/05/2010	143	17.77	18.7	59.81	0.59	0	25.41	13.51	82.55	29.67	3.04	9.46
24/05/2010	144	17.4	19.27	61.43	0.59	0	27.23	13.59	85.54	28.49	3.06	10.41
25/05/2010	145	17.2	19	63.3	0.55	0	25.93	13.49	81.95	37.47	2.96	9.71
26/05/2010	146	16.85	19.78	60.24	0.54	0	27.45	13.93	80.14	32.69	2.97	10.69
27/05/2010	147	16.44	20.18	60.58	0.61	0	28.16	14.72	79.18	32.89	3.01	11.44
28/05/2010	148	17	21.33	45.59	0.89	0	29.69	13.72	69.58	19.24	3.41	11.7
29/05/2010	149	8.09	18.77	57.01	1.22	0	23.08	16.36	79.93	34.46	1.82	9.72
30/05/2010	150	3.33	15.23	77.71	0.58	4.32	16.34	14.2	88.74	63.45	0.75	5.27
31/05/2010	151	7.44	16.16	76.6	0.37	0	19.81	13.14	90.94	54.76	1.34	6.47
					Jun-10							
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/06/2010	152	16.39	17.06	62.72	0.55	0	23.69	11.57	84.94	34.66	2.76	7.63
02/06/2010	153	14.7	17.25	60.45	0.61	0	24.14	12.36	84.38	30.51	2.54	8.25
03/06/2010	154	16.13	16.34	61.26	0.69	0	23.13	11.58	81.8	34.93	2.7	7.35
04/06/2010	155	16.18	17.08	50.84	0.79	0	25.24	11.34	75.26	23.68	2.95	8.29
05/06/2010	156	16.5	18.99	45.55	0.91	0	27.01	12.42	64.26	21.36	3.11	9.72
06/06/2010	157	15.89	18.08	63.91	0.58	0	25.09	12.63	81.7	37.04	2.68	8.86
07/06/2010	158	16.36	19.65	52.67	0.58	0	29.8	13.03	79.71	19	2.99	11.41
08/06/2010	159	16.16	20.18	50.61	0.68	0	29.6	13.03	74.44	20.4	3.03	11.32
09/06/2010	160	15.37	19.48	55.28	0.76	0	26.28	12.64	73.12	36.94	2.76	9.46
10/06/2010	161	8.44	18.34	71.93	0.7	0	21.61	15.92	81.2	55.25	1.61	8.77
11/06/2010	162	11.14	17.23	71.69	0.61	0	22.36	14.18	85.61	50.2	1.95	8.27
12/06/2010	163	13.45	18.42	66.99	0.7	0	25.08	13.51	82.78	42.49	2.47	9.3
13/06/2010	164	15.23	20.12	54.23	0.7	0	29.14	13.71	81.87	23.36	2.95	11.42

14/06/2010	165	15.25	21.9	38.69	0.76	0	31.12	14.22	64.22	16.35	3.13	12.67
15/06/2010	166	15.94	19.07	28.09	2.51	0	23.95	13.65	52.82	16.87	4.55	8.8
16/06/2010	167	15.93	13.15	31.77	0.92	0	19.52	6.75	48.81	16.61	2.73	3.13
17/06/2010	168	14.86	13.04	46	0.68	0	19.27	7.25	71.69	24.79	2.37	3.26
18/06/2010	169	14.79	13.21	51.62	0.69	0	20.27	6.96	69.94	28.48	2.43	3.62
19/06/2010	170	14.69	14.72	58.51	0.59	0	21.72	9.69	80.92	29.28	2.42	5.7
20/06/2010	171	15.07	14.95	51.62	0.62	0	22.96	8.84	79.71	22.21	2.55	5.9
21/06/2010	172	15.09	16.06	46.64	0.86	0	22.89	10.88	60.68	25.87	2.68	6.88
22/06/2010	173	14.63	16.87	44.45	0.6	0	25.51	10.13	68.5	17.15	2.58	7.82
23/06/2010	174	14.37	16.86	48.59	0.64	0	24.65	9.88	72.19	25.91	2.48	7.26
24/06/2010	175	13.45	16.84	61.78	0.81	0	23.58	11.08	84.22	38.08	2.42	7.33
25/06/2010	176	13.77	17.41	52.35	0.55	0	25.58	11.7	74.5	22.07	2.41	8.64
26/06/2010	177	13.93	18.67	44.42	0.59	0	28.24	11.86	67.36	19.65	2.6	10.05
27/06/2010	178	12.43	17.26	50.45	1.06	0	23	10.95	69.59	38.14	2.54	6.97
28/06/2010	179	3.6	17.03	79.26	0.5	1.52	18.66	15.85	90.39	74.54	0.74	7.25
29/06/2010	180	6.89	17.05	73.19	0.44	0	20.05	14.39	86.62	55.7	1.26	7.22
30/06/2010	181	9.89	18.24	60.93	0.6	0	24.76	14.58	86.1	24.75	1.89	9.67
						Jul-10						
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/07/2010	182	8.68	17.56	61.16	0.8	0	22.84	12.29	78.67	39.51	1.88	7.57
02/07/2010	183	3.72	15.35	84.07	0.48	6.1	18.07	13.44	93.71	68.9	0.76	5.75
03/07/2010	184	14.18	16.53	68.04	0.5	0	22.69	11.97	90.91	37.21	2.35	7.33
04/07/2010	185	11.86	17.89	69.7	0.58	0	23.45	13.87	89.15	45.5	2.19	8.66
05/07/2010	186	14.47	17.48	70.15	0.68	0	23.5	13.71	87.11	42.52	2.52	8.61
06/07/2010	187	15.22	18.04	61.03	0.69	0	24.68	11.92	86.89	32.82	2.67	8.3
07/07/2010	188	13.95	17.63	63.02	0.95	0	23.29	11.96	81.5	44.83	2.64	7.62
08/07/2010	189	7.99	17.42	69.9	0.59	0	21.8	14.65	82.47	47.61	1.53	8.23
09/07/2010	190	15.17	17.44	62.32	0.6	0	23.9	12.1	86.29	32.53	2.66	8

10/07/2010	191	15.68	17.55	51.75	0.78	0	24.82	11.69	74.78	25.1	2.89	8.25
11/07/2010	192	15.75	19.25	39.8	0.99	0	27.49	11.71	65.77	17.62	3.21	9.6
12/07/2010	193	15.52	19.14	34.5	1.75	0	22.36	14.11	61.3	18.56	3.67	8.24
13/07/2010	194	15.77	15.12	51.63	0.8	0	20.96	8.88	80.39	26.51	2.65	4.92
14/07/2010	195	14.87	14.9	63.04	0.79	0	20.56	10.76	82.36	39.32	2.51	5.66
15/07/2010	196	13.79	17.26	58.48	0.64	0	24.54	11.32	76.35	34.26	2.53	7.93
16/07/2010	197	16.18	17.69	27.53	1.95	0	21.76	12.46	68.74	11.67	3.88	7.11
17/07/2010	198	16.04	14.95	39.93	0.65	0	23.1	7.89	67.94	13.9	2.69	5.49
18/07/2010	199	15.88	15.96	40.35	0.67	0	23.19	9.05	57.65	20.37	2.71	6.12
19/07/2010	200	11.93	16.9	58.19	0.55	0	21.88	12.6	82.83	36.91	2.11	7.24
20/07/2010	201	14.96	17.35	58.27	0.71	0	23.25	13.2	80.75	32.66	2.67	8.23
21/07/2010	202	10.52	17.08	63.63	0.68	2.29	22.82	10.97	90.14	35.85	2.09	6.89
22/07/2010	203	11.48	17.86	71.6	0.51	0.25	21.63	13.45	90.69	47.48	1.97	7.54
23/07/2010	204	14.33	19.18	64.66	0.64	0	25.63	13.32	87.88	35.2	2.64	9.47
24/07/2010	205	14.54	19.5	55.3	0.67	0	26.32	14.34	78.41	27.65	2.78	10.33
25/07/2010	206	15.44	20.22	50.63	0.76	0	27.2	12.48	84.16	25.06	2.98	9.84
26/07/2010	207	12.22	19.44	61.4	0.7	0	24.7	16.04	84.81	34.22	2.33	10.37
27/07/2010	208	14.68	20.1	50.99	0.61	0	27.73	14.06	75.97	24.3	2.8	10.9
28/07/2010	209	15.64	19.59	45.32	0.67	0	26.52	14.04	64.96	24.24	2.96	10.28
29/07/2010	210	12.68	17.86	58.98	0.82	0	23.11	12.69	77.25	37.25	2.45	7.9
30/07/2010	211	5.28	16.6	65.34	0.62	0.25	19.43	13.59	90.17	45.82	1.2	6.51
31/07/2010	212	13.71	17.26	62.22	0.51	0	23.08	13.71	81.3	38.56	2.37	8.39
					Mar-11							
Dates	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/03/2011	60	24.2	22.89	62.39	0.79	0	28.39	17.73	87.64	36.84	4.81	13.06
02/03/2011	61	25.14	23.21	60.48	0.95	0	29.05	18.26	86.09	35.22	4.93	13.66
03/03/2011	62	24.55	26.05	50.39	0.67	0	33.77	18.48	77.52	27.47	5.21	15.24
04/03/2011	63	18.94	25.39	58.39	0.59	0	30.33	21.91	74.24	37.9	4.05	16.12
05/03/2011	64	15.84	24	58.74	0.59	0	29.3	20.75	78.32	35.29	3.4	15.02

06/03/2011	65	24.37	24.07	57.84	0.7	0	30.2	17.62	86.64	30.79	4.95	13.91
07/03/2011	66	20.78	24.61	60.45	0.66	0	30.09	20.87	79.7	37.36	4.35	15.48
08/03/2011	67	17.94	24.67	61.68	0.66	0	29.7	21.51	80.11	38.58	3.79	15.6
09/03/2011	68	23.11	25.78	55.08	0.77	0.51	32.56	20.89	78.81	26.61	4.94	16.45
10/03/2011	69	22.29	25.69	53.48	0.66	0	32.13	20.52	75.57	30.45	4.69	16.26
11/03/2011	70	20.98	25.27	57.55	0.7	0	32.13	19.66	81.74	32.24	4.46	15.83
12/03/2011	71	20.85	26.53	57.19	0.7	0	32.75	20.92	75.98	35.34	4.56	16.46
13/03/2011	72	15.11	27.57	59.88	0.7	0	33.16	23.25	73.37	38.7	3.51	17.62
14/03/2011	73	19.93	26.36	70.42	0.96	58.93	33.58	21.36	91.28	39.2	4.38	16.68
15/03/2011	74	13.52	24.71	76.14	0.54	1.52	28.58	21.54	90.32	58.37	2.85	15.06
16/03/2011	75	18.11	25.46	68.69	0.68	0	30.15	22.53	84.37	47.03	3.83	16.34
17/03/2011	76	19.39	24.32	67.66	0.72	0	29.55	20.63	90.38	44.9	4	15.09
18/03/2011	77	20.89	26.48	63.17	0.88	0.25	32.84	21.26	84.54	38.39	4.66	16.63
19/03/2011	78	14.43	24.27	70.47	0.81	8.38	28.46	21.3	87.94	44.96	3.21	14.88
20/03/2011	79	7.39	22.53	83.87	0.41	0	24.88	20.79	91.17	71.33	1.58	12.83
21/03/2011	80	19.57	25.83	66.3	0.89	0	33.06	20.96	84.9	36.78	4.38	16.48
22/03/2011	81	21.18	27.59	58.02	0.69	0	34.45	21.43	81.59	31.12	4.66	16.72
23/03/2011	82	16.66	26.81	69.42	0.68	12.19	32.3	22.99	87.94	50.21	3.63	17.49
24/03/2011	83	20.49	28.45	62.2	0.6	0	35.49	22.77	86.81	35.47	4.49	17.38
25/03/2011	85	13.23	26.43	68.16	0.78	0	29.86	24.41	79.91	54.42	2.92	17.13
26/03/2011	86	11.35	25	74.16	0.75	0	28.54	22.73	89.26	57.26	2.56	15.64
27/03/2011	87	14.44	24.92	70.48	0.64	0	29.94	21.74	86.74	48.08	3.04	15.84
28/03/2011	88	18.56	25.94	67.98	0.85	11.68	34.72	21.48	83.25	31.16	4.13	16.74
29/03/2011	89	20.06	24.87	65.32	0.78	0	29.97	20.33	79.54	46.39	4.05	15.15
30/03/2011	90	17.23	25.26	65.75	0.61	0	30.46	22.23	81.49	43.86	3.62	16.34
31/03/2011	91	20.1	24.75	59.7	0.7	0	30.88	19.93	81.29	36.62	4.15	15.41
						Apr-10						
DATES	**DOY**	**Rn**		**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/04/2011	91	20.1	24.75	59.7	0.7	0	30.88	19.93	81.29	36.62	4.15	15.41

02/04/2011	92	18.82	26.21	53.45	0.8	0	33.48	19.94	73.45	28.67	4.19	15.97
03/04/2011	93	17.47	26.33	61.31	0.81	29.46	32.71	20.23	88.51	38.44	3.78	16.12
04/04/2011	94	11.97	21.9	82.56	0.82	67.06	27.37	19.26	93.14	60.12	2.55	13.31
05/04/2011	95	10.31	20.7	78.64	0.89	2.54	24.02	18.7	92.18	61.23	2.15	11.36
06/04/2011	96	11.78	21.14	72.36	0.58	0.51	24.57	18.06	91.13	53.12	2.32	11.32
07/04/2011	97	17.19	23.88	62.02	1.25	0	30.7	17.72	86.86	38.43	3.96	14.21
08/04/2011	98	13.77	21.22	67.55	0.97	0	24.32	18.38	82.18	54.03	2.82	11.35
09/04/2011	99	16.83	20.12	65.66	0.59	0	25.24	15.57	87.72	42.44	3.15	10.4
10/04/2011	100	19.67	20.44	61.3	0.66	0	27.16	14.51	83.39	34.59	3.69	10.83
11/04/2011	101	19.36	20.16	60.56	0.7	0	26.16	14.4	85.11	37.2	3.64	10.28
12/04/2011	102	16.96	21.11	63.12	0.7	0	26.17	17.16	83.46	39.69	3.25	11.67
13/04/2011	103	12.62	21.6	73.61	0.54	18.29	26.54	18.4	89.77	51.78	2.51	12.47
14/04/2011	104	8.42	20.19	83.8	0.36	1.78	24.26	17.62	90.89	62.67	1.71	10.94
15/04/2011	105	11.19	20.45	82.1	0.53	28.7	24.97	18.09	92.99	59.74	2.16	11.53
16/04/2011	106	12.9	21.33	77.08	0.67	44.2	26.33	18.64	92.48	51.75	2.57	12.49
17/04/2011	107	3.05	18.51	88.37	0.59	16.26	19.5	17.73	92.2	82.04	0.72	8.62
18/04/2011	108	4.24	18.02	81.64	0.79	0	19.68	16.98	86.85	70.69	0.96	8.33
19/04/2011	109	7.84	19.2	81.36	0.51	0	21.84	17.12	89.82	67.67	1.57	9.48
20/04/2011	110	10.89	21.13	77.45	0.58	0	25.57	17.14	90.94	57.16	2.21	11.36
21/04/2011	111	7.14	21.03	80.6	0.58	4.57	25.8	18.08	90.41	64.15	1.55	11.94
22/04/2011	112	2.09	18.65	82.65	0.53	1.78	19.52	17.23	89.92	73.05	0.62	8.37
23/04/2011	113	5.5	18.07	85.86	0.39	1.27	19.92	16.95	90.28	78.18	1.1	8.43
24/04/2011	114	11.84	21.3	72.83	0.7	0	26.77	16.53	91.22	48.75	2.49	11.65
25/04/2011	115	16.62	23.21	60.75	0.58	0	30.48	17.77	83.38	31.94	3.39	14.12
26/04/2011	116	16.61	24.05	61.88	0.75	12.95	31.52	17.99	84.96	34.68	3.54	14.75
27/04/2011	117	17.9	25.43	57.32	1.32	0.25	29.84	20.97	80.18	41.53	3.96	15.41
28/04/2011	118	7.97	20.27	78.45	0.65	0	23.56	18.83	87.06	59.92	1.58	11.19
29/04/2011	119	10.09	19.79	80.38	0.68	1.78	23.73	17.65	92.4	58.63	1.91	10.69
30/04/2011	120	15.37	21.98	66.91	0.67	0	29.05	16.45	88.72	42.78	3.04	12.75

					May-11							
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/05/2011	121	2.54	17.54	89.19	0.59	18.03	19.13	16.99	92.51	78.4	0.59	8.06
02/05/2011	122	11.9	18.92	79.78	0.54	0.51	23.41	16.85	91.68	56.46	2.18	10.13
03/05/2011	123	17.16	20.65	71.42	0.58	0	27.44	14.72	88.39	44.33	3.16	11.08
04/05/2011	124	7.36	18.96	73.92	0.54	0	21.36	16.27	85.19	63.43	1.4	8.81
05/05/2011	125	14.58	19.95	69.43	0.59	0	25.32	15.68	84.4	47.61	2.66	10.5
06/05/2011	126	16.56	20.95	70.34	0.64	0	27.37	15.19	88.59	47.68	3.13	11.28
07/05/2011	127	15.46	22.11	63.81	0.59	0	28.49	16.9	80.27	39.58	3	12.69
08/05/2011	128	15.74	20.38	72.53	0.65	0	26.16	15.24	93.67	47.81	2.99	10.7
09/05/2011	129	17.65	19.42	66.6	0.59	0	25.35	14.07	88.76	39.81	3.14	9.71
10/05/2011	130	16.71	18.52	71.7	0.75	0	24.46	12.42	90.69	49.48	2.99	8.44
11/05/2011	131	16.46	21.01	65.96	0.61	0	28.46	14.92	88.42	38.84	3.12	11.69
12/05/2011	132	16.79	22.34	56.29	0.61	0	30.2	16.94	77.94	30.01	3.26	13.57
13/05/2011	133	16.27	22.65	53.73	0.86	0	29.42	16.52	76.35	28.94	3.33	12.97
14/05/2011	134	14.17	22.56	57.13	0.76	0	28.6	16.92	76	33.76	2.94	12.76
15/05/2011	135	15.01	22.7	55.06	0.71	0	29.29	16.93	73.89	30.87	3.05	13.11
16/05/2011	136	13.77	23.09	53.2	0.67	0.25	29.97	18.56	73.95	30.61	2.83	14.26
17/05/2011	137	13.66	22.37	59.98	0.6	2.29	28.32	17.25	79.57	36.21	2.67	12.78
18/05/2011	138	11.68	20.76	69.14	0.99	2.29	26.56	16.87	88.29	43.46	2.45	11.72
19/05/2011	139	12.47	20.72	71.83	0.56	1.02	27.28	14.96	91.46	50.06	2.38	11.12
20/05/2011	140	4.17	17.41	74.99	0.69	0.25	19.94	14.45	84.86	62.11	0.97	7.2
21/05/2011	141	15.08	19.7	59.43	0.79	0	27.22	13.47	87.36	31.26	2.89	10.34
22/05/2011	142	15.34	19.74	50.75	0.63	0	27.33	13.22	69.65	27.58	2.87	10.27
23/05/2011	143	14.88	21.35	54.75	0.76	0	28.94	15.27	75.98	26.78	2.97	12.1
24/05/2011	144	14.92	22.3	47.25	0.91	0	30.33	14.66	73.69	22.22	3.2	12.5
25/05/2011	145	14.7	23.94	38.85	2.19	0.76	31.34	16.45	71.8	20.84	4.81	13.9
26/05/2011	146	14.72	17.57	34.64	2.11	0	21.57	13.23	57.78	24.9	3.75	7.4

27/05/2011	147	14.1	15.66	52.51	0.84	0	22.06	10.83	69.53	31.07	2.56	6.45
28/05/2011	148	13.91	15.35	59.34	0.99	0	21.79	10.4	80.83	36.49	2.49	6.09
29/05/2011	149	14.61	17.17	42.1	0.89	0	25.57	9.99	67.94	14.37	2.87	7.78
30/05/2011	150	14.15	19.32	40.29	0.61	0	27.89	11.4	59.82	20.09	2.66	9.64
31/05/2011	151	14.24	21.27	27.56	1.3	0	27.01	14.9	59.82	12.83	3.54	10.95
					Jun-11							
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/06/2011	152	13.88	15.14	43.63	0.71	0	21.55	9.19	69.57	19.96	2.45	5.37
02/06/2011	153	14.2	15.78	40.59	0.61	0	24.81	8.36	71.21	13.42	2.51	6.59
03/06/2011	154	14.02	17.65	32.74	0.67	0	27	10.95	45.82	15.43	2.65	8.97
04/06/2011	155	13.78	18.75	27.85	0.62	0	28.52	11.74	42.06	10	2.57	10.13
05/06/2011	156	11.89	18.08	39.57	0.67	0	25.24	12.02	54.95	24.92	2.34	8.63
06/06/2011	157	12.3	19.64	48.59	0.49	0	26.42	14.13	64.36	27.69	2.27	10.28
07/06/2011	158	6.68	17.66	68.06	0.48	0	21.11	14.61	78.07	56.34	1.25	7.86
08/06/2011	159	3.89	17.21	79.46	0.51	0.51	20.09	14.63	89.71	58.25	0.83	7.36
09/06/2011	160	13.54	16.67	36.39	1.9	0	20	14.5	46.66	28.44	3.15	7.25
10/06/2011	161	13.37	17.6	39.6	2.08	0	21.4	14.97	49.18	29.94	3.28	8.18
11/06/2011	162	13.17	18.93	53	0.56	0	25.89	12.62	73.89	31.8	2.43	9.26
12/06/2011	163	11.84	19.09	64.97	0.5	0	23.89	15.28	82.03	48.53	2.12	9.58
13/06/2011	164	6.98	17.9	71.73	0.61	0	21.44	15.95	81.03	57.28	1.38	8.7
14/06/2011	165	12.56	17.99	64.5	0.55	0	23.81	13.99	83.21	38.24	2.23	8.9
15/06/2011	166	12.91	17.36	58.45	0.58	0	24.57	11.8	79	31.94	2.32	8.19
16/06/2011	167	13.01	19.75	44.08	1.09	0	27.76	11.51	71.7	21.47	3.03	9.63
17/06/2011	168	13.67	20.21	24.31	1.47	0	24.82	14.05	53.57	13.97	3.47	9.44
18/06/2011	169	13.24	15.84	55.78	0.77	0	21.71	11.13	75.44	31.75	2.28	6.42
19/06/2011	170	13.34	16.72	51.09	0.64	0	24.82	9.3	77.77	25.05	2.41	7.06
20/06/2011	171	12.87	21.91	32.75	1.35	0	29.26	15.61	73.46	13.22	3.27	12.43
21/06/2011	172	8.11	17.27	68.63	0.85	0	20.91	13.54	87.21	48.41	1.52	7.22
22/06/2011	173	12.52	17.16	60.9	0.52	0	24.9	11.55	87.29	28.35	2.23	8.23

23/06/2011	174	12.82	18.28	44.99	0.75	0	26.34	11.66	67.27	21.91	2.57	9
24/06/2011	175	12.57	18.54	34	2.13	0	24.27	12.8	57.31	16.81	3.87	8.54
25/06/2011	176	13.52	15.04	23.16	2.53	0	19.71	10.36	28.95	17.9	3.8	5.04
26/06/2011	177	13.63	15.58	29.24	0.84	0	22.54	9.36	45.73	15.43	2.57	5.95
27/06/2011	178	13.19	15.99	33.91	0.52	0	24.28	8.67	50.25	17.32	2.32	6.47
28/06/2011	179	13.49	17.74	30.85	0.61	0	26.77	11.38	46.56	11.98	2.55	9.07
29/06/2011	180	13.37	18.51	29.17	0.44	0	28.47	11.26	45.68	11.82	2.45	9.86
30/06/2011	181	13.38	20.4	21.72	1.06	0	28.39	13.58	35.48	8.84	3.17	10.98
						Jul-11						
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/07/2011	182	12.73	16.14	55.81	0.74	0	23.62	11.64	85.71	21.51	2.26	7.63
02/07/2011	183	12.14	16.16	55.45	0.85	0	24.15	8.72	87.52	15.97	2.34	6.43
03/07/2011	184	13.09	17.84	34.64	0.81	0	23.22	12.99	74.55	20.79	2.48	8.11
04/07/2011	185	3.36	15.7	70.55	0.65	0	18	14.06	78.52	57.95	0.87	6.03
05/07/2011	186	4.36	15.43	74.5	0.36	0	18.49	13.77	81.75	61.98	0.88	6.13
06/07/2011	187	12.58	16.03	40.2	0.81	0	21.53	11.88	64.79	22.78	2.35	6.7
07/07/2011	188	13.41	14.95	48.87	0.66	0	22.15	8.57	72.75	26.37	2.35	5.36
08/07/2011	189	12.2	15.79	56.03	0.64	0	22.06	9.56	85.69	31.92	2.2	5.81
09/07/2011	190	9.15	15.27	64.89	0.86	0	19.92	9.7	86.74	38.46	1.82	4.81
10/07/2011	191	6.96	14.6	70.35	0.71	0.51	18.43	12.63	84.86	43.29	1.35	5.53
11/07/2011	192	13.89	15.82	59.94	0.65	0	21.35	12.34	84.77	29.07	2.37	6.84
12/07/2011	193	13.03	15.41	57.93	0.65	0	21.35	10.13	80.86	36	2.24	5.74
13/07/2011	194	7.98	14.54	66.75	0.72	0	19.37	9.65	78.36	41.37	1.54	4.51
14/07/2011	195	13.9	15.56	56.76	0.58	0	21.84	9.14	89.34	26.31	2.36	5.49
15/07/2011	196	13.22	15.97	54.72	0.58	0	23.43	10.35	79.53	26.24	2.34	6.89
16/07/2011	197	13.54	17.38	48.56	0.63	0	24.65	10.79	69.87	23.57	2.5	7.72
17/07/2011	198	13.53	16.89	51.42	0.78	0	24.31	10.68	79.13	22.68	2.62	7.49
18/07/2011	199	13.99	17.03	47.65	0.82	0	25.1	10.74	80.21	14.49	2.69	7.92

19/07/2011	200	13.78	17.09	43.92	0.77	0	25.86	10.38	71.75	15.57	2.7	8.12
20/07/2011	201	14.24	18.78	32.77	0.89	0	27.69	11.21	59.9	10.31	3.09	9.45
21/07/2011	202	13.99	19.76	26.34	0.57	0	29.2	11.17	48.27	10.92	2.65	10.18
22/07/2011	203	13.53	17.47	48.45	0.61	0	24.63	11.14	75.18	29.19	2.38	7.88
23/07/2011	204	10.43	16.62	65.85	0.49	0	22.61	13.13	85.39	40.15	1.88	7.87
24/07/2011	205	13.35	18.01	52.11	0.58	0	27.12	10.85	82.85	19.27	2.58	8.98
25/07/2011	206	11.96	18.85	47.54	0.48	0	27.13	12.18	78.21	20.05	2.35	9.65
26/07/2011	207	1.92	14.72	71.04	0.73	0	15.89	11.67	80.29	60.11	0.68	3.78
27/07/2011	208	14.34	15.24	58.48	0.66	0	22.78	8.84	86.67	29.1	2.52	5.81
28/07/2011	209	14.61	16.01	56.75	0.83	0.76	23.45	8.55	82.98	31.47	2.75	6
29/07/2011	210	15.69	17.27	31.83	2.3	0	21.69	12.49	66.37	14.55	4.24	7.09
30/07/2011	211	15.8	15.77	46.29	0.86	0	22.99	7.51	72.09	24.53	2.9	5.25
31/07/2011	212	12.36	15.39	58.85	0.67	0	21.64	9.4	79.35	35.55	2.29	5.52

TSHIOMBO					Mar-12							
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/03/2012	61	10.44	22.65	74.28	1.23	0.51	25.94	20.13	83.97	62.94	2.31	13.04
02/03/2012	62	16.78	23.57	68.36	1.82	0	28.34	18.93	91.02	46.48	3.92	13.63
03/03/2012	63	25.2	25.5	55.76	0.9	0	32.57	18.55	87.03	28.7	5.29	15.27
04/03/2012	64	24.67	29.19	37.25	0.84	0	37.56	21.01	64.88	14.82	5.76	16.5
05/03/2012	65	21.56	26.46	58.8	1.84	0	32.34	22.69	78.37	37.66	5.27	17.35
06/03/2012	66	9.17	21.77	64.44	2.2	0	23.51	19.58	75.55	56.47	2.63	11.55
07/03/2012	67	15.73	21.54	62.89	1.09	0	26.33	18.02	79.94	42.08	3.34	12.17
08/03/2012	68	23.52	23.93	51.59	0.78	0	29.61	17.86	74.84	32.02	4.88	13.74
09/03/2012	69	18.7	23.5	59.34	0.61	0	29.44	19.06	81	35.94	3.84	14.25
10/03/2012	70	24.28	25.42	49.89	0.83	0	32.01	19.28	71.03	26.06	5.23	15.64
11/03/2012	71	18.04	24.58	58.93	1.89	0	29.89	20.76	84.64	34.46	4.39	15.32
12/03/2012	72	22.64	24.31	56.27	0.97	0	29.33	19.5	78.09	35.02	4.65	14.42

13/03/2012	73	20.61	25.95	56.78	0.85	0	33.73	20.19	84.26	29.86	4.67	16.09
14/03/2012	74	23.23	24.35	59.5	1.58	0	29.48	20.14	81.07	39.24	5.02	14.81
15/03/2012	75	14.8	22.68	66.52	0.72	0	26.84	19.15	88.49	47.92	3.01	12.99
16/03/2012	76	16.35	25.34	54.85	0.61	0	31.35	20.86	71.85	33.13	3.62	16.11
17/03/2012	77	17.56	26.94	52.96	0.8	0	32.64	21.87	78.12	30.36	3.9	16.94
18/03/2012	78	3.96	21.85	72.09	1.61	0	26.22	19.87	86.39	41.47	1.31	13.05
19/03/2012	79	14.85	22.1	73.26	0.65	2.03	27.02	18.45	93.58	50.36	2.95	12.74
20/03/2012	80	17.22	24.35	59.11	0.91	0	29.31	19.59	77.69	38.05	3.78	14.45
21/03/2012	81	18.18	23.62	61.31	0.96	0	28	20.33	87.57	34.22	3.73	14.16
22/03/2012	82	23.25	25.08	46.55	0.7	0	30.81	19.63	67.49	26.96	4.84	15.22
23/03/2012	83	18.34	23.63	56.8	1.05	0	29.03	19.33	82.77	31.8	3.96	14.18
24/03/2012	84	14.64	24.01	64.16	1.17	0.76	28.58	20.2	92.16	37.46	3.37	14.39
25/03/2012	85	14.42	22.67	68.63	1.34	0	27.11	19.43	84.72	49.71	3.01	13.27
26/03/2012	86	19.74	24.47	62.86	0.59	0.76	29.87	20.52	90.63	34.46	3.95	15.2
27/03/2012	87	22.31	25.64	48.65	0.57	0	31.39	20.05	74.22	24.2	4.55	15.72
28/03/2012	88	18.37	24.66	55.14	0.8	0	29.66	20.1	70.38	39.77	3.91	14.88
29/03/2012	89	15.98	25.78	62.84	0.71	7.62	31.59	21.59	84.91	37.48	3.42	16.59
30/03/2012	90	19.07	26.31	65.97	0.74	0.25	33.15	21.13	88.45	40.33	4.11	16.56
31/03/2012	91	17.94	24.48	69.59	1.55	7.87	30.95	19.7	93.74	41.14	4.04	15.33
					Apr-12							
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/04/2012	92	5.21	18.27	76.7	1.64	4.83	21.19	15.74	94.42	61.54	1.42	8.46
02/04/2012	93	20.04	19.26	59.04	1.96	0	24	15.62	76.03	36.72	4.06	9.81
03/04/2012	94	21.81	18.92	60.44	1.21	0	24.34	14.69	86.7	31.47	4.01	9.52
04/04/2012	95	22.23	19.94	54.88	0.76	0	26.15	13.97	86.25	28.93	4.13	10.06
05/04/2012	96	22.03	21.44	47.37	1.36	0	27.66	16	67.27	26.74	4.81	11.83
06/04/2012	97	16.92	20.14	62.1	1.17	0	24.66	16.1	88.92	37.3	3.3	10.38
07/04/2012	98	18.83	21.39	58.81	0.52	0	26.78	16.27	83.39	36.16	3.52	11.53
08/04/2012	99	19.14	24.09	44.57	0.59	0	30.56	18.33	60.74	27.31	3.86	14.44

09/04/2012	100	18.91	26.74	35.96	0.71	0	33.6	21.5	52.4	19.86	4.2	16.75
10/04/2012	101	10.75	20.94	62.03	1.02	0	24.83	18.27	81.63	35.54	2.18	11.55
11/04/2012	102	14.13	20.13	63.5	0.8	0	24.54	16.5	82.99	45.96	2.72	10.52
12/04/2012	103	11.22	19.6	64.24	1.14	4.32	23.68	16.46	77.57	47.21	2.41	10.07
13/04/2012	104	13.88	18.27	66.51	1.6	0.76	22.19	15.68	92.02	38.18	2.8	8.93
14/04/2012	105	16.89	18.36	59.7	0.7	0	23.16	13.68	84.72	37.39	3.01	8.42
15/04/2012	106	18.21	20.59	44.88	0.63	0	26.96	14.11	69.86	23.23	3.56	10.54
16/04/2012	107	20.05	22.23	39.81	0.88	0	27.31	18.15	59.8	25.78	4.06	12.73
17/04/2012	108	19.67	21.24	58.98	0.6	0	26.23	16.96	85.82	37.2	3.6	11.59
18/04/2012	109	18.67	21.88	49.94	0.96	0	27.92	16.7	69.23	27.27	3.96	12.31
19/04/2012	110	13.53	20.15	61.83	1.05	0	24.38	16.99	81.83	42.06	2.67	10.69
20/04/2012	111	12.68	19.04	71.9	0.6	1.02	23.92	15.98	90.8	51.87	2.33	9.95
21/04/2012	112	18.97	20.84	60.55	0.53	0	26.51	14.93	85	38.71	3.47	10.72
22/04/2012	113	17.44	23.69	46.84	0.72	0	30.07	16.48	74.62	27.58	3.62	13.27
23/04/2012	114	9.65	20.5	66.56	1.55	0	23.22	18.02	82.69	41.25	2.2	10.62
24/04/2012	115	3.16	15.25	93.22	1.39	17.02	18.05	13.97	95.29	82.83	0.64	6.01
25/04/2012	116	3.93	15.42	93.32	0.8	8.89	16.72	14.11	95.63	87.34	0.77	5.41
26/04/2012	117	10.48	17.48	75.97	0.46	0	21.28	14.69	89.88	57.51	1.92	7.99
27/04/2012	118	19.02	21.7	50.79	0.55	0	28.9	15.04	75.98	30.13	3.61	11.97
28/04/2012	119	18.78	25.11	35.18	0.47	0	32.24	19.45	47.96	20.36	3.7	15.73
29/04/2012	120	18.46	25.1	38.04	0.54	0	32.29	18.83	58.86	19.4	3.7	15.41
30/04/2012	121	18.57	26.26	29.9	0.69	0	32.41	20.91	41.91	19.22	3.93	16.45
						May-12						
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/05/2012	122	18.52	25.96	34.17	0.58	0	32.49	20.2	52.22	18.11	3.72	16.1
02/05/2012	123	14.31	21.68	57.87	0.9	0	26.58	17.52	84.88	32.73	2.87	12.05
03/05/2012	124	18.7	23.72	47.35	0.52	0	30.36	18.64	74.47	21.1	3.58	14.5
04/05/2012	125	18.46	25.9	31.81	0.47	0	32.49	19.37	46.73	14.7	3.54	15.69

05/05/2012	126	18.08	25.22	34.42	0.7	0	31.83	19.92	65.19	19.28	3.69	15.87
06/05/2012	127	10.54	20.86	71.87	1.26	0.25	24.45	18.68	93.31	50.71	2.15	11.56
07/05/2012	128	5.59	20.27	72.97	0.8	0	23.92	17.59	94.2	52.39	1.31	10.76
08/05/2012	129	12.04	20.44	67.79	0.99	0	24.78	17.33	89.65	46.05	2.43	11.06
09/05/2012	130	15.72	20.46	62.28	0.42	0	25.61	16.7	80.13	43.32	2.77	11.16
10/05/2012	131	17.47	20.46	51.82	0.42	0	26.23	15.23	74.72	29.32	3.07	10.73
11/05/2012	132	15.58	19.75	54.94	0.78	0	24.55	15.08	67.54	39.77	2.91	9.81
12/05/2012	133	14.51	18.72	60.03	0.44	0	23.48	13.76	81.72	36.95	2.47	8.62
13/05/2012	134	17.27	20.19	47.41	0.49	0	25.46	14.15	67.89	28.47	3.03	9.81
14/05/2012	135	15.67	22.31	39.96	0.6	0	27.55	16.34	60.96	23.8	3.02	11.94
15/05/2012	136	15.32	24.01	30.25	0.59	0	29.89	19.29	59.88	16.68	3.02	14.59
16/05/2012	137	9.5	18.4	70.84	0.91	0	21.75	16.31	83.49	55.87	1.8	9.03
17/05/2012	138	15.45	19.82	61.89	0.54	0	25.65	15.1	86.08	29.58	2.78	10.38
18/05/2012	139	16.4	22.42	36.18	0.8	0	28.42	16.66	59.88	19.13	3.35	12.54
19/05/2012	140	17.04	24.29	16.72	0.81	0	29.64	20.17	23.22	10.74	3.49	14.9
20/05/2012	141	14.65	19.2	54.9	0.61	0	24.93	13.41	81.09	20.79	2.59	9.17
21/05/2012	142	2.94	16.7	79.75	1.33	0.51	18.65	15.37	94.09	66.01	0.89	7.01
22/05/2012	143	8.31	16.51	68.25	0.84	0	20.07	14.05	88.51	48.92	1.5	7.06
23/05/2012	144	16.47	18.77	46.17	0.68	0	24.6	13.17	67.51	26.77	3	8.89
24/05/2012	145	16.11	22.03	28.14	0.79	0	27.88	16.06	47.11	15.66	3.15	11.97
25/05/2012	146	15.85	19.39	38.75	0.66	0	24.54	14.85	51.86	28.4	2.8	9.7
26/05/2012	147	15.85	18.22	53.17	0.48	0	23.39	13.06	71.06	34.64	2.65	8.22
27/05/2012	148	6.55	17.12	63.44	0.45	0	21.31	14.36	85.05	47.8	1.26	7.83
28/05/2012	149	9.85	17.66	65.76	0.49	0.51	22.45	14.81	88.2	44.15	1.79	8.63
29/05/2012	150	14.95	18.98	57.29	0.44	0	23.99	13.97	84.64	35	2.57	8.98
30/05/2012	151	14.78	20.88	36.8	0.43	0	26.29	15.57	56.91	22.35	2.64	10.93
31/05/2012	152	10.52	18.25	63.66	1.31	0	23.01	15.61	87.88	39.27	2.22	9.31
						Jun-12						
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**

01/06/2012	153	14.92	18.19	57.98	0.44	0	23.67	14.05	83.18	31.74	2.49	8.86
02/06/2012	154	12.41	17.83	58.24	0.51	0	22.36	13.15	80.98	43.52	2.12	7.75
03/06/2012	155	14.61	17.63	57.89	0.99	0	22.4	13.06	77.07	37.3	2.7	7.73
04/06/2012	156	14.02	16.45	58.08	0.75	0	21.05	12.09	82.7	33.73	2.32	6.57
05/06/2012	157	15.72	16.96	49.02	0.44	0	23.06	11.88	66.72	30.44	2.57	7.47
06/06/2012	158	14.54	19.53	38.47	0.98	0	25.15	13.74	57.37	23.06	3.09	9.45
07/06/2012	159	14.88	20.8	29.46	0.97	0	26.37	15.16	50.55	15.29	3.09	10.76
08/06/2012	160	15.32	23.19	17.76	1.87	0	28.49	17.54	23.03	13.17	4.36	13.02
09/06/2012	161	15.52	18.91	23.89	2.06	0	24.1	14.22	36.17	15.32	4.15	9.16
10/06/2012	162	15.99	14.86	25.83	1.53	0	19.61	11.07	32.48	17.49	3.19	5.34
11/06/2012	163	15.41	14.4	40.18	0.83	0	19.34	9.97	60.65	26	2.5	4.66
12/06/2012	164	15.5	16.5	42.87	0.67	0	23.32	10.8	68.49	21.34	2.71	7.06
13/06/2012	165	15.11	17.37	33.14	0.89	0	22.08	13.98	48.6	23.06	2.74	8.03
14/06/2012	166	8.44	15.3	61.34	0.69	0	18.96	12.12	78.79	46.4	1.47	5.54
15/06/2012	167	8.72	16.45	62.63	0.45	0	20.88	13.09	78.14	43.25	1.55	6.99
16/06/2012	168	11.56	17.33	56.83	0.44	0	21.54	13.5	76.22	39.04	1.99	7.52
17/06/2012	169	14.7	17.75	51.51	0.51	0	23.4	12.23	69.39	33.27	2.48	7.81
18/06/2012	170	13.35	19.52	48.48	0.48	0	24.95	14.04	68.2	32.16	2.41	9.49
19/06/2012	171	6.47	17.08	67.89	0.54	0	20.41	13.66	81.5	52.26	1.23	7.04
20/06/2012	172	13.3	18.47	62.58	0.46	0.25	23.71	13.62	87.09	38.9	2.32	8.66
21/06/2012	173	1.69	15.71	80.22	0.49	10.16	17.63	13.48	90.34	59.18	0.47	5.55
22/06/2012	174	7.5	16.17	83.8	0.42	2.54	19.9	14.04	93.37	68.63	1.29	6.97
23/06/2012	175	14.12	19.94	60.52	0.63	0	28.19	14.6	86.25	29.06	2.65	11.4
24/06/2012	176	13.85	23.44	33.93	1.55	0	29.22	18.85	52.72	18.32	3.72	14.04
25/06/2012	177	15.57	18.76	23.71	0.88	0	25.11	12.35	35.97	13.83	3	8.73
26/06/2012	178	15.19	15.9	45.94	0.53	0	21.95	9.77	73.88	22.38	2.4	5.86
27/06/2012	179	15.48	19.41	34.89	0.57	0	26.79	13.51	55.38	15.2	2.78	10.15
28/06/2012	180	12.95	17.76	51.65	0.83	0	22.31	13.68	78.65	21.86	2.3	7.99
29/06/2012	181	15.03	19.09	51.99	0.4	0	25.44	13.44	73.69	33.5	2.56	9.44

30/06/2012	182	15.22	21.25	31.03	0.62	0	27.52	16.64	47.36	15.37	2.78	12.08
						Jul-12						
DATES	**DOY**	**Rn**	**T**	**RH**	**WS**	**Rain**	**Tx**	**Tn**	**RHx**	**RHn**	**Evap**	**HU**
01/07/2012	183	15.07	19.82	34.2	0.6	0	24.85	16.08	44.24	25.1	2.69	10.47
02/07/2012	184	15.11	20.33	36.54	0.52	0	27.04	15.12	52.88	19.91	2.67	11.08
03/07/2012	185	15.03	18.74	38.48	0.6	0	23.61	15.3	51.36	28.5	2.6	9.46
04/07/2012	186	15.14	19.61	44.6	0.45	0	26.04	13.42	63.46	28.25	2.65	9.73
05/07/2012	187	2.52	16.34	64.13	1.03	0	18.8	12.38	81.89	36.87	0.81	5.59
06/07/2012	188	12.39	17.76	67.72	0.52	0	23.34	14.48	85.82	43.98	2.19	8.91
07/07/2012	189	15.06	19.54	48.28	0.52	0	26.29	13.82	78.12	23.87	2.71	10.05
08/07/2012	190	14.11	19.64	43.53	0.95	0	25.94	14.92	72.35	22.56	2.83	10.43
09/07/2012	191	7.99	17.06	77.33	0.9	0.51	20.66	14.64	94.09	56.71	1.51	7.65
10/07/2012	192	14.15	19.25	55.22	0.49	0	25.32	14.09	80.89	30.88	2.53	9.7
11/07/2012	193	13.93	20.63	42.68	0.63	0	26.35	15.92	61.22	23.74	2.61	11.13
12/07/2012	194	4.92	16.81	66.66	0.89	0	19.51	14.94	81.53	42.91	1.15	7.23
13/07/2012	195	8.66	16.71	72.12	0.41	0	21.01	12.89	88.43	52.04	1.6	6.95
14/07/2012	196	12.9	20.65	50.51	0.66	0	26.72	15.65	72.42	29.17	2.56	11.18
15/07/2012	197	16.03	17.82	24.1	1.29	0	22.65	13.19	36.37	17.02	3.32	7.92
16/07/2012	198	16.03	16.01	31.27	1.24	0	20.08	12.53	56.15	22.21	3.11	6.31
17/07/2012	199	15.56	15.18	44.92	0.69	0	21.31	8.97	66.32	25.55	2.71	5.14
18/07/2012	200	15.39	14.25	56.26	1.16	0	18.84	10.09	80.43	35.21	2.55	4.47
19/07/2012	201	15.91	15.09	52.68	0.52	0	21.9	9.3	79.67	26.96	2.56	5.6
20/07/2012	202	15.77	18.66	34.75	0.83	0	25.44	11.55	56.27	18.36	3.17	8.49
21/07/2012	203	16.4	21.2	18.69	0.94	0	27	14.98	29.04	10.44	3.42	10.99
22/07/2012	204	16.09	22.05	14.98	0.8	0	28.25	16.89	20.62	9.53	3.3	12.57
23/07/2012	205	9.09	17.3	53.3	1.17	0	20.58	12.53	78.4	14.14	1.85	6.56
24/07/2012	206	7.78	16.85	72.22	0.61	1.02	20.93	14.62	92.72	48.08	1.44	7.77
25/07/2012	207	14.39	17.81	59.13	0.7	0	22.41	14.03	71.62	42.76	2.57	8.22

26/07/2012	208	13.57	16.37	62.7	0.53	0	20.66	13.41	83.97	38.87	2.24	7.03
27/07/2012	209	15.79	19.74	34.14	0.78	0	26.6	14.28	52.32	13.52	3.06	10.44
28/07/2012	210	11.39	16.63	57.93	1.43	0	20.45	13.86	81.7	23.74	2.31	7.15
29/07/2012	211	8.28	15.32	69.81	0.67	0	19.84	13.11	88.41	45.47	1.49	6.47
30/07/2012	212	13.4	15.58	63.01	0.66	0	21.14	11.31	83.65	42.45	2.31	6.23
31/07/2012	213	13.96	18.09	47.55	0.6	0	23.86	12.12	71.22	26.82	2.55	7.99

PHALABORWA (SUMMARY)									
Year	**Month**	**Tx**	**Tn**	**RHx**	**RHn**	**Rain**	**Rs**	**U2**	**ET0**
2011	3	35.69	20.05	88.64	28.56	22.1	18.84	0.92	130.14
2011	4	29.82	16.88	91.25	41.15	65.79	14.09	0.71	85.54
2011	5	30.49	12.44	88.04	28.36	9.65	14.95	0.41	86.56
2011	6	28.16	8.68	79.59	22.26	2.54	14.04	0.46	74.26
2011	7	25.17	8.68	86.97	29.85	0.51	13.21	0.26	68.67
2012	3	33.99	19.17	87.82	30.66	53.09	12.57	0.52	88.84
2012	4	29.53	14.11	89.49	32.44	4.57	10.85	0.2	64.8
2012	5	30.12	12.34	85.7	27.32	2.03	38.67	0.4	179.62
2012	6	27.68	9.22	83.67	24.82	0	39.42	0.27	199.59
2012	7	26.86	9.06	84.46	27.63	0	39.37	0.27	203.76