EVALUATION OF THE CERES-MAIZE MODEL IN SIMULATING MAIZE (*ZEA MAYS* L.) GROWTH, DEVELOPMENT AND YIELD AT DIFFERENT PLANTING DATES AND NITROGEN RATES IN A SUBTROPICAL ENVIRONMENT OF ZAMBIA

BY

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DECLARATION

I Charles Bwalya Chisanga hereby declare that the dissertation is my own original work, and has not been submitted for a degree award in any other University.

Charles Bwalya Chisanga

28-10-2014

Date

APPROVAL

This dissertation of Charles Bwalya Chisanga was approved as fulfilling part of the requirement for the award of the degree of Master of Science in Integrated Soil Fertility Management (ISFM) by the University of Zambia.

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ABSTRACT

Crop simulation models can accurately predict yield with a priori knowledge of the soil properties and crop management practices. Generation of new information through traditional agronomic research practices is not sufficient to meet the needs for new agro-technologies and they are generally season specific, expensive and time consuming. Crop simulation models have not been widely used in sub-Sahara Africa due to lack of knowledge and under the local condition very little work has been done to evaluate the DSSAT (Decision Support System for Agrotechnology Transfer) v4.5 CERES (Crop Environmental Resource Synthesis Model) -maize model. The objective of this study was to evaluate the performance of CERES-maize model in simulating the effect of date of planting, nitrogen fertilizer and root-zone soil water profile on growth and yield of maize (*Zea mays* L.). A split-plot field experiment with three replicates was conducted at the Agricultural Field Station (15° 24' S, 28° 20' E; 1,261 m asl), University of Zambia, Lusaka during the 2013/2014 on Ustic Isohyperthermic Paleausalf. The main plot was assigned to date of planting (PD) (24th November [PD1], 8th December [PD2] and 22nd December [PD3]) and subplots were assigned to nitrogen application rates (112 and 168 kg N ha^{-1}) under rain-fed condition. Plant analysis data was observed at vegetative and reproductive stages. Treatments effects were analyzed using Analysis of Variance and mean separation by Least Square Difference using GenStat version 16. Date of planting significantly ($P < 0.05$) affected number of ears at anthesis, dough, and maturity stages, aboveground biomass and grain yield. Nitrogen application significantly affected vegetative and reproductive stages at $P < 0.05$. Grain yield production varied from 7.6 to 10.7 ton ha^{-1} based on the results of a 14-day delay in planting date which significantly decreased the biomass production. Generalized Likelihood Uncertainty Estimation (GLUE) within DSSAT v4.5 was used to compute the genetic coefficients using phenological stages, grain yield and yield components so that the observed data compared well with simulated outputs. Phenological stage deviation from the observed were from -4.0% to 14.0%. Grain yield and yield components were also accurately simulated, with prediction deviations ranging from -8.0 % to 45.0 % for the three planting dates. Grain yield root mean square error (RMSE) and normalized RMSE were 1.8 ton/kg and 21.4%, respectively. The model accurately simulated tops (aboveground biomass) weight (d-stat=0.96) and vegetative weight (d-stat=0.93) with reasonable accuracy. The leaf area index (LAI), leaf weight and stem weight were simulated with less accuracy due to poor values of forecasting efficient (-3.17 - -0.65) and d-stat (0.52 - 0.59). The LAI low coefficients of determination were due to poor performance of the model. Simulation of soil root water availability demonstrated that substantial potential yield may have been lost due to water stress under rain-fed conditions especially for the second and third date of planting. The CERES-maize model can be used to accurately predict planting date, aboveground biomass and grain yield under the local condition with reasonable accuracy. This study recommends that future studies should focus on evaluating and validating the CERES-maize model using maize and other field crops under the three agro-ecological regions of Zambia.

DEDICATION

To my wife Astridah Lombe Chisanga for her full hearted support, love and patience and to my mother Felister Manjesani. I also extend my dedication to my late father Emmanuel Musuba Chisanga.

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ABBREVIATIONS and ACRONYMS

AAO	Antarctic Oscillation
AGRA	Alliance for a Green Revolution in Africa
ANOVA	Analysis of variance
AUC	African Union Commission
CIAT	Centro Internacional de Agricultura Tropical
CERES	Crop Environmental Resource Synthesis Model
CHU	Crop Heat Units
CIAT	Integrated Soil Fertility Management
CIMMYT	International Maize and Wheat Improvement Center
CUL	Cultivar
CSM	Cropping System Model
CSO	Central Statistics Office
CSPs	Cultivar Specific Parameters
cv	Coefficient of Variation
Cwa	A humid subtropical climate (Köppen climate classification Cwa)
CTA	Technical Centre for Agricultural and Rural Cooperation
dap	Days after planting
DC	Drainage Constant
DUL	Drainage Upper Limit
DSSAT	Decision Support System for Agrotechnology Transfer
DSS	Decision Support System
DST	Decision Support Tool
EF	Forecasting Efficiency
ENSO	El Niño Southern Oscillation
ET	Evapotranspiration
FAO	Food and Agriculture Organization
FARA	Forum for Agricultural Research in Africa
FUE	Fertilizer Use Efficiency
G2	Maximum possible number of kernels per plant

G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/kernel d)
GDD	Growing Degree Days
GENCALC	Genotype Coefficient Calculator
GentState	General Statistical Package Software
GLUE	Generalized Likelihood Uncertainty Estimation
GPS	Geographical Information System
IBSNAT	International Benchmark Sites Network for Agrotechnology Transfer
ISFM	Integrated Soil Fertility Management
LAI	Leaf Area Index
LL	soil water content lower limit or permanent wilting point
K	Potassium
K_2O	Potassium Oxide
LAI	Leaf Area Index
LL	soil water content lower limit or permanent wilting point
MAE	Mean absolute error
ME	Mean error
MAFF	Ministry of Agriculture and Fisheries
MDS	Minimum Data Set
MZCER	Maize CERES file
N	Nitrogen
NEPAD	New Partnership for Africa's Development
NH_4OAc	Ammonium acetate
NSW DPI	New South Wales Department of Primary Industries
NRMSE	Normalized Root Mean Square
P	Phosphorus
P1	Thermal time (base 8°C) from seedling emergence to the end of the juvenile phase
P2	Photoperiod sensitivity coefficient (0-1.0)
P_2O_5	Phosphorus pentoxide
P5	Thermal time (base 8°C) from anthesis to physiological maturity
PAR	Photosynthetically Active Radiation

PD	Planting date
PHINT	Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances
PM	Physiological maturity
PPT	Precipitation
PWP	Permanent Wilting Point
R1	Anthesis
R4	Dough stage
R6	Physiological maturity
R7	Final harvest
REC	Regional Economic communities
RMSE	Root Mean Square Error
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Use
SAT	Saturated Water Content
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Use
SCS USDA	Soil Conservation Service, United States Department of Agriculture
SRAD	Solar Radiation
SSA	Sub-Saharan Africa
TMAX	Maximum temperature
TMIN	Minimum temperature
UNZA	University of Zambia
V	Vegetative stage
VE	Seedling emergence stage
VT	Tasseling
WUE	Water Use Efficiency
WP	Water Productivity
ZARI	Zambia Agricultural Research Institute
ZMS	Zambia Seed Company

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

1.1.1 Maize Production

Maize (*Zea mays* L.) is the third most important cereal crop species in the world after wheat and rice (NSW DPI, 2009). It is grown across a wide range of climates, but mainly in the warmer temperate and humid subtropical regions (NSW DPI, 2009; Nagaraju, 2006). In western countries maize production is highly mechanized whilst in many development countries such as Zambia, the crop is grown by small to medium-scale farmers using traditional and low-input technologies. The low cost of maize production, ease of processing and high yields make maize the most popular cereal crop worldwide (Nurudeen, 2011). Africa is a minor producer of maize by world standards, as it accounts for only 7% of global production. Average annual production in Africa was estimated at 49 million tons during the period 2005-2007 (FARA, 2009); increasing from 32 million tons during the period 1985-1987. On the other hand, most of the maize produced and consumed in Africa comes from smallholder rural farms (FARA, 2009). Jibrin *et al.* (2012) reported that small scale farmers depend on rain-fed agriculture and usually plant with the first rains to achieve food security and also to capture the flush soil nitrogen. Rain-fed agriculture often suffers from water stress caused by erratic and spatial rainfall distribution and this is one of the major causes of maize yield variation from year to year around the world (Bruce *et al.*, 2002) and Zambia in particular.

Tsimba (2011) observed that most maize planting recommendations are based on a specific set of agronomic field experiments that are rarely repeatable overtime and in space due to environmental and seasonal variation. The generation of new data through the use of traditional agronomic research practices and its publication are not sufficient to meet increasing needs for new agro-technologies (Tsuji *et al.*, 1998). Furthermore, traditional fertilizer experiments make research findings site and season specific, time consuming and expensive (Jones *et al.*, 2003). Results from fertilizer experiments take long to be published, and therefore delay the dissemination of agro-technology information to targeted farmers and other beneficiaries. Additionally, determining the optimal seasonal maize planting dates requires repeated studies over a number of seasons to capture rainfall variability.

Maize as a carbon four (C4) (tropical) plant uses carbon dioxide, solar radiation, water and nitrogen more efficiently during photosynthesis process than C3 (temperate) crops (NSW DPI, 2009). It also uses water more efficiently which is approximately double that of C3 crops grown at the same sites. In sub-Saharan Africa, agricultural production is hindered by low use of improved varieties, mineral, and organic fertilizers and low inherent highly weathered soils with low fertility (Struif Bontkes and Wopereis, 2003). Fertilizer application rates are also very low (5–10 kg/ha) in SSA, far below the target of 50 kg/ha set by the Abuja Declaration and up to ten times smaller compared with application rates in regions more economically developed (Fairhurst, 2012). To address the low fertility status of these soils and sustain relatively high yields, integrated soil fertility management (ISFM) is beeg promoted. ISFM is defined as a set of soil fertility management practices that include the use of fertilizer, organic inputs, and improved germplasm, combined with knowledge on how to adapt these practices to local conditions, thus maximizing agronomic use efficiency of the applied nutrients and crop productivity (CIAT, 2011).

1.1.2 Crop simulation models

Integrated Soil Fertility Management (ISFM) is integrated in Decision Support Tools (DSTs) and crop simulation models so as to assist diagnosis and analysis of soil fertility, yield and identify options for improving ISFM packages. DSTs and crop simulation models are recommended for evaluating site-specific ISFM technologies targeted to the diversity and dynamics of farmer environment. Crop simulation models form part of the formulation of ISFM packages as they can be used to test a combination of crop management strategies. The crop simulation models have not been widely used in sub-Saharan Africa (SSA) due to lack of knowledge on how to use them and this has prevented their widespread application (Struif Bontkes *et al.*, 2001).

Crop simulation modeling offers an opportunity to researchers, planners, policy makers and educators to explore cultivar potential for new areas before establishing costly and time consuming field experiments (Kihara *et al.*, 2012). Crop simulation models such as the Decision Support System for Agro-technology Transfer (DSSAT) has the capability of simulating crop yield, growth, nutrient use and evaluates the potential change in crop management (Ritchie *et al.,* 1995). It allows users to screen new agro-technology packages, such as a new cultivar or fertilizer management strategies.

DSSAT v4.5 (Cropping System Model) CSM -CERES-Maize model describes daily phenological development and growth in response to environmental factors (Jones and Kiniry, 1986). The model accurately predicts yield variability, nitrogen uptake and maize growth response to nitrogen (Pang *et al.*, 1997). It is the most widely used maize model (Lizaso *et al.*, 2011) and has been used to determine optimum planting date which is largely dependent on temperature (Soler *et al.*, 2005). Processes modeled by the CERES-maize model include phenological development, biomass production and partitioning among plant parts, and root system dynamics (Smith and Tirpak, 1989; Jones and Kiniry, 1986). The model has subroutines that simulate the soil water and nitrogen balance. It has the capability to simulate the effects of nitrogen deficiency and soil water deficit on photosynthesis and carbohydrate relocation in the crop components (Jones and Kiniry, 1986). Simulation results when based on reliable input data can provide critical information for defining the best nitrogen management strategies from both economic and environmental perspective (Bowen *et al.*, 1998). The CERES-maize model uses six cultivar specific parameters (CSPs) and these affect plant development rates, yield and yield components (Panda and Halder, 2010).

Literature revealed indicated that little work has been done on CERES-Maize model under local conditions in Agro-ecological Region II of Zambia; hence this study was undertaken to evaluate the effect of planting dates and nitrogen application rates on growth and yield of maize.

1.2 Main Objective

The main objective of the study was to evaluate the performance of CERES-maize model in simulating the effect of planting date and nitrogen fertilizer on growth and yield of maize.

1.2.1 Specific objectives

1. To assess the effect of planting date and N application rate on maize growth and yield;
2. To characterize the minimum data sets required by the CERES-maize model;
3. To assess the CERES-Maize model's ability to simulate responses of maize growth and yield to planting date and N application rate; and
4. To assess maize root-zone soil water availability under three planting dates and two N application rates.

1.3 Hypothesis

H_1: There are significant differences between measured and simulated output on planting date, nitrogen application rate, root-zone soil water availability, and maize growth and yield using the CERES-maize model.

CHAPTER TWO: LITERATURE REVIEW

2.1 INTRODUCTION

2.1.1 Origin and physiology of maize

The origin of maize (*Zea mays L.*) is Central America an area considered to be the home of the teosinte (*Euchleana Mexican schrad*) an ancestor of present day maize (Galinat, 1988; MAFF, 1997). Maize is a monoecious annual grass with separate male and female flowers on the same plant (MAFF, 1997). The male flowers are located at the top of the plant in the tassel while the female flowers are approximately half way down the plant in the ear shoot. The only function of the tassel is to produce enough pollen that fertilizes the ovules in the female flower (NSW DPI, 2009). The female inflorescences, the ears, develop in leaf axils on the stalk, which terminates in the male inflorescence, the tassel. The broad leaf sheaths are overlapping around the stalk and the leaves are arranged in two opposing rows along the stalk. Maize is an open as well as cross pollinated crop since the male and female flowers are separate.

2.1.2 Maize production

In 1997, FAO and CIMMYT (1997) reported that the world production of white maize was estimated at about 65 to 70 million tons, relatively small compared to the annual output of around 500 million tons of yellow maize. Maize is cultivated worldwide and represents a staple food for a significant proportion of the world's population. The United States produces 40% of the world's harvest while China, Brazil, Mexico, Indonesia, India, France and Argentina are the other top producers. Worldwide maize production was 817 million tons in 2009 - more than rice (678 million tons) or wheat (682 million tons) (FAO, 2009). In 2009, over 159 million hectares of maize were planted worldwide, with an average yield of over 5 tons/hectare (FAO, 2009). White maize plays a very important role in the diet of more than 400 million people worldwide, especially in sub-Saharan Africa (SSA) and Central America (FAO and CIMMYT, 1997). Pioneer (2013) noted that maize was the most important cereal crop in SSA and an important staple food for more than 1.2 billion people in SSA and Latin America. Maize production in Africa is predominantly rain-fed and irregular rainfall and prolonged dry spells may triggers famines. According to the 2007 FAO estimates[1], 158 million hectares of maize are harvested worldwide while in Africa harvests are from 29 million hectares, with Nigeria being the largest maize producer in SSA, harvesting 3%, followed by Tanzania[2]. Maize production in Africa is increasing faster (2.8% per annum) than global production (2.5% per annum). However, global yields are increasing faster (1.6% per annum) than yields in Africa (1.3% per annum) (FARA, 2009). In 2006, maize yield in Africa were quite low by world standards and averaged 1.7 tons/ha compared to the global average of about 5 tons/ha.

2.2 Policy Declarations

At the Abuja Summit on Food Security in Africa, African Heads of State and Government identified maize, among other crops as a strategic commodity for achieving food security and poverty reduction. African countries, regional economic communities (RECs), the African Union Commission (AUC) and the New Partnership for Africa's Development (NEPAD) were encouraged at the Abuja Summit to promote maize production on the continent and achieve food self-sufficiency by 2015 (AUC, 2006). Fertilizer use in Africa is the lowest averaging only eight kilograms per hectare and this is only 10 percent of the world average due to non-availability and high cost (Fosu *et al.*, 2004). Farmers apply about 9 kg/ha fertilizer in Africa compared to 86 kg/ha in Latin America, 104 kg/ha in southern Asia, and 142 kg/ha in Southeast Asia (Kelly, 2006). Yields have increased only marginally over the last two decades and most of the increase in production has been as a result of expanding area cultivated rather than from increased productivity. The area cultivated increased from 131 million hectares in 1986 to 152 million hectares in 2006 (FARA, 2009).

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[1] http://www.iita.org/maize accessed: 18th August 2013

[2] http://www.iita.org/maize accessed: 18th August 2013

2.3 Maize types and their uses

Maize is used in the preparation of foods or drinks, as animal feed or for industrial purposes. All parts of the crop can be used for food and non-food products[3]. Maize types are classified based on endosperm and kernel composition (Nurudeen, 2011; Australian Government, 2008; Purseglove, 1972):

2.3.1 Dent maize (Zea mays var indentata)

The seed has a cap of soft starch that shrinks upon drying and form a dent at the top of the kernel. It is the highest yielding and commonly grown for grain and silage.

2.3.2 Flint maize (*Zea mays var indurate*)

The kernel is hard and smooth. It is indigenous variety in Africa which is more resistant to storage insects like weevil than the dent and floury maize. It is predominately grown in Latin America, Europe and Africa for food use.

2.3.3 Floury maize (*Zea mays var amylaceae*)

The seed has a soft starch and is prone to storage insects and breakages than the harder types. Its endosperm is mainly composed of soft starch, making it easy to grind and process into foods.

2.3.4 Sweet maize (*Zea mays var saccharata* and *Zea mays var. rugosa*)

The seed is yellow in colour and has very high sugar content than any ordinary maize. It is also consumed in the immature stage when only about one-third of the potential grain yield has been accumulated. It is more prone to insect damage especially on the ears.

2.3.5 Popcorn (*Zea mays var evareta*)

The endosperm surrounds a small area of soft starch. This soft starch contains a significant amount of moisture which when heated, generates steam and pressure resulting in swelling and bursting giving a pop sound.

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[3] http://www.iita.org/maize accessed: 18th August 2013

2.3.6 Waxy maize (*Zea mays var. ceratina*)

The kernel contain almost entirely amylopectin as their starch rather than the normal 70% amylopectin and 30% amylose. Waxy maize is preferred for food in some parts of East Asia and for some industrial uses.

2.4 Maize husbandry

Maize is a sub-tropical plant and prefers hot sunny conditions with reliable and evenly distributed rainfall. The lowest mean daily temperature should be about 10°C for germination to occur. Maize can be grown successfully on a wide range of soils from loamy sands to clays provided there is sufficient depth and the crop is properly fertilized, soil pH ranging from 4.7-6.5. Efficient land preparation is essential if maize is to be grown successfully and weeds can be controlled by the use of hoes, cultivars or herbicides.

Rows 75-90 cm with intra row spacing of 20-30 cm is recommended to achieve the desired population in Zambia. Depth of planting is generally about 5-8 cm but this can vary with soil moisture status. Dry planting which is done before the start of the rains (2 - 3 weeks) is usually 7.5 – 10 cm so that ineffective light rainfall showers will not cause incomplete germination.

2.4.1 Maize Fertilizer and Water Requirement

2.4.1.1 Maize fertilizer requirement

The maize plant yields high dry matter and therefore, has a high requirement for nutrients especially nitrogen (N), phosphorus (P) and potassium (K) (Aldrich *et al.*, 1986). The amount of nitrogen fertilizer required by maize crop varies depending on the yield potential and the amount of residual nitrogen in the soil prior to planting. Pre-plant soil and plant tissue analysis during the season can be very useful in monitoring the nitrogen needs of the crop. N is essential for maize growth and yield, and its deficiency will reduce maize yield substantially. N rates are calculated according to maize yield potential. N rate of 170 kg/ha, 45 kg/ha and 20 kg/ha N in South Africa are recommended for yield levels of 8 t/ha, 3 t/ha and 2 t/ha, respectively. Nitrogen is applied within eight weeks after planting, depending on rainfall distribution (Aldrich *et al.*, 1986).

On the other hand, Aldrich *et al.* (1986) reported that phosphorus (P) application rates are based on soil analysis using Bray 1, Bray 2, or Ambic 1. Phosphorus application rates up to 300 kg/ha, 100 kg/ha or 45 kg/ha as P_2O_5 are applied to the maize plants for yield potentials of 8 t/ha, 3 t/ha or 2 t/ha, respectively. Potassium (K) application rates are based on soil analysis using NH_4OAc or Ambic 1. Potassium fertilizers of up to 120 kg/ha, 45 kg/ha or 30 kg/ha for yields of 8 t/ha, 3 t/ha and 2 t/ha, respectively are used. Application of lime to the soil is done to reduce exchangeable acidity to approximately 10%. Micronutrients are used to prevent zinc deficiency. Zinc-containing fertilizer mixtures are used on soils with <1.5-2 parts per million (ppm) Zinc. In acidic soils boron and molybdenum deficiency are common and hence maize seed is treated with molybdenum, boron-containing fertilizers or boron-foliar sprays are used.

In Zambia recommended fertilizer requirement for maize production per hectare is 200 - 300 kg compound D [10% N, 20% P_2O_5, 10% K_2O] as basal dressing and 200 - 300 kg Urea [46% N] as top dressing (MAL, 2012).

2.4.1.2 Maize water requirement

Maize needs 450 to 600 mm of water per season, which is mainly acquired from the soil moisture reserves (du Plessis, 2003). Shaw (1977) reported that maize generally requires 410 to 640 mm of water to product an acceptable crop yield per season while others such as Lamm *et al.* (1995) observed that normal yields with as little as 300 mm can be achieved. About 15.0 kg of grain is produced for each millimeter of water consumed (Lamm *et al.*, 1995). In order to achieve good yield, planting of maize seed should be timed to avoid moisture stress at during anthesis and grain filling stages (Jibrin *et al.*, 2012). According to Huanga *et al.* (2006), the most critical period for water stress in maize is ten to fourteen days before and after anthesis, with grain yield reduced two to three times more when water deficit coincides with flowering compared with other growing stages (Grant *et al.*, 1989). Maize grain yield reduction is correlated with kernel number per plant due to water stress at anthesis and during grain filling (Bolanos and Edmeades 1996) indicating the importance of adequate water supplies during flowering.

du Plessis (2003) observed that at maturity, each plant will have consumed 250 liters of water. Furthermore, the total leaf area at maturity may exceed one square meter per plant. Fertilizer may be applied before planting or at the same time as planting. NSW DPI (2009) reported that the demand for nitrogen increases dramatically about 40 days after seedling emergence due to increase in photosynthesis. The assimilation of nitrogen, phosphorus and potassium reaches a peak during anthesis (NSW DPI, 2009) and at maturity the total nutrient uptake of a single maize plant is 8.7 g of nitrogen, 5.1 g of phosphorus, and 4.0 g of potassium (du Plessis, 2003). By the end of flowering, the plant will have taken up more than 90% of its potassium requirement. The plant continues taking up nitrogen until about 2 weeks after flowering, and it keeps taking up phosphorus for a month after flowering (NSW DPI, 2009). Furthermore, each ton of grain produced removes 15.0 to 18.0 kg of nitrogen, 2.5 to 3.0 kg of phosphorus and 3.0 to 4.0 kg of potassium from the soil.

2.4.1.3 Factors affecting maize growth

The New South Wales Department of Primary Industries (2009) reported that reproductive development of maize is affected by moisture, temperature, pollination, growth of silks, assimilate supply and competition from other parts. Stress during pollination can have substantial effects on yield and yield components and moisture is most critical at periods from 10 to 14 days before and after flowering. The amount of water available for silk growth substantially influences when silks emerge, their rate of growth, the duration of their receptivity, and their ability to supply water and nutrients to support pollen tube growth and fusion of the gametes. Maize being a fast growing crop yields best with moderate temperatures and a plentiful supply of water. The ideal daytime temperature for normal maize growth should be 26°C to 30°C, but higher temperatures can be tolerated with full irrigation. On the other hand, temperatures higher than 38°C make it difficult to maintain adequate water movement through the plant, even under irrigation.

Yield potential of maize is dependent on the amount of intercepted solar radiation, water and nitrogen supply, moderated by factors that limit physiological processes such as temperature (Fageria, 2000). The photosynthetic efficiency of leaves is dependent on nitrogen concentration in leaves (Fageria, 2000; Muchow and Davis, 1988). Muchow and Davis (1988) noted that planting time is known to influence yield due to the effect of environmental conditions on canopy production function and crop development processes. Yield potential of maize varies according to location, variation in radiation, temperature and water supply.

Tadross *et al.* (2009) studied the changes in rainfall as it affect maize cropping, using daily rainfall observations from 104 stations across Malawi, Mozambique, Zambia and Zimbabwe. The data was used to detect trends in planting dates, rainfall cessation and duration of the rainfall season, as well as number of dry days, length of dry spells and measures of rainfall intensity during critical periods for growing maize. It was concluded that the El Niño Southern Oscillation (ENSO) was associated with changes in planting and cessation dates as well as the frequency of rain-days during the rainfall season (particularly early in the season). Antarctic Oscillation (AAO) mainly affected rain-days towards the end of the season when maize was planted late.

Banda (2005) reported that the most important climatic factor that affects maize production is the distribution in time and the amount of rainfall. It has been established that wet spells in drought years increased maize yields. According to Banda (2005), Lusaka Province is prone to one-year droughts with the most severe droughts not being the most intense droughts. It was also discovered that before 1988 few factors influenced high maize yields whilst after 1989 the factors at interplay doubled causing Lusaka Province to plummet in rank in level of maize production.

2.5 Vegetative and Reproductive Stages of Maize

There are several vegetative (V) and reproductive (R) stages of maize plant. Subdivisions of the V stages are designated numerically as VE (Emergency), V1 (collar is visible on lowest leaf), V2 (second leaf), V3 (third leaf), through V(n), where (n) represents the last leaf stage before VT (Tasseling) for the specific hybrid under consideration. The first and last V stages are designated as VE (emergence) and VT (tasseling). The (n) will fluctuate with hybrid and environmental factors.

Figure 1 and Figure 2 shows the V2 and V3 stages of a maize plant whilst Figure 3 below shows maize development stages.

The six subdivisions of the reproductive stages are designated numerically and these are: R1 (anthesis), R2 (blister), R3 (milk), R4 (dough), R5 (dent) and R6 (physiological maturity) (Ritchie and Hanway, 1993). All plants in a given field will not be in the same stage at the same time. When staging a field of maize, each specific V or R stage is defined only when 50 percent or more of the plants in the field are in or beyond that stage (Ritchie *et al.*, 1992).

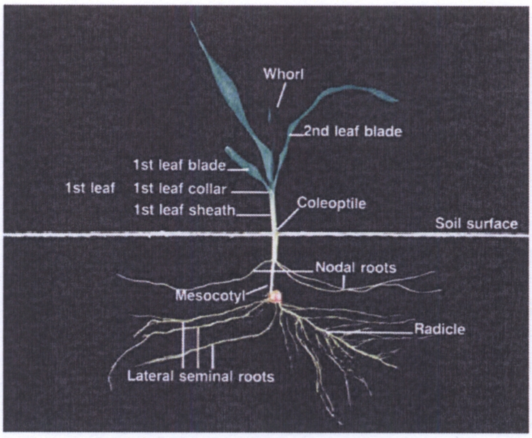

Figure 1: A V2 plant. *Source*: Ritchie *et al.* (1992)

Figure 2: A V3 plant. *Source*: Ritchie *et al.* (1992)

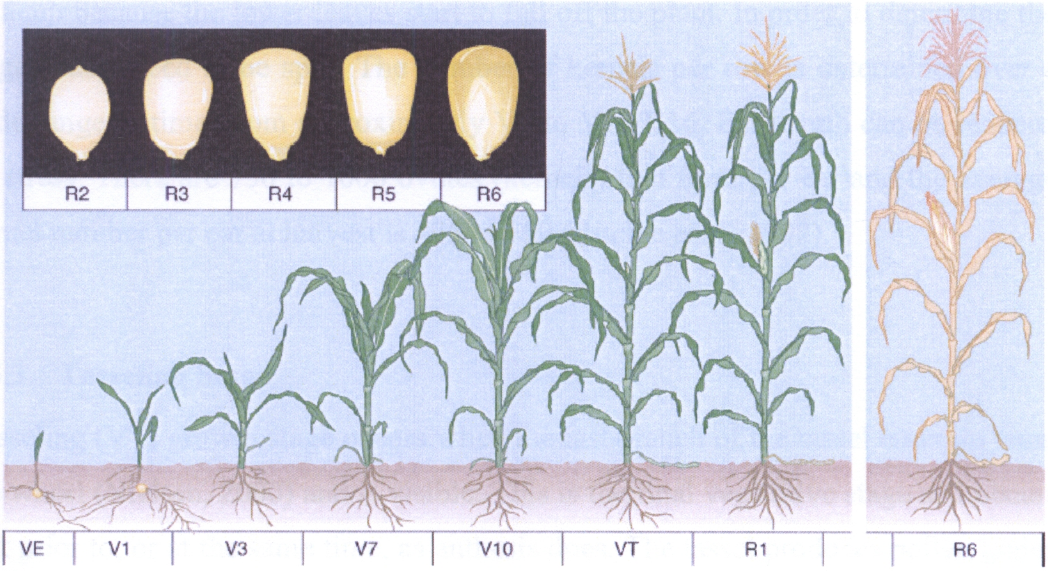

Figure 3: Maize plant development. *Source*: Nafziger (2000)

2.5.1 Germination and Emergence

Maize seed begins germination when the seed contains at least 30% moisture (NSW DPI, 2009). The first seedling structure to emerge from the maize seed is the radicle (root), followed by the coleoptile (shoot) with the enclosed plumule (first leaves and growing point). Emergence of the radicle first allows the young seedling to anchor in the soil and obtain an adequate supply of water and later obtain both water and nutrients. To emerge, the first internode on the maize plant, the mesocotyl elongates toward the soil surface and continues until the coleoptile reaches light (NSW DPI, 2009). Emergence takes place when the young shoot pushes through the soil surface. Emergence occurs within 4-5 days after planting in optimum conditions and up to 14 days in cool or dry conditions. The first leaf of the maize plant has a rounded tip which is useful for identification while subsequent leaves have pointed tips. A maize leaf consists of three distinct morphological components namely: the leaf blade, leaf collar and leaf sheath. Moreover, a new growth stage is reached for each new leaf that has a collar.

V6 is one of the key stages for development and at this point, there are six leaves with visible collars (NSW DPI, 2009; Ritchie *et al.*, 1992). At V6, the growing point is above ground, ear shoots and tassels are initiated. At V10+, staging becomes difficult because the lower leaves start to fall off the plant. In order to determine the stage, stalks need to be split. The number of kernels per row is determined over a wide range of time, from approximately V7 to V15/V16. Ear length can be reduced by stress. There are 750 to 1000 ovules (kernels) that form per ear and the average kernel number per ear at harvest is 475 to 550 (Ritchie *et al.*, 1992).

2.5.2 Tasseling Stage

Tasseling (VT) growth stage occurs when the last branch of the tassel emerges from the whorl (Nielsen, 2000) and is visible. This is the final vegetative stage and occurs just prior to, or at the same time, as anthesis does. The tassel produces pollen grains with more than half a million shed per plant per day at the peak. Pollen shed for a field typically lasts for about a week (NSW DPI, 2009). VT stage occurs two to three days before anthesis, when the last branch of the tassel is completely visible but silks have not yet emerged from the ear shoot (NSW DPI, 2009; Ritchie *et al.*, 1992). When the plant reaches full height, the pollen shedding begins and the time between VT and R1 can vary with different cultivars and due to environmental conditions. When determining reproductive developmental stages, the focus is to look at the kernels in the middle of the ear (Nielsen, 2000).

2.5.3 Reproductive Stage

The six reproductive (R) stages of maize are R1 (anthesis), R2 (blister), R3 (milk), R4 (dough), R5 (dent) and R6 (physiological maturity).

2.5.3.1 Anthesis Stage

At anthesis (R1) N and P uptake are rapid and about 50% of total N is taken up after R1 while K uptake is nearly complete (Ritchie and Hanway, 1993) and at least 50% of plants in the field will have 1 or more silks emerged. Pollen grains will land on silks and if receptive, fertilization occurs. Silks are viable and receptive to pollen for at least 5 days. The plant uses the most water per day (0.875 cm) during R1, making it very sensitive to stresses. Silks have highest water content among all parts of the maize plant and drought causes silk elongation to slow down and pollen shed to speed up (Ritchie *et al.*, 1992).

2.5.3.2 Blister Stage

At blister (R2) stage the plant has small, white kernels, and kernel fluid is clear. The R2 stage occurs about 10-12 days after anthesis. At this point the kernel is visible and resembles a blister and is filled with clear fluid. At blister stage the embryo is barely visible and contains about 85% moisture content (Ritchie and Hanway, 1993).

2.5.3.3 Milk Stage

This is the third reproductive stage (R3) and occurs approximately 18-20 days after anthesis. The kernel is colored yellow with the inside containing ‘milky’ white fluid. Kernel moisture content is approximately 80% and starch is beginning to accumulate in the kernel (Ritchie and Hanway, 1993). At R3 stage, kernels can be aborted from the tip downward if severe stress occurs such as drought. Kernel abortion will occur until the plant has a sufficient supply of carbohydrates for the remaining kernels (Ritchie *et al.*, 1992).

2.5.3.4 Dough Stage

The dough (R4) stage occurs approximately 24-26 days after anthesis. At this point, the interior of the kernel has thickened to a dough or paste-like substance. At this stage kernel moisture content is approximately 70% and kernels may begin to dent at the base of the ear and stresses may reduce kernel weight at this stage (Ritchie *et al.*, 1992). The kernel is dent on the top due to starch accumulation and is about ½ of total dry weight and five leaves will also have formed in the kernel.

2.5.3.5 Dent Stage

The dent (R5) stage is the second last stage of maize development and at the beginning of R5, kernels have 60% moisture content and stresses will reduce kernel weight at this time. R5 occurs approximately 31-33 days after anthesis. Kernels are dented in at the top with the "milk line" separating the liquid and solid (starch) portions. Within R5, kernels are often staged according to the progression of the milk line; i.e. ¼, ½, and ¾ (Ritchie *et al.*, 1992).

2.5.3.6 Physiological maturity

There is maximum dry matter accumulation at physiological maturity (R6) and kernel moisture is about 30 - 35% at physiological maturity and varies by cultivar and environment (NSW DPI, 2009). Black layer occurs after physiological maturity and serves as a visual verification that the plant is mature. At this stage external stress such as plant lodging or insect feeding can reduce maize yield (Ritchie and Hanway, 1993). Dry matter accumulation at various reproductive stages is shown in Figure 4 below. The number of days required to reach maturity depends on location and date of planting, and the weather to which the plant is subjected in a particular growing season (Vanderlip and Fjell, 2007).

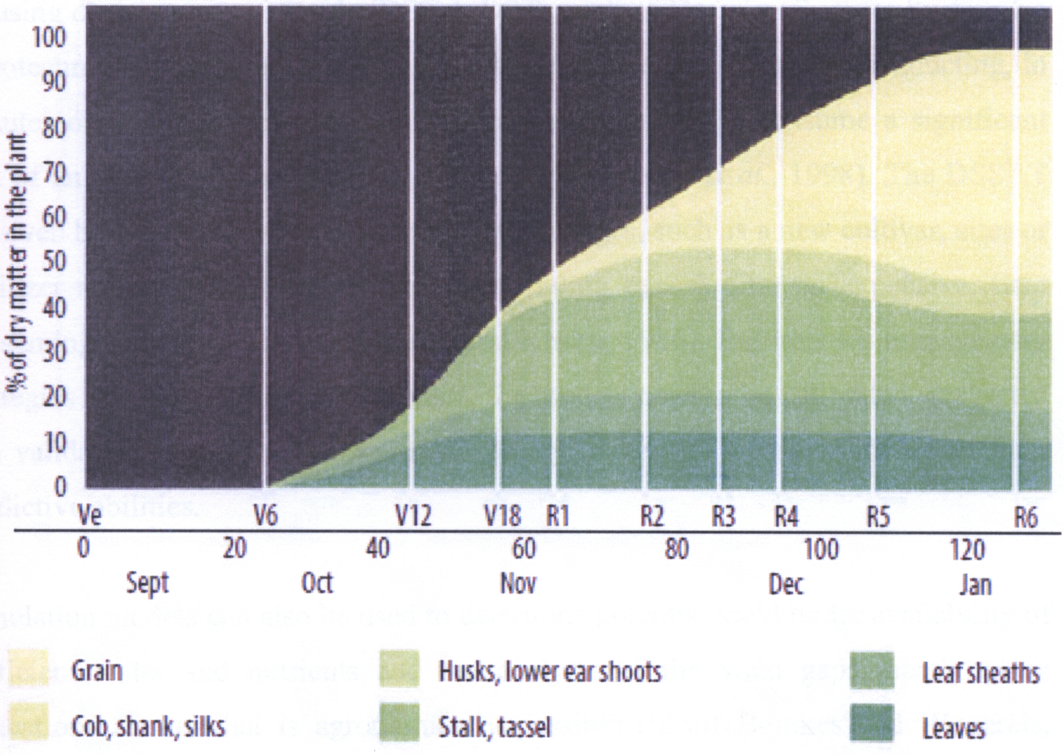

Figure 4: Dry matter accumulation at various stages in the maize plant (NSW DPI, 2009)

2.6 Crop growth Models

Cheeroo-Nayamuth (1999) observed that agricultural models are mathematical equations that try to represent the reactions that occur within the plant and the interactions between the plant and its environment. Models can be used to predict crop yields under different management scenarios as well as individual land qualities important to crop yield such as moisture, nutrient supply and solar radiation. Crop growth models integrate the effects of soils, weather, management, cultivar specific parameters (CSPs), irrigation, and pests on daily growth, and can be used to gain insight into spatial yield variability.

Fertilizer field trials are site specific and take longer periods of time for the findings to be published and disseminated to farmers. Because of this, there is need to transfer agrotechnology and solve agricultural problems through less expensive system-based research. Crop Simulation Models are therefore, used to characterize, develop and assess field crop production practices (Liu *et al.*, 2010). The use of system-based experiments can facilitate quicker agrotechnology transfer to farmers by using decision support tools (DSTs). DSTs such as Decision Support System for Agrotechnology Transfer (DSSAT) allows user to simulate results by conducting, in minutes on a desktop computer, experiments which would consume a significant part of an agronomists and soil scientist's career (Jones *et al.*, 1998). The DSSAT can even be used to screen new technology packages, such as a new cultivar, sites or fertilizer management strategy, without spending excess time on expensive, time consuming fertilizer field trials (Jones and Kiniry, 1986). Before such management strategies are made available to farmers, the models need to be calibrated, evaluated and validated in order for farmers and policy makers to have confidence in their predictive abilities.

Simulation models can also be used to determine potential yield under availability of sufficient water and nutrients and the analysis of the yield gaps merely gives indications about what is agronomically possible (Struif Bontkes and Wopereis, 2003). They can also be used for impact assessment and supporting policy decisions on temporal and spatial scales (Romero *et al.*, 2012).

2.6.1 Overview of the DSSAT

The DSSAT was originally developed by an international network of scientists, working in the International Benchmark Sites Network for Agrotechnology Transfer project (IBSNAT) (IBSNAT, 1993; Jones *et al.*, 1998). IBSNAT facilitates the application of crop models in a systems approach to facilitate agronomic research. Its initial development was motivated by a need to integrate knowledge about soil, weather, crops and management practices for making better decisions about transferring agrotechnology (IBSNAT, 1993; Uehara, 1998).

The decision support system for agrotechnology transfer (DSSAT) version 4.5 is a Windows-based computer software application programme that comprises of crop simulation models for over 28 crops. DSSAT is supported by database management programmes for soil, weather, and crop management and experimental data, and by utilities and application programs (Hoogenboom *et al.*, 2010b). Hoogenboom *et al.* (2012) reported that the crop simulation models in DSSAT simulate growth, development and yield as a function of the soil-plant-atmosphere dynamics, and they have been used for many applications ranging from on-farm and precision management to regional assessments of the impact of climate variability and climate change. All the crops share a common input-output format, and are similar in level of detail and operate on a daily time step based on an understanding of biophysical processes. The DSSAT models are process oriented, designed to have global applications, and work independent of location, season, crop cultivar, and management strategy (Jones *et al.,* 2003). It has been in use for more than 20 years by researchers, educators, consultants, extension agents, growers, and policy and decision makers in over 100 countries worldwide.

The DSSAT includes improved application programmes for seasonal, spatial, sequence and crop rotation analyses that assess the economic risks and environmental impacts associated with irrigation, fertilizer and nutrient management, climate variability, climate change, soil carbon sequestration, and precision agriculture (Hoogenboom *et al.*, 2010a; Jones *et al.,* 2003).

As a computerized system it assists planners, researchers, educators, policy makers and farmers make intelligent decisions as they seek solutions to solve specific agricultural problems. The DSSAT has advantage by reducing the time and human resources required for analyzing complex agricultural problems (Tsuji *et al.*, 1998) and provide a framework for scientific cooperation through research to integrate new knowledge in agro-technologies.

2.6.1.1 CERES-maize model

The DSSAT CERES-maize code was developed by J.T. Ritchie, U. Singh, D.C. Godwin and W.T. Bowen and the DSSAT-CSM structure is shown in Figure 5 below. CERES-maize model is a predictive, deterministic model designed to simulate maize growth, soil water, and temperature and soil nitrogen dynamics at a field scale for one growing season (Jones and Kiniry, 1986). A deterministic model is one that makes definite predictions for quantities without any associated probability distribution, variance, or random element (Brockington, 1979). The CERES-Maize model was developed for simulating the development and performance of maize and has been used as a tool for planning and decision making by farmers in several countries (Lizaso *et al.*, 2011).

Use of the CERES-maize model is a cost-effective methodology to examine the results of alternative crop management practices on agricultural production, estimate use efficiency of resources, and assess the sustainability of cropping systems. It is the most widely used maize model and is a recognized reference for comparing new developments in maize growth, development and yield simulation (Lizaso *et al.*, 2011). The model is able to accurately predict yield variability, nitrogen uptake and maize growth response to nitrogen (Pang *et al.*, 1997). It can also be used to explore the potential of new cultivars for new areas before establishing costly field experiments (Kihara *et al.*, 2012). Additionally, the CERES-maize model can also be used to determine the optimum planting dates (Soler *et al.*, 2005).

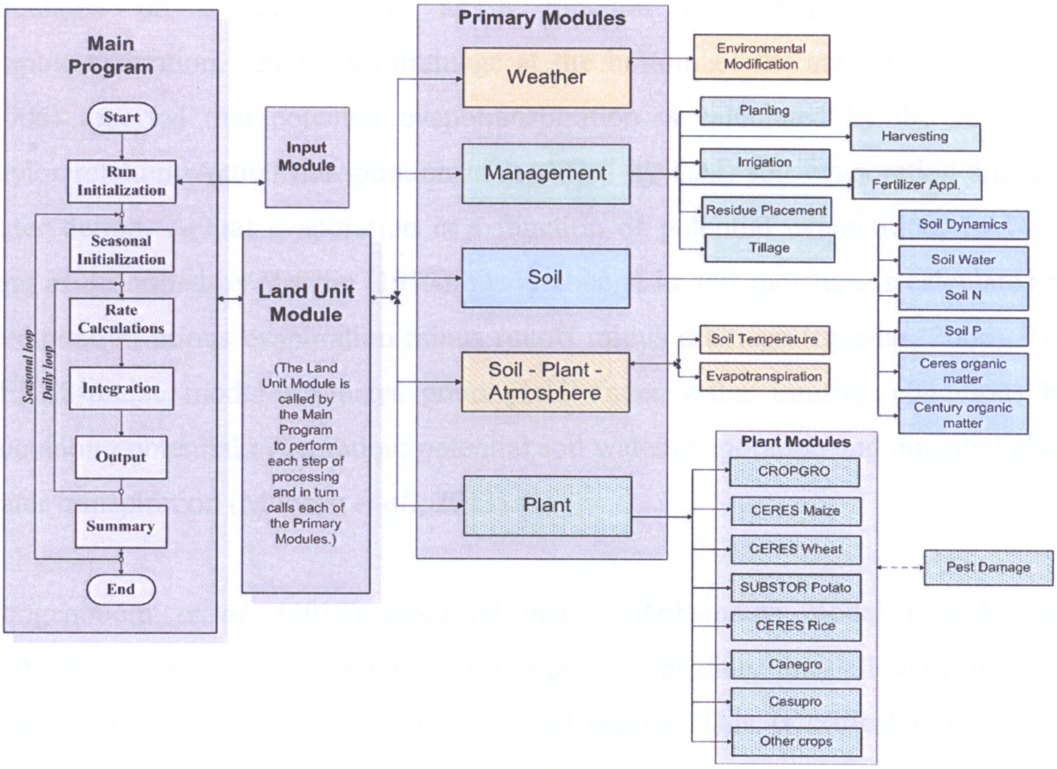

Figure 5: Overview of the components and modular structure of DSSAT-CSM (adapted from DSSAT4.5 Vol. 1, 2010)

Jones and Kiniry (1986) observed that in CERES-maize model, the potential dry matter production is calculated as a function of solar radiation, leaf area index (LAI) and reduction factors for temperature and moisture stress. Six phenological stages are simulated based on growing degree days (GDDs) which are also used to calculate leaf and stem growth rates. Available photosynthate is initially partitioned to leaves and stems and later to the ear and grain growth and any remaining photosynthate is allocated to root growth. Moreover, if dry matter available for root growth is below a minimum threshold, grain, leaves and stem allocations are reduced and the minimum level of root growth occurs. The model uses separate subroutines to calculate water balance, including runoff, infiltration, saturated and unsaturated water flow and drainage. The subroutines have the capability to simulate the effects of nitrogen deficiency and soil water deficit on photosynthesis and carbohydrate distribution in the crop (Iglesias, 2006).

The soil water balance is simulated to evaluate the potential yield reduction caused by soil water deficits (Soler *et al.*, 2005). Additionally, the soil water balance is calculated on a daily basis as a function of precipitation, irrigation, evapotranspiration, runoff and drainage at the bottom of the soil profile. Iglesias (2006) reported that potential evapotranspiration is calculated by the Priestley-Taylor relation. Actual transpiration is modified by LAI, soil evaporation and soil water deficit. Actual evaporation is a function of potential evaporation, LAI and time as described by Ritchie (1972). Daily change in soil moisture is calculated as precipitation minus evaporation minus runoff minus drainage (Iglesias, 2006). The CERES-maize model simulates grain yield under water limiting conditions by calculating potential evaporation; potential soil water evaporation and potential plant water transpiration (Mubeen *et al.*, 2013).

Hoogenboom *et al.* (2012) observed that CERES-maize model provides for evaluation of crop model outputs with experimental data, thus allowing users to compare simulated outcomes with observed results. This is critical prior to any application of the model, especially if real-world decisions or recommendations are based on modeled results. Crop model evaluation is accomplished by inputting the user's minimum data, running the model, and comparing outputs with observed data. By simulating probable outcomes of crop management strategies, CERES-maize model offers users information with which to rapidly appraise new maize varieties and practices for adoption.

2.6.1.2 DSSAT Model Data requirement

According to Hoogenboom *et al.* (2012), the CERES-maize model require daily weather data (latitude and longitude, solar radiation and daily temperature and precipitation), surface soil data and profile information (soil albedo, initial soil water content, nitrate, and ammonium and soil layer thickness), and detailed crop management data (sowing date, plant density, and irrigation schedules) and Cultivar Specific Parameters (CSPs) (genetic coefficients) as input (Ritchie *et al.*, 1989). Simulations are initiated either at planting or prior to planting through the simulation of a bare fallow period. These simulations are conducted at a daily step and, in some cases, at an hourly time step depending on the process and the crop model. At the end of the day the plant and soil water, nitrogen and carbon balances are updated, as well as the crop's vegetative and reproductive development stage.

Other data requirements includes: Saturation (SAT), drained upper limit (DUL) and lower limit (LL) and these three key levels of water availability for each layer are required as inputs (Godwin *et al.*, 1984). Timsina and Humphreys (2003) reported that soil moisture content at lower limit (LL, 15 bars), drained upper limit (DUL, 1/3 bar), and at saturation (SAT) for various depths if not available could be estimated from percentages of sand, silt, and clay and bulk density. In this current study the lower limit (LL), drained upper limit (DUL), saturation (SAT) were estimated using the soil data tool-SBuild pedo-transfer functions in DSSAT (Uryasev *et al.*, 2003).

Leaf area index (LAI) measurements provide indices of plant growth with time and are normally used as inputs for crop simulation models. Hoogenboom *et al.* (1999) reported that methods used in measuring leaf area are classified into two categories: direct and indirect. In the direct methods, the area of leaves is measured using an area meter, whereas the indirect methods employ leaf area and leaf weight relationships to estimate leaf area. Beside the two methods above, one other method is adopted from Turner and Begg (1973) and McKee (1964). This method involves measuring the length and maximum width of each green leaf on a plant and adjusting the length-width product by 0.73.

2.6.1.3 DSSAT Simulation and output files

Every DSSAT simulation consists of an Experiment file (FileX), which defines crop management for a particular experiment (set of model runs or treatments) and references soil data (FileS), cultivar data (FileC) and weather data (FileW) files (Figure 6below). These files are separated in this way because soil definitions and weather data can be used in several simulations and different crops, whereas the experimental file is unique to a particular experiment (Jones and Singels, 2008). The DSSAT SBuild programme is used for creating soil (FileS) files and each soil in DSSAT is defined as a soil profile and stored in a soil file. Soils are named, coded and the soil code is used in the experimental file to refer to soil information. Each soil profile has a number of soil layers and each layer is associated with specific physical and chemical characteristics (Jones and Singels, 2008). According to

Hoogenboom *et al.* (2010a) the model creates a number of output files for each simulation run as shown in Figure 6 below.

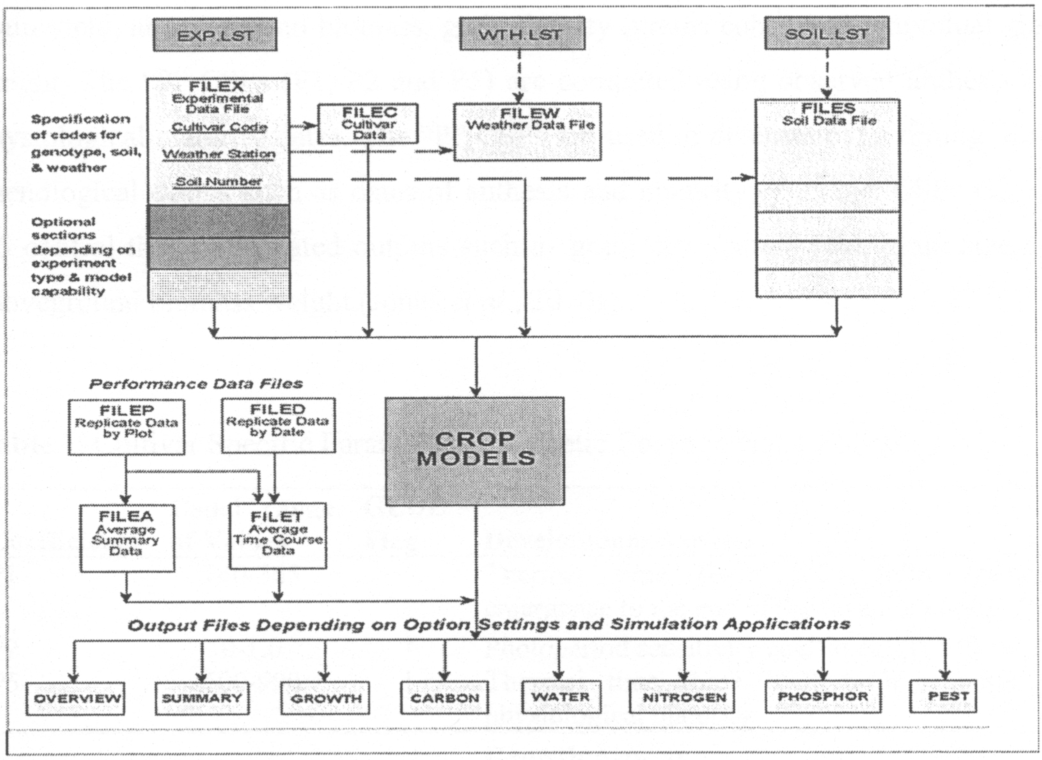

Figure 6: Overview of input and output files used by DSSAT crop models (adapted from DSSAT4.5 Vol. 1, 2010)

2.6.1.4 Calibration and Cultivar Specific Parameter Estimation

Model calibration is the adjustment of cultivar specific parameters (CSPs) so that simulated values compare well with observed field data (Jones *et al.*, 2010b).

Two methods are used with CERES-maize to obtain CSPs are: (1) direct experimental measurement; and (2) the GLUE (Generalized Likelihood Uncertainty Estimation) program. The GLUE program in DSSAT v4.5 is used for estimating CSPs of the different crops. The first tool, developed by L. A. Hunt and others, for estimating CSPs was the GENCALC (Genotype Coefficient Calculator) software available in DSSAT v 3.0 and v3.5. The GLUE CSP estimation method was integrated into DSSAT v4.5 using the R language[4], a free software environment for statistical computing and graphics (Jones *et al.*, 2010b; He *et al.*, 2010). The six

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[4] R Core Team, 2009; http://www.R-project.org

CSPs in the CERES-maize model (Jones *et al.*, 2010b) that are estimated in the DSSAT using GLUE are show in Table 1. The minimum data set required to calibrate the CSPs include emergence date, anthesis, physiological maturity date, grain yield, above ground biomass, grain density (grains cob^{-1}) and individual grain weight. The "P" CSPs (P1, P2 and P5) are computed using observed anthesis and physiological maturity dates. The "P" CSPs are used to determine the timing of the phenological events such as dates of anthesis and maturity of maize. CSPs G2 and G5 control the yield-related outputs such as grain dry matter yield, grain size and aboveground biomass weight (Jones *et al.*, 2010a).

Table 1: Cultivar Specific Parameters or Genetic Coefficients of Maize

Coefficients	**Usual range of Values**	**GLUE Flag**	**Development Aspects**
P1	140-365	1	Thermal time (base 8°C) from seedling emergence to the end of the juvenile phase
P2	0-1.0	1	Photoperiod sensitivity coefficient (0-1.0)
P5	600-990	1	Thermal time (base 8°C) from anthesis to physiological maturity
			Growth Aspects
G2	500-908	2	Maximum possible number of kernels per plant
G3	5.0-12.0	2	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/kernel d)
PHINT			Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances

GLUE flag is an indicator to show in which round of the procedure the parameter will be estimated

Source: Jones *et al.* (2010a)

According to He *et al.* (2010) computing the development CSPs, measurements of anthesis, physiological maturity, and first reproductive organ appearance dates are all used. For the growth coefficients, final grain yield, above ground biomass, maximum leaf area during the season, final main stem leaf number, and unit grain weight are used. Moreover, the measurements that go into FileA in DSSAT are used; these are variables measured only one time during the season, most of which are measured at the time of harvest.

Simulating date of tassel initiation is very important, because that is when the growing point changes from producing leaves to producing reproductive organs. Determination of tassel initiation in the field is difficult and requires destructive sampling. In CERES-maize model, tassel initiation is controlled by two coefficients: duration of the juvenile phase (P1) and photoperiod sensitivity (P2). The approximate end of P1 is assumed to be 4 days before tassel initiation (Jones and Kiniry, 1986) and for cultivars that are photoperiod sensitive, tassel initiation is delayed with photoperiods longer than 12.5 h (Hanks and Ritchie, 1991).

2.7 Data for Model Evaluation and Application

According to Kihara (2012) there are three levels or groups of crop simulation models. Level 1 defines the data required for model applications, Level 2 defines the data required for general model evaluation, and Level 3 defines the data required for detailed model calibration and evaluation. Godwin *et al.* (1984) reported that the CERES-maize model applications that may facilitate agrotechnology transfer are:

1. Identification of the physiological and phenological attributes of a cultivar needed to exploit to the maximum the climatic and soil environment to produce a higher yield;
2. Evaluation of various fertilizer management strategies such as timing, rate, and depth of incorporation at a particular site; and
3. Evaluation of irrigation and other agronomic strategies such as planting date and plant population.

2.8 Statistics for model evaluation

Willmott (1982) reported that the D-index (index of agreement), RMSEs (root mean square error systematic), RMSEu (root mean square unsystematic) and RMSE (root mean square error) are four indicators that are recommended for model evaluation. Hyndman and Koehler (2006) noted that the root-mean-square error (RMSE) is a frequently used measure of the differences between values predicted by a model and the observed value. The RMSE represents the sample standard deviation of the differences between predicted values and observed values and these individual differences are called residuals. The RMSE serves to aggregate the magnitudes of the errors in predictions for various times into a single measure of predictive power.

RMSE is a good measure of accuracy, but only to compare forecasting errors of different models for a particular variable and not between variables, as it is scale-dependent. The accuracy of the model is measured by using the RMSE (Graeff *et al.*, 2012) and the advantage of using RMSE over R^2 for model evaluation is that RMSE provides information about both on the calibration data and on new data not used in developing the model to estimate the true predictive ability of the model (Drummond *et al.*, 2003). Hyndman and Koehler (2006) noted that the mean absolute error (MAE) measures the average magnitude of the errors in a set of forecasts, without considering their direction. It measures accuracy for continuous variables and is used for comparing forecasts with their eventual outcomes.

According to Willmott (1982), the d-stat (index of agreement) of a “good” model should approach unity and the RMSEs approach zero, whereas the RMSEu should approach the RMSE. The mean absolute error (MAE) and RMSE are among the best overall measures of model performance, as they summarize the mean difference in the units of observed and predicted (Willmott, 1982) (Equations [1] and [2]). Statistics defined by Willmott (1982) should be used as an agreement index instead of correlation coefficients which has limitations. Cross-validation is another more robust, reliable method of measuring prediction accuracy (Stone, 1973) of crop models.

$$MAE = N^{-1}\sum_{i=1}^{N} | P_i - O_i | \qquad [1]$$

$$RMSE = [N^{-1}\sum_{i=1}^{n} (P_i - O_i)^2]^{0.5} \qquad [2]$$

N is the number of observed values and the O_i and P_i are observed and predicted values for the *i-th* data pair. Willmott (1982) noted that the systematic and unsystematic RMSE require calculating the intercept (a) and slope (b) of the least-squares regression, $P' = a + b0P_i$ (Equations [3] and [4] below).

$$RMSEs = [N^{-1}\sum_{i=1}^{n} (P'_i - O_i)^2]^{0.5} \qquad [3]$$

$$RMSEu = [N^{-1}\sum_{i=1}^{n}(P_i - P'_i)^2]^{0.5} \qquad [4]$$

Where P' is regarded as the best estimate of the predicted quantity (Jones *et al.*, 2010a; Savage, 1993). The advantage of RMSEs is that it indicates the bias (deviation of the actual slope value from the 1:1 line) in a particular model, instead of the random variation (RMSEu) that may occur (Jones *et al.*, 2010a; Savage, 1993). Willmott (1982) proposed an "index of agreement" (D) of the form (Equation [5]):

$$D = 1 - \left[\sum_{i=1}^{n}(P_i - O_i)^2 / \sum_{i=1}^{n}\left(|P'_i| + |O'_i|\right)^2\right] \qquad [5]$$

Where $P'=P_i-O$ (average of the observed) and $O'_i=O_i-O$. The index (D) is intended to be a descriptive measure.

Observed vs. simulated graphs, also known as 1:1 graphs are widely used in simulation evaluations (Willmott 1982; Jones and Kiniry 1986). It is appropriate to combine whatever statistical method is used with a 1:1 graph since it may be particularly helpful in identifying the pattern of differences between the predicted and observed values (Harrison, 1990).

2.9 Research works done using CERES maize model

The CERES-maize model has been extensively used and tested on different soil types and under a wide range of climatic conditions and with different types of hybrids. Pang *et al.* (1998) evaluated the CERES-maize model for characterizing nitrate leaching potential in various soil types. The research results indicated that the CERES-maize model can be used as a tool for soil specific nitrogen leaching characterization and to increase food production and for efficient use of nutrient (fertilizers) and water management (Sarkar, 2009) in both developed and developing countries. According to literature cited by Tsimba *et al.* (2005), the CERES-maize model has been evaluated in Zimbabwe, Malawi and South Africa. The model has also been extensively tested in Kenya and under tropical conditions in Hawaii, Indonesia and the Philippines. Chinene (1983) tested the CERES-maize model to simulate maize phenological development and yield components on Wahiawa silty clay in Hawaii and found a high correlation between measured and simulated values.

2.10 Limitation of modeling

Sinclair and Seligman (1996) observed that there is no universal crop model since calibration is required to make the model account for differences in cropping conditions, cultivars, and the cropping environment for the researcher's desired study site. The models need data and technical expertise and they do not provide an answer and/or a solution to all the problems and needs, therefore stakeholder interaction is essential. Simulation models are widely used in crop production studies, environmental assessment projects, and soil and landscape evaluation exercises. However, interpretation and visualization of the diverse range of agricultural model outputs is time-consuming. In addition, comparison of simulated and measured data usually requires the use of statistical packages (Garrison *et al.*, 1999; Greenwood *et al.*, 1996; Yang *et al.*, 2000). Crop growth models facilitate the extrapolation of effects on the level of single plant organs to the growth of a complete canopy over the season in a continuously changing field environment (Spliters and Schapendon, 1990).

Computer simulation modeling and agronomic experimentation are complementary endeavors in agricultural research (Bakhsh *et al.*, 2001; Thorp *et al.*, 2007) and while experimentation can provide detailed datasets that describe the conditions, processes, and management outcomes of agricultural systems, the work is usually expensive, labor-intensive, and time-consuming. Adequate funding and labor over multiple growing seasons are required to capture enough relevant information to adequately characterize the agricultural system responses to environmental conditions and management practices. However, all simulation models are developed with certain limiting assumptions and must, therefore, be adequately tested against measured data to ensure that the simulation results are reasonable (Thorp *et al.*, 2009).

Lobell and Burke (2010) reported that low coefficient of determination (R^2) between predicted and observed values are due to poor performance or a poor job by the model in representing crop yield responses to climate. Statistical models are not without serious shortcomings, however, and in particular they are subject to problems of co-linearity between predictor variables such as temperature and precipitation, assumptions of stationarity that past relationships will hold in the future, even if management systems evolve, and low signal- to-noise ratios in yield or weather records in many locations. Co-linearity and signal-to-noise are factors that challenge statistical approaches and these vary with scale. It is therefore important to evaluate statistical models at a range of different spatial scales.

CHAPTER THREE: MATERIALS AND METHODS

3.0 Study Area

The field experiment was conducted at the School of Agricultural Sciences Field Station, University of Zambia, Lusaka (latitude 15° 24' S, longitude 28° 20' E and elevation 1,261 meters above sea level). The study area is located in Agro-ecological Region II of Zambia which constitutes the central plateaux with rainfall of 800 to 1,000 mm. The soil for the study site was classified as Ustic Isohyperthermic Paleausalf according to the USDA Soil Taxonomy (SCS, USDA. 1984). According to the Koppen-Geiger climate classification, agro-ecological Region II is a humid subtropical climate (Cwa) (warm temperature, winter dry, hot summer) subtropical with warm to wet hot summers (October to April) and cool dry winters (May to September) (Kottek *et al.*, 2006).

3.1 Experimental Field Description

3.1.1 Experimental Design and Agronomic Practices

The experiment was a split plot design replicated three times. The main plots were the planting dates at a 14 day spacing (24th November [PD1], 8th December [PD2] and 22nd November [PD3] 2013) and subplots were nitrogen application rates (112 [N1] and 168 [N2] kg N/ha). Subplots were arranged in five rows of 5 meter length. A medium maturing three-way white maize hybrid (ZMS 606 cultivar) with maturity ranging from 125 – 130 days was used in the study. Fertilizer application rates consisted of two D-compound NPK (200 and 300 kg ha^{-1} of 10% N, 20% P_2O_5, 10% K_2O) as basal dressing and urea (200 and 300 kg ha^{-1}) as top dressing. Nitrogen fertilizer applied were: 20 kg N ha^{-1} and 30 kg N ha^{-1} as basal dressing per main plot to subplots and banded beneath the soil surface. Top dressing of 200 kg urea ha^{-1} (92 kg N ha^{-1}) and 300 kg urea (46% N) ha^{-1} (138 kg N ha^{-1}) were used as the two N application rates. The total N rates applied per ha were 112 kg as N1 and 168 kg as N2, respectively. Urea was applied once in the eighth week from germination before tasseling stage. In this study the two N rates were used as they are the recommended requirement in kilogram per ha as basal dressing (20 and 30) and top dressing (92 and 112) for small-scale and commercial farming (MAL, 2012), respectively.

The planting distance was 0.75 m between rows and 0.30 m between plants to give a plant population of 44, 444 plants ha^{-1} (4.4 plants m^{-2}). The maize seeds were planted directly at a depth of 7 cm. Three seeds were planted and later thinned to one plant per hill. Thinning was done after the plants were well established. Phenology was observed independently in the subplots per each main-plot. The experimental plot layout is as shown in Figure 7 below.

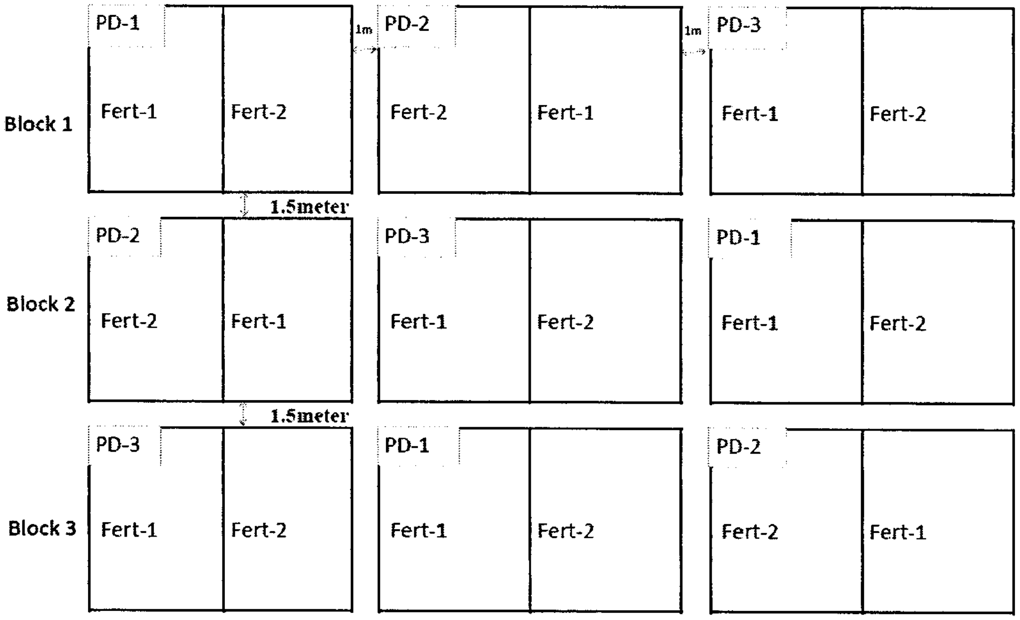

Figure 7: Experimental plot layout for the treatments

3.1.2 Weed control and plant protection measures

The experimental plots were kept free from weeds throughout the crop growth periods by pre-emergent application of MRI 700 Glyphosate (Glyphosate acid 700g/kg) at 3 kg/ha and manually with a hoe where necessary. Adequate plant protection measures were adopted to control the major insect pests and diseases. On 23rd December 2013 Atrazin (485g/L [3 litre/ha]) was applied to control broad leaf weeds. To control stalk borer AVI-Monocrotophos (monocrotophos 400g/l) at 75 ml/ha was sprayed to all the plants.

3.1.3 Climatic and physio-chemical parameter data collection

Hoogenboom *et al.* (2010a) indicated that the minimum data set (MDS) required to run the CERES-maize model and evaluate the simulation and outputs are: daily weather data (air temperature, rainfall, relative humidity, wind speed and solar radiation); soil characterization data (physical, chemical and morphological properties for each layer); cultivar specific parameters (CSPs); crop management data; and observed field experimental data. The study followed the standard data collection procedures as suggested by IBSNAT in Technical Report I (IBSNAT, 1988) and Hoogenboom *et al.* (1999).

3.1.3.1 Soil sampling, preparation and characterization

Sampling of the soil for initial conditions was done on 20th November 2013. Soils were tested for soil water content, ammonium and nitrate content at depths of 0-20, 20-40, 40-60, 60-100 cm with a soil auger. A 2 meter profile pit adjacent to the experimental field was used to collect core-ring samples for the determination of bulk density. The bulk density was determined using the core ring method from soil samples collected at soil depths of 0-20, 20-40, 40-60, and 60-100 cm according to the IBSNAT (1988).

The collected soil water content data by layer was used to run the water balance sub-module of the CERES-maize model. Soil samples taken from the experimental field for physical analysis were air dried by placing them on shallow trays in a well-ventilated area. The sampled soil was sieved through a 2 mm sieve, by gently rubbing the aggregates through the sieve.

Particle size distribution was determined from soil samples collected with an auger from each subplot at depths: 0-20, 20-40, 40-60, and 60-100 cm using the Hydrometer Method (Bouyoucos, 1962) while the volumetric water content (cm^3/cm^3) was determined according to Hoogenboom *et al.* (1999) and IBSNAT (1988). Mechanical analysis using the hydrometer method is presented in Table 2.

Soil physio-chemical and morphological properties were analyzed using standard methods. Samples from each layer and subplot were mixed thoroughly to form a composite sample and a subsample of 200 g collected for soil chemical analysis. The following parameters were chemically analyzed: organic carbon (%), total nitrogen (%), pH in water, and buffer, phosphorus extractable (mg/kg), potassium exchangeable (cmol/kg), NH_4-N (g[N]/mg soil), NO_3-N (g[N]/mg soil)] and cation exchange capacity (CEC) (cmol/kg) for each soil profile. Soil chemical analysis was done at Zambia Agricultural Research Institute (ZARI) while soil physical analysis was carried out at the University of Zambia (UNZA). The pH of the soil in water ranged from 6.5 to 6.9 which is considered within the neutral to optimal range for crop growth. The nitrogen percentage was determined using the Kjeldahl method and the values ranged from 0.01 to 0.06 percent and therefore considered low. Soil organic carbon (OC) was determined using the Walkley and Black method (Black *et al.*, 1965) and values ranged from 0.18 to 0.66 and considered to be low. The critical value for OC is 1.58 percent. The Walkley-Black Method can recover about 76% of carbon though variable (Cheatle and Van't Klooster, 1984). Bray I was used to determine exchangeable phosphorus (P) while ammonium acetate (NH_4OAc) was used to determine the exchangeable bases (calcium, magnesium and potassium). The exchangeable bases Ca^{2+}, Mg^{2+} and K^+ were extracted with 1.0 *M* neutral NH_4OAc extract (Black *et al.*, 1965). After the extraction, the Ca^{2+} and Mg^{2+} were determined using a Perkin-Elmer atomic absorption spectrophotometer at wavelength of 422.7 nm and 285 nm respectively. K^+ was determined by an Eppendorf flame photometer at wavelengths of 766.5 nm. The soil characterization data is shown in Table 2 below.

Table 2: Soil parameters characterized and entered in FileX and FileS in DSSAT

Variables	Units	Layer (cm)				critical values	Method employed
Horizon		0-20	20-40	40-60	60-100		
Soil initial conditions							
Textural class (USDA)		Loam	Clay	Clay	Clay		
Sand	%	42.0	24.0	28.0	22.0		Hydrometer method (Bouyoucos, 1962)
Silt	%	31.6	33.6	31.6	33.6		
Clay	%	26.4	42.4	40.4	44.4		
Vol. water PD1	cm^3/cm^3	0.142	0.138	0.135	0.109		SCS, USDA. 1984; Hoogenboom *et al.*,1999
Vol. water PD2	cm^3/cm^3	0.155	0.139	0.146	0.141		
Vol. water PD3	cm^3/cm^3	0.161	0.133	0.144	0.128		
NH_4	g[N]/mg soil ($x10^{-4}$)	85.4	5.04	4.48	6.72		Modified Kjeldahl's method (Page *et al.*, 1982)
NO_3	g[N]/mg soil ($x10^{-4}$)	4.06	5.32	3.78	6.86		
pH ($CaCl_2$)		6.2	6.5	6.2	6.4	4.5	1:1 Soil to H_2O (Hoogenboom *et al.*,1999)
pH (water)		6.5	6.7	6.9	6.9	-	
OC	%	0.66	0.60	0.34	0.18	1.58	Walkley and Black method
Total N	%	0.06	0.04	0.02	0.01	0.10	Modified Kjeldahl's method (Page *et al.*, 1982)
SOC	%	2.2	2.6	2.4	2.0		Hoogenboom *et al.* (1999)

CEC; Vol. water: Volumetric water; PD: Planting date; OC: organic carbon; SOC: soil organic carbon; Cation exchange capacity, LL, DUL and SAT: lower limit, drained upper limit and saturated limit of available soil water; BD: Bulk density

Table 2 cont'd

P extractable	mg/kg	33	19	8	3	15	Bray 1 method (SCS, USDA. 1972)
Ca exchangeable	cmol/kg	3.74	1.36	2.77	1.09	1.00	Ammonium acetate (Black *et al.*, 1965)
Mg	mg/kg	79	31	81	55	50	
K exchangeable	cmol/kg	0.450	0.079	0.235	0.056	0.102	
CEC	cmol/kg	12	10	15	8		
Magnesium	mg/kg	79.00	31.00	81.00	55.00	50.00	
DUL	cm^3/cm^3	0.280	0.368	0.356	0.370		Soil data tool-SBuild pedo-transfer functions in DSSAT (Uryasev *et al.*, 2003; Ritchie *et al.*, 1999).
LL	cm^3/cm^3	0.167	0.252	0.240	0.375		
SAT	cm^3/cm^3	0.376	0.374	0.370	0.375		
Sat hydraulic conductivity	cm/h	1.32	0.06	0.06	0.06		
Root growth factor		1.000	0.548	0.368	0.202		
BD	g/cm^3	1.65	1.66	1.67	1.65		Core sampler technique (SCS, USDA. 1984)

CEC; Vol. water: Volumetric water; PD: Planting date; OC: organic carbon; SOC: soil organic carbon; Cation exchange capacity, LL, DUL and SAT: lower limit, drained upper limit and saturated limit of available soil water; BD: Bulk density

In each sampling experimental plot, 2 meter length access tubes were installed for root zone moisture monitoring during the experimental period using the Diviner 2000 series II (Figure 8). The access tubes were installed at the center of each subplot and soil water content readings taken two to three times per week to the depths of 160 cm. A series of readings taken by the Diviner 2000 series II help to show trends in crop water use in the soil profile (Sentek, 2009).

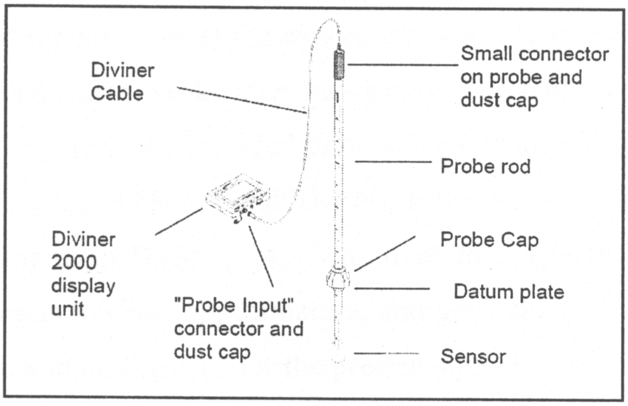

Figure 8: Components of the Diviner 2000 display unit and probe

3.2 Measured parameters

CERES-maize model input data included: Weather data; Soil data; Crop management practices; Observed aboveground biomass; and Genetic coefficients. The CERES-maize model calibration, simulation and evaluation was accomplished by creating experimental (FileX,) soil (FileS), weather (FileW), in-season growth data (FileT) and summary averages (FileA) data files, running the model, and comparing measured verses simulated outputs. DSSAT v4.5 XBuild programme was used for entering and editing of the experimental data file. DSSAT v4.5 ATCreate programme tool was used for entering and editing detailed growth analysis measurements (aboveground biomass, leaf weight, stem weight, grain weight, ear mass, number of ears per square meter, grain number per square meter and leaf area index-green leaves) and soil water content versus depth. ATCreate programme requires information on average performance for each treatment recorded during the course of the growing season of the crop (FileT) and at the end of the season

(FileA). FileT and FileA were created using phenology, biomass measurements and soil water content collected from each treatment.

3.2.1 Weather Data

Daily maximum and minimum air temperature (°C), rainfall (mm), relative humidity (%) and solar radiation data (MJ/m^2-day) was obtained from an automated weather station of the School of Agricultural Sciences, University of Zambia situated adjacent to the field experimental plots. The length of weather records for evaluation at minimum covered the duration of the experiment and began a few weeks before planting and continued a few weeks after harvesting. The daily weather input data columns in weather file (FileW) included date, solar radiation (SRAD), maximum and minimum temperatures (TMAX and TMIN), sunshine hours and rain (RAIN). WeatherMan programme in DSSAT v4.5 was used to create the FileW and this programme assists users in cleaning, formatting and generating weather and climate data. The weather data input file used for the present study is given in Appendix 1.

Plants require a specific amount of heat to develop from one point in their life-cycle to another, such as from seeding to the six-leaf stage and this heat is called Growing Degree Days (GDD) or heat units and are calculated for each day starting the day after planting. Cumulative growing GDDs and crop heat units (CHUs) were computed from the minimum and maximum temperatures (Brown, 1997) using Equations [6] and [7]. A CHU is a measure of the heat accumulated over the growing season specific to the physiological needs of a maize plant. Maize has a base temperature of 8°C and each maize hybrid has a certain GDD requirement to reach maturity (Neild and Newman, 1987).

$$GDD = \sum\left(\left(\frac{T_{\max} - T_{\min}}{2}\right) - T_{base}\right) \qquad [6]$$

$$Daily\ CHU = \frac{\left[1.8(T_{\min} - 4.4) + 3.33(T_{\max} - 10) - 0.084*(T_{\max} - 10)^2\right]}{2} \qquad [7]$$

3.2.2 Soil data and initial conditions

The DSSAT CERES-maize model uses a simple, multilayered one dimensional soil-water balance model developed by Ritchie (1985). The initial soil profile conditions entered in FileX were initial soil water content (cm^3 cm^{-3}), initial nitrate (g[N] mg^{-1} soil), ammonium (g[N] mg^{-1} soil) and phosphorus (mg kg^{-1}). Other parameters entered in FileX were: percent sand, percent silt, percent clay, pH in water, percent organic carbon, percent total N, cation exchange capacity (CEC) (cmol kg^{-1}), exchangeable potassium (cmol kg^{-1}) and extractable phosphorus (mg kg^{-1}). Soil data tool (SBuild) under the tools section in DSSAT v 4.5 was used for the creation and editing of soil profile database used for general simulation purposes (Hoogenboom, *et al.*, 1999; Ritchie *et al.*, 1990; IBSNAT, 1988). The soil surface and soil profile data is required by the model to run the simulations. If the initial conditions are not defined, the model normally defaults to a 0 value for all the soil nutrients, while the moisture is set to the drained upper limit.

3.2.4 Observed aboveground biomass data

Hoogenboom *et al.* (1999) indicate that there should be three biomass harvests at phenology stages as shown in Table 3 before the final harvest of the maize. In this study aboveground biomass harvests were done at vegetative (V) and reproductive (R) stages: V6 (50% of plant with collar of 6th leaf visible), R1 (50% of plants with some silk visible outside husks), R4 (50% of plants in "dough" stage – endosperm with pasty consistency – often 24-28 days after anthesis) and R6 (50% of plants at physiological maturity) growth stages (IBSNAT, 1988).

Table 3: Growth analysis and biomass harvest

Crop	Harvest #	Code	Growth stages Description
Maize	1st	V6	50% of plant with collar of 6th leaf visible
	2nd	R1	50% plants with some silks visible outside husks
	3rd	R4	50% plant in "dough" stage-endosperm with pasty consistency-often 24-28 days after anthesis
	Final harvest	R6	50% of plants with black layer at the base of the seed. Also in the absence of a black layer, grains become shiny and translucent.

One (1) meter plant row length was marked with sticks at three observation units in each of the main treatment. Observations at specified V-and R-stages were done on the 1-meter row length. The number of plants that had emerged were counted and recorded in each 1-meter row section on each day. The average number of plants (50 percent of the plants with some part visible at the soil surface) that had emerged on each day was calculated in 1-meter row length of plants. The day at which >50% emergence relative to the final count was recorded as VE (emergence). Total number of plants per meter row length was counted at emergence and data reported as plants per meter.

The numbers of plants bearing silk were counted on every alternate day when silk appearance started. Dates at which the vegetative (V) and reproductive (R) growth stages occurred were recorded and the phenology for the vegetative (V) phase was recorded by counting the leaves' collar appearance on a daily basis for all the treatments. The day when 50 percent of plants in the 1-meter observational rows reached the V and R phase, the date was recorded, biomass harvested, oven dried and expressed as g m^{-2} (Table 4). To harvest all the aboveground biomass, a knife was used to cut the plant close to the ground as possible. Harvested materials were weighed and placed in paper bags and oven dry at 70°C to constant weight for 7 days in order to determine the dry weights of above ground biomass (leaf blade, leaf sheath stems, and tassel, cob and grain). Physiological maturity was determined by regularly sampling on cobs per plot to assess the presence of black layer at the base of the grain, indicating that no further accumulation of grain starch was possible

(Daynard and Duncan, 1969). Grains were removed from the base, middle and distal end of each cob. Days to physiological maturity was recorded when at least 75 % of the grains in each cob had black layer (Figure 9). Ramawat *et al.* (2012) observed that to establish physiological maturity stage, 2 cobs per plot can randomly be taken from sampling row on alternate days and oven dried at 70°C. Oven dried grains can be threshed and 100 grains counted and their weight recorded. This procedure is continued till the two consecutive readings of 100-grain weight became constant.

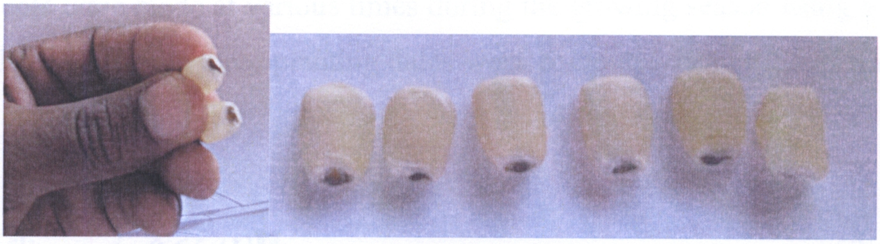

Figure 9: Maize grain in physiological maturity (Black layer)

Table 4: Data collection schedule

Parameter	**PD1**		**PD2**		**PD3**	
	N1	**N2**	**N1**	**N2**	**N1**	**N2**
Levels of N (kg/ha)	112	168	112	168	112	168
Land preparation	14-17th November2013					
Pre-plant sampling	20th November 2013					
Planting date and basal dressing	24th November 2013		8th December 2013		22nd December 2013	
Thinning date	18th December 2013		3rd January 2014		17th January 2014	
Top dressing	13th January 2014		27th January 2014		10th February 2014	
Vegetative stage						
VE	1st December 2013		16th December 2013		28th December 2013	
V1	3rd December 2013		19th December 2013		30th December 2013	
V2	5th December 2013		22nd December 2013		2nd January 2013	
V6	26th December 2013		8th January 2014		20th January 2014	
VT	31st January 2014		14th February 2014		25th February 2014	
Biomass sampling						
V6	26th December 2013		8th January 2014		20th January 2014	
R1 (Anthesis)	2nd February 2014		16th February 2014		27th February 2014	
R4 (dough stage)	27th February 2014		13th March 2014		25th March 2014	
R6 (Physiological maturity)	6th April 2014		15th April 2014		3th May 2014	
R7 (Final harvest)	23rd April 2014		1st May 2014		15th May 2014	

3.2.5 Crop management practices

Crop management practices data collected during the study included: Number of days to 50% tasseling, Anthesis day (50% anthesis, dap), one hundred seed weight, Physiological maturity day (dap), Yield at harvest maturity (kg [dm]/ha), Number at maturity (no m^{-2}), Tops weight at maturity (kg [dm]/ha), By-product produced (stalk) at maturity (kg[dm]/ha, Maximum Leaf area index (LAI)-green leaves, Harvest index at maturity, Tops weight at anthesis (kg [dm]/ha), Number of kernels per plant, leaf number per stem at maturity and Emergence day (dap).

In this study the LAI measurements were estimated from green canopy cover measurements obtained using a digital camera. The canopy cover (CC) measurements were made at various times during the growing season using a digital camera. The LAI for the three planting dates were computed from the CC (Hsiao *et al.*, 2009) using equation [8]:

$$CC = 1.005[1 - \exp(-0.6LAI)]^{1.2} \qquad [8]$$

Maturity was determined when all the silk appeared dry and the eye of the grain appeared dark. The top weight at maturity was calculated by adding the weight of the stover (leaf blade, leaf sheath, stem, and tassel, cob and husk) and seeds and expressed as kg[dm]/ha. The harvest index was calculated as a ratio of grain yield (kg/ha) and aboveground biomass (tops) weight at maturity (kg[dm]/ha) using the grain yield and yield components. The unit grain weight of a single grain from each plot was weighed and recorded in gram (g).

3.2.6 Procedure for Final Harvest

Harvest at maturity included harvestable plant identification, harvesting, plant preparation and drying procedures. Procedures proposed by Hoogenboom *et al.* (1999) and IBSNAT (1988) were used in conducting the final harvest of biomass and cobs. For each treatment, a net plot of 11 m^2 was used to harvest the maize at maturity. A sub-sample of ten (10) representative ears for dry weight and seed number determination was selected and undried ear subsample weight was recorded. Seeds were removed from the cob of subsample and seed subsample weight (undried) was recorded. Three sets of 100 seeds were counted and the average weight computed. The seed and cob of subsample were dried to constant weight at

70°C for 7 days. The weight of dry seed and cob of subsample was recorded separately. The number of seed (seed/m^2), dry seed weight (g/m^2) and dry cob weight (g/m^2) were calculated according to equations [9], [10] and [11] below and data recorded.

$$\begin{matrix} seed\ no \\ (seed/m^2) \end{matrix} = \frac{ear\ wt\ (undried)\ X \dfrac{\begin{matrix} seed\ subsamp. \\ wt\ (undried) \end{matrix}}{\begin{matrix} ear\ subsamp. \\ wt\ (undried) \end{matrix}}\ X \dfrac{100}{100\ seed\ wt}}{harvest\ area} \qquad [12]$$

$$seed\ wt.\ dry\ (g/m^2) = \frac{ear\ wt\ (undried)\ X \dfrac{\begin{matrix} seed\ subsamp. \\ wt\ (dry) \end{matrix}}{\begin{matrix} ear\ subsamp. \\ wt\ (undried) \end{matrix}}}{harvest\ area} \qquad [13]$$

$$cob\ wt.\ dry\ (g/m^2) = \frac{ear\ wt\ (undried)\ X \dfrac{\begin{matrix} cob\ subsamp. \\ wt\ (dry) \end{matrix}}{\begin{matrix} ear\ subsamp. \\ wt\ (undried) \end{matrix}}}{harvest\ area} \qquad [14]$$

Ten (10) representative plants were selected out of the fifty plants. The plants were separated into the following plant components: leaf blade, husk, leaf sheath and stem (including tassel). The undried weights of each plant component was weighed and logged. After chopping the components separately, a well-mixed, 500 g subsample (undried) of each component was weighed and logged. The components were oven dried to constant weight at 70°C for 7 days. The dry weights of leaf blade, leaf sheath, stem (including tassel) and husk were weighed and calculated in g/m^2. The dry leaf blade, leaf sheath, stem (including tassel), and husk plus cobs were computed using equation [15]. The dry stover weight was calculated using equation [16] while aboveground biomass was calculated using equation [17]. The three equations are shown below:

$$\begin{matrix} leaf\ blade \\ wt.\ dry\ (g/m^2) \end{matrix} = \frac{leafblade\ wt\ (undried)\ X \dfrac{\begin{matrix} leafblade\ subsamp. \\ wt\ (dry) \end{matrix}}{\begin{matrix} leafblade\ subsamp. \\ wt\ (undried) \end{matrix}}}{harvest\ area} \quad [18].$$

$$\begin{matrix} stover\ wt. \\ dry\ (g/m^2) \end{matrix} = \begin{matrix} leafblade \\ wt.\ (dry) \end{matrix} + \begin{matrix} leafsheath \\ wt.\ (dry) \end{matrix} + \begin{matrix} stem \\ wt.\ (dry) \end{matrix} + \begin{matrix} (cob + husk) \\ wt.\ (dry) \end{matrix} \quad [19]$$

$$\begin{matrix} aboveground \\ biomass\ dry\ (g/m^2) \end{matrix} = \begin{matrix} seed\ wt. \\ (dry) \end{matrix} + \begin{matrix} stover\ wt. \\ (dry) \end{matrix} \quad [20]$$

3.3 Model calibration and computation of cultivar specific parameters

The Generalized Likelihood Uncertainty Estimation (GLUE) was used to compute the cultivar specific parameters for the CERES-maize model. The "P" CSPs (P1, P2 and P5were computed using observed emergence, anthesis and physiological maturity dates. The values for the thermal time from seedling to emergence to the end of juvenile phase (P1), photoperiod sensitivity coefficient (P2), and thermal time from anthesis to physiological maturity (P5) were calibrated to 213.8, 0.831 and 822.5 respectively. A comparison between the observed and simulated anthesis day (dap)) and emergence (dap) showed good correspondence for all planting dates at all treatment levels. The final grain yield, above ground biomass, harvest index, leaf number per stem at maturity, tops weight at maturity, stem weight at maturity and unit grain weight were used to compute the growth coefficients (G2 and G3). The yield and yield component variables at harvest were measured only one time during the season and entered into FileA in DSSAT (He *et al.*, 2010). The Potential kernel number per plant (G2) and potential kernel growth rate (mg seed^{-1} day^{-1}) (G3) and Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances (PHINT) CSPs were 979.7, 9.791 and 60.00, respectively. The computed CSPs values for ZMS606 cultivar were copied into the cultivar (CUL) file (MZCER045.CUL) to operate the simulation in DSSAT applications and used for further model evaluations.

3.3 Water Productivity

Water productivity is the response of the yield produced by a crop to the amount of water used. Water productivity was calculated using the following parameters: grain yield from the observed and predicted, total amount of precipitation received during the growing season and the actual amount of water used by the crop during the same period. Water productivity was calculated using equations [21] and [22] below:

$$Water\ productivity\ under\ PPT\ \left(kg/ha/m^3\right)=\frac{Grain\ yield}{Total\ precipitation} \qquad [23]$$

$$Water\ productivity\ under\ ET\ \left(kg/ha/m^3\right)=\frac{Grain\ yield}{ET} \qquad [24]$$

Where: ET = evapotranspiration

PPT = precipitation

3.4 Sensitivity Analyses

Sensitivity analysis is defined as the percentage change in model output parameters due to variations in input parameters (Savage, 2001). The CERES-maize models' ability to simulate response of maize yield to three planting dates, soil water availability and N application rate was analyzed. The sensitivity analysis was performed to quantify the impact of soil types, weather (solar radiation, temperature and precipitation) and CSPs (G2 and G3) on model output using the fully calibrated CERES-maize model. It is site and condition-dependent; therefore, it is an essential step in model evaluation (Penning de Vries and Van Laar, 1982). Environmental modification on temperature, rainfall and solar radiation were made and evaluated. The effects of the changes in CSPs (G2 and G3) inputs parameters were considered on grain yield, tops weight at anthesis and tops weight at maturity. This was done to ascertain their impact on aboveground biomass and grain yield. The virtual experiment was based on a crop management scenario and N application rates for the current study. The percentage change was calculated by the difference in output value divided by a base output value and multiplied by 100. A positive sign of the percentage change reflected an increase in output, while a negative sign meant a decrease in output using Equation [25].

$$Percentage\ change = \frac{output\ 2 - output\ 1}{output\ 1} \qquad [26]$$

Where: Output 1 = base input

Output 2 = output change as a result of changes in input parameters.

3.5 Seasonal Analysis

The calibrated CERES-maize model was used to simulate maize yields through seasonal analysis program utilizing the same weather data, soil data, cultivar and experimental file in performing multiple runs of the model for one season. In undertaking seasonal analysis, three basic steps were followed: (i) creation of an appropriate CERES-maize model input file; (ii) running CERES-maize model using seasonal analysis program; and (iii) biophysical analysis of the results of the simulation using the seasonal analysis program.

3.6 Statistical analysis and model evaluation

Analysis of variance (ANOVA) is a collection of statistical models used to analyze the differences between group means and their associated procedures. Comparison of treatments effects were analyzed using Analysis of Variance (ANOVA) and mean separation by Least Square Difference (LSD) using GenStat version 16 for Split-plot design.

Tools provided in DSSAT v4.5 were used to create input data files and for conducting the statistical analysis. The statistical data analysis tools used included GBuild, EasyGrapher and Microsoft Office. Comparison between the measured and simulated outputs was done by using the root mean square error, normalized root mean square error, mean error, d-stat, forecasting efficient and coefficient of variation. The CERES-maize model was evaluated against measured data using emergence, anthesis, and maturity dates, yield at harvest maturity, number at maturity (no m^{-2}), number at maturity (no/unit), tops weight at maturity, tops weight at anthesis, leaf number per stem, leaf area index (LAI), grain yield and time series plant analysis data.

The root mean squared errors (RMSE) were used to determine statistical differences between simulated and measured yields. Normalized RMSE, Mean error (ME or E) and forecasting efficiency (EF) were also used in this study. The E was used to identify whether the model prediction trends were to over or under-estimated. Yang and Huffman (2004) observed that positive and negative errors can negate each other in the mean error therefore an alternative statistic used as a measure of accuracy for simulated outputs was the MAE. RMSE is a measure of the deviation of the simulated from the measured values and is always positive, but a value of zero is ideal. Lower values of RMSE indicate higher accuracy of model prediction. Kiniry *et al.* (1997) reported that the RMSE has been used widely as a standard for model evaluation and in this study the RMSE was computed using the equation [27] below.

$$RMSE = [N^{-1}\sum_{i=1}^{n}(P_i - O_i)^2]^{0.5} \qquad [28]$$

Where n is the number of observations within each treatment, P_i is the predicted value for the ith measurement, and O_i is the observed value for the observation of the ith measurement.

According to Soler *et al.* (2007) and Jamieson *et al.* (1991) the Normalized RMSE values provide a measure (%) of relative differences between observed and simulated output. A simulation is considered to be excellent, good, fair, and poor if the normalized RMSE is < 10 %, > 10 % but less than 20 %, > 20 % but less than 30 %, and > 30 %, respectively [29]. Percentage prediction deviations (PDs) from the observed were also calculated for aboveground biomass and grain yield. Negative and positive deviations indicated an under-or-over-prediction, respectively. The concordance index (d-stat) (Wallach, 2006) and regression coefficient were used to assess how close the observed data were to the simulated results. The closer the *d*-statistics values to unit, the better the simulation quality (Equation [30]).

$$NRMSE = \frac{RMSE}{\bar{O}} X100\% \qquad [31]$$

$$d = 1 - \left[\frac{\sum (P_i - O_i)^2}{\sum (| P_i' | + | O_i' |)^2} \right] \qquad [32]$$

3.7 Limitation of the study

Hoogenboom *et al.* (1999) reported that if evaluation of the model includes modeling soil water balance under rain-fed conditions, then volumetric soil water contents and root length density should be measured. On the other hand, if evaluation involves modeling N balance aspects, then data from tissue analysis for N concentrations, and initial soil nitrate, ammonium, and organic matter for various soil layers should be collected. In this study plant tissue analysis and root length density was not considered, hence comprehensive soil water balance was not done. The weakness of the study could be attributed to the staging of vegetative and reproductive stages of the maize crop which is generally influenced by the researcher's experience and a relatively small error in stage description may have affected the overall statistics and simulation outcomes.

The other limitation of this study was the method used to observed Leaf area index (LAI). Canopy covers were taken using a digital camera overhead instead of direct and methods suggested by Turner and Begg. This could have affected values of LAI and subsequent simulations.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Effect of planting date and N application rate on maize growth and yield

4.1.1 Planting date

GenStat version 16 for Split-plot design was used to analyze the aboveground biomass, grain and yield components. Comparison of treatment effects was done using the analysis of variance (ANOVA) (see Appendix 1) and mean separation by Least Square Difference (LSD).

Using the ANOVA, results indicated that dry matter accumulation was affected by the date of planting. Analysis of the minimum date sets (MDS) indicated that the cumulative rainfall and mean minimum, and maximum air temperatures received during each period of maize growth reduced with delay in planting date (PD). This means that water and temperature being critical affected the rate of photosynthesis and dry matter accumulation (Reddy, 2006) from emergence to maturity (Streck *et al.*, 2008). Planting date significantly affected leaf blade at 50% vegetative (V6) and anthesis (leaf blade) stages. Furthermore, planting date significantly affected stem weight (g[dm]/m^2) while ear, husk, leaf and tops weight (g[dm]/m^2) were highly significant ($P < 0.05$) affected by planting date at 75% physiological maturity. PD had significant effect on ear number per plant at anthesis (CV=22.9%), physiological maturity (CV=19.1%) and final harvest (CV=15.9%). There was interaction of the treatment effect at $P < 0.05$ between planting date and nitrogen application rate at the dough stage (leaf number). Results future indicated that the number of ears per plant reduced with delay in PD. The harvest at maturity of aboveground biomass and grain yield was affected by the treatment effects at $P < 0.05$ as presented in Table 7. The maize husks and stover yield were significantly affected by date of planting at $P < 0.05$. Results for individual grain yield at each treatment level showed that grain yield reduced with delay in PD. Overall grain yield results indicate that grain yield (g/m^2) reduced with delay in PD. Poor amount of rainfall (Ngoma, 2008) received during the third planting date may have had an effect of photosynthesis and accumulation of dry matter. The 100 seed weight was not significantly ($P < 0.05$) affected by date of planting and nitrogen application rate at all treatment levels.

4.1.2 Nitrogen application rate

Nitrogen (N) application rate significantly ($p<0.05$) increased dry matter accumulation at vegetative (V6), anthesis (stem, ear and shuck, tops), dough (ear and shuck) stages and their coefficient of variation (cv) were 12.9%, 24.9%, 27%, 15.9% and 22.1%, respectively. At all treatment levels, there was more aboveground biomass produced with 168 kg N/ha compared to 112 kg N/ha. N application rate (N1 and N2) affected grain yield at PD1 (N1=9511 kg/ha, N2=10720 kg/ha), PD2 (N1=7618 kg/ha, N2=8048 kg/ha) and PD3 (N1=7965 kg/ha, N2=7049 kg/ha), respectively. The coefficient of variation for grain yield and aboveground biomass were 9.0 and 8.2% respectively which was below 12% and considered to be efficient by Gomez and Gomez (1984). Harvest index (HI) of grain and cobs (g m^{-2}) were not significantly affected by nitrogen application rate at $P < 0.05$ and there was no interaction between treatments. The results of this study agree with Muhammad *et al.* (2010) who also observed that N application rate did not affect HI. There was no interaction between the planting dates and N application rates at all treatment levels as presented in Table 5, Table 6 and Table 7 except for dough stage (leaf number).

Table 5a: Effect of planting date and N application rate on vegetative stage and anthesis, dough stage on maize growth

	V6	Anthesis (R1)				
Treatment		**Stem**	**Leaf blade**	**Ear & shuck**	**Leaf sheath**	**Tops**
Planting date						
PD1	6.11^b	54.09^a	31.25^b	12.80^a	17.97^a	116.9^a
PD2	4.74^a	47.70^a	29.90^b	8.70^a	15.58^a	101.9^a
PD3	4.85^a	46.79^a	23.74^a	9.85^a	15.83^a	96.2^a
Significance	**	NS	**	NS	NS	NS
LSD 5%	0.853	15.89	3.395	3.631	1.834	21.43
N application rate						
N1	4.74	42.8	27.74	8.45	16.18	95.2
N2	5.55	56.2	28.86	12.46	16.73	114.8
Significance	*	*	NS	*	NS	*
LSD 5%	0.696	12.97	2.772	2.965	2.246	17.50
Cv %	12.9	24.9	9.3	27	10.6	15.9
Interaction (PD * N rate)						
Significance	NS	NS	NS	NS	NS	NS
LSD 5%	1.206	22.47	4.802	5.135	3.176	30.31

Means sharing same letter in the table do not differ statistically at $p \leq 0.05$; PD1 = First planting date; PD2 = Second planting date; PD3 = Third planting date; N1 = 112 kg N/ha; N2 = 168 kg N/ha; LSD = Least Mean Differences; * = Significant at 5% level; ** = Highly significant at 5%; NS = Non significant

Table 5b: Effect of planting date and N application rate on dough stage and physiological maturity on maize growth

	Dough stage (R4)					Physiological maturity (R6)					
Treatment	**Stem**	**Leaf blade**	**Ear & shuck**	**Leaf sheath**	**Tops**	**Ear**	**husk**	**Leaf**	**sheath**	**Stem**	**Tops**
Planting date											
PD1	60.83^{a}	26.92^{a}	96.76^{a}	17.17^{ab}	201.7^{a}	167.3^{b}	33.25^{b}	25.40^{b}	14.70^{b}	47.7^{b}	303.5^{b}
PD2	68.1^{a}	29.58^{a}	83.65^{a}	18.09^{b}	199.4^{a}	95.0^{a}	19.35^{a}	20.75^{a}	13.10^{b}	42.5^{ab}	190.8^{a}
PD3	65.38^{a}	26.33^{a}	84.41^{a}	15.68^{a}	191.8^{a}	79.1^{a}	17.58^{a}	18.25^{a}	10.69^{a}	29.3^{a}	158.8^{a}
Significance	NS	NS	NS	*	NS	**	**	**	**	*	**
LSD 5%	25.45	4.690	24.15	1.538	45.62	23.38	5.372	2.169	1.460	12.63	38.78
N application rate											
N1	64.8	25.84	77.4	16.45	184.5	109.9	21.48	21.16	12.78	40.1	211.2
N2	64.8	29.38	99.2	17.47	210.8	117.7	25.31	21.78	12.88	39.6	224.2
Significance	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS
LSD 5%	20.78	3.829	19.72	1.256	37.25	19.09	4.386	1.771	1.192	10.31	31.67
Cv %	30.5	13.2	22.1	7	17.9	16.0	17.9	7.9	8.8	24.6	13.9
Interaction (PD * N rate)											
Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LSD 5%	36.00	6.632	34.15	2.175	64.51	33.06	7.597	3.068	2.064	17.85	54.85

Table 6: Ear and leaf number per plant as affected by planting date and N rate

Treatment	Ear and leaf number per plant							
	Anthesis (R1)		Doug stage (R4)		R6		Final harvest	
	Ear#	Leaf#	ear#	Leaf#	ear#	Leaf#	ear#	Leaf#
PD1	1.833^{b}	15.33^{a}	1.917^{a}	14.917^{a}	1.750^{b}	14.25^{ab}	1.750^{b}	14.25^{a}
PD2	**1.167^{a}**	15.17^{a}	1.917^{a}	15^{a}	1.833^{b}	15.17^{a}	1.833^{b}	15.17^{b}
PD3	**1.750^{b}**	14.83^{a}	1.833^{a}	18.833^{a}	1.167^{a}	13.58^{a}	1.167^{a}	14.57^{ab}
Significance	*	NS	NS	NS	*	*	*	*
LSD 5%	0.466	0.547	0.3252	0.3895	0.3895	14.33	0.3249	0.687
N1	1.417	15.17	1.833	14.833	1.556	14.33	1.604	14.61
N2	1.75	15.06	1.944	15	1.611	15	1.562	14.71
Significance	NS	NS	NS	NS	NS	NS	NS	NS
LSD 5%	0.3805	0.446	0.2655	0.318	0.3180	0.983	0.2653	0.561
cv %	22.9	2.8	13.4	2	19.1	6.5	15.9	3.7
Interaction (PD * N rate)								
Significance	NS	NS	NS	*	NS	NS	NS	NS
LSD 5%	0.6591	0.773	0.4598	0.5508	0.5508	1.702	0.4594	0.972

Means sharing same letter in the table do not differ statistically at $p \leq 0.05$; PD1 = First planting date; PD2 = Second planting date; PD3 = Third planting date; N1 = 112 kg N/ha; N2 = 168 kg N/ha; LSD = Least Mean Differences; * = Significant at 5% level; ** = Highly significant at 5%; NS = Non significant; swt=seed weight

Table 7: Harvest at maturity as affected by PD and N rate

Treatment	Final harvest (R7) g/m^2									100 swt (g)
	Aboveground biomass	Grain	HI	Cob	Stem	Leaf blade	Husk	Stover	Leaf sheath	
PD1	1361^{b}	1012^{b}	0.75^{a}	134.0^{a}	93.7^{a}	33.0^{a}	60.8^{b}	349.5^{b}	28.02^{a}	48.05^{a}
PD2	1087^{a}	783^{a}	0.72^{a}	121.2^{a}	93.5^{a}	28.8^{a}	36.1^{a}	303.7^{ab}	24.08^{a}	43.95^{a}
PD3	1038^{a}	751^{a}	0.72^{a}	121.3^{a}	72.1^{a}	26.7^{a}	43.7^{a}	286.9^{a}	23.13^{a}	44.38^{a}
Significance	**	**	NS	NS	NS	NS	*	*	*	NS
LSD 5%	122.2	97.8	0.034	14.26	43.80	6.29	13.64	50.22	24.85	4.74
N1	1133	836	0.7352	123.0	75.9	28.3	44.5	296.4	25.31	46.74
N2	1191	861	0.7217	128.0	97.0	30.7	49.2	330.3	330.3	44.18
Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LSD 5%	99.6	79.8	0.028	11.64	35.76	5.14	11.14	41.01	3.597	3.87
cv %	8.2	9.0	3.7	8.8	39.4	16.6	22.6	12.5	13.7	8.1
Interaction (PD * N rate)										
Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LSD 5%	172.8	138.2	0.048	20.16	61.94	8.90	19.30	71.03	6.231	6.71

Means sharing same letter in the table do not differ statistically at $p \leq 0.05$; PD1 = First planting date; PD2 = Second planting date; PD3 = Third planting date; N1 = 112 kg N/ha; N2 = 168 kg N/ha; LSD = Least Mean Differences; * = Significant at 5% level; ** = Highly significant at 5%; NS = Non significant; swt=seed weight

4.2 Characterization of Minimum Data Set

4.2.1 Weather data, Soil data and Crop management practices

CERES-maize model evaluation required: weather data (Table 9); soil data (Table 2, Appendix 4; initial soil conditions; crop management data (Table 3, Table 4); cultivar specific parameters (Table 10); and observed aboveground biomass, grain yield, yield components and soil water content data (Appendix 5, Appendix 6). The cumulative total rainfall, solar radiation, growing degree days (GDDs), and crop heat unit, minimum and maximum air temperature for each maize growing period were computed and are presented in Table 8, Table 9 and Figure 10 below. From the data it is evident that the rainfall and air temperature (minimum and maximum) decreased with delay in planting date. Banda (2005) reported that there are many weather factors that influence maize production potential of an area, but of the weather factors, the most important are the distribution in time and the amount of rainfall. The first planting date (PD1) received more growing degree days (GDD), crop heat units (CHU) and solar radiation (SRAD) compared to the second (PD2) and third (PD3) plantings dates. PD3 received more GDD, CHU and SRAD but less rainfall than PD1 and PD2. Figure 10 shows how the GDD was changing over the course of the maize growing season.

The variation in planting date of maize determines the amount of solar radiation intercepted by the crop and thermal conditions during its growth. Muchow *et al.* (1990) observed that the amount of incident solar radiation and the proportion that is intercepted directly by the crop determines crop growth rate and its yield. Warrington and Kanemasu (1983) reported that temperature is important and affects duration of crop growth and yield. Furthermore, the maximum time that the incident radiation can be intercepted is of particular importance in the length of the grain filling period since the dry matter accumulated in the grain in maize is largely from dry matter that accumulates after flowering (Warrington and Kanemasu, 1983; Allison and Daynard, 1979). Maobe *et al.* (2010) reported that aboveground biomass yield is closely related to the intercepted photosynthetically active radiation and the rate of its conversion into dry matter also known as radiation use efficiency (RUE). Crop growth rate and biomass yield depends on the amount of SRAD intercepted and converted into dry matter (Fageria, 2000). The desired soil and management data required by the model are presented in Chapter 3.

Table 8: Indices for crop growth

Parameters	Planting date		
	PD1	PD2	PD3
Growing Degree days (GDDs)	1904.5	1778.7	1830.0
Crop Heat Units (CHUs)	3668.8	3489.4	3613.4
Solar radiation (SRAD), MJ/m^2 /d	2308.7	2116.7	2269.6
Cumulative Rain fall, mm	515.2	498.8	476.6
Average Relative humidity, %	81.4	84.9	83.3
Average Minimum temperate, °C	16.9	16.6	16.2
Average Maximum temperature, °C	27.6	27.0	26.8

Table 9: Weather data for 2013/2014

	Precipitation	Solar Radiation	Temperature (°C)		Relative humidity
Month	(mm)	(MJ m^{-2} d^{-1})	Max	Min	(%)
Jun-13	0.0	16.8	13.3	9.4	0.0
Jul-13	0.0	18.0	23.1	9.4	0.0
Aug-13	0.0	18.8	26.2	12.3	0.0
Sep-13	0.0	20.0	31.0	16.5	0.0
Oct-13	56.8	19.7	30.0	17.5	5.0
Nov-13	93.0	19.8	30.4	18.9	9.0
Dec-13	141.8	18.5	28.6	18.0	17.0
Jan-14	155.4	16.6	27.4	17.5	26.0
Feb-14	99.8	14.9	26.6	17.8	18.0
Mar-14	85.6	17.3	27.3	16.8	14.0
Apr-14	87.2	16.7	25.6	14.9	5.0
May-14	0.0	17.9	24.9	12.0	0.0

Sources: School of Agriculture Automatic Weather Station, University of Zambia

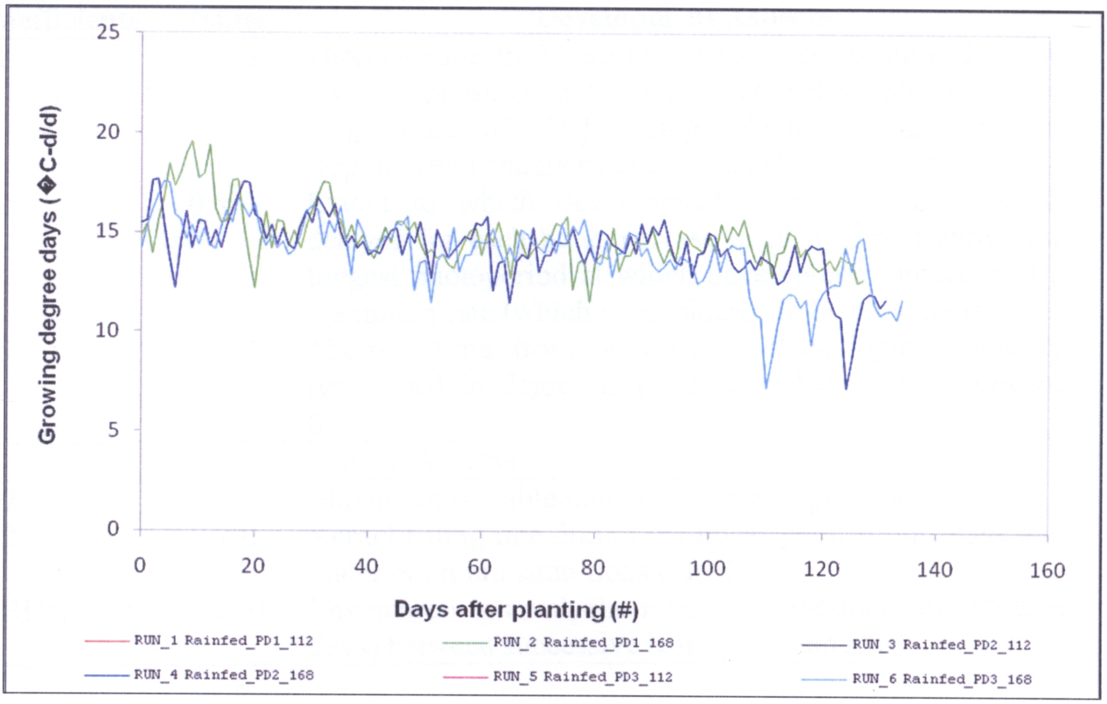

Figure 10: Growing degree days

4.3 Calibration and evaluation of CERES-maize model

4.3.1 Calibration of CERES-maize model

The cultivar specific parameters (CSPs) for the ZMS 606 were computed as described in Chapter 3 and are presented in Table 10 below. The deviation of simulated from observed outputs are presented in Table 11 below for all the treatments. Phenological stage deviation from the observed were from -4.0% to 14.0%. The deviation percentage of grain yield ranged from 8% - 29% and 3% - 23% for N1 and N2, respectively as shown in Table 10. The tops (aboveground biomass) weight at anthesis and maturity percent deviation from observed ranged for N1 (-2% - 39%) and N2 (-8% to 45%), respectively. Leaf area index percent deviation was between 45% - 68% for all the treatments. The deviation of seed number at maturity (no m^{-2} and no $unit^{-1}$) ranged between -11% - 67%. Harvest index at all treatment levels were under-predicted as presented in Table 11 and the percent deviation at all treatment levels ranged from 8% - 19%.

Table 10: Cultivar specific parameters for ZMS 606 cultivar

Coefficients	Values	Development Aspects
P1	213.8	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod.
P2	0.831	Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours)
P5	822.5	Thermal time from anthesis to physiological maturity (expressed in degree days above a base temperature of 8°C)
		Growth Aspects
G2	979.7	Maximum possible number of kernels per plant
G3	9.791	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)
PHINT	60.00	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances

Table 11a: Calibration results for CERES-maize model using average performance data for each treatment

	PD1N1		
	Measured	**Simulated**	**%D**
Anthesis day (dap)	70	69	1
Physiological maturity day (dap)	133	127	5
Yield at harvest maturity (kg [dm]/ha)	9,511	6,783	29
Number at maturity (no/m2)	2,458	2,052	17
Number at maturity (no/unit)	558	466	16
LAI	3.24	1.78	45
Tops weight at maturity (kg [dm]/ha)	12,586	10,877	14
Harvest index at maturity	0.760	0.624	18
Tops weight at anthesis (kg [dm]/ha)	4,597	3,097	33
Leaf number per stem at maturity	14	16	(14)
Emergence day (dap)	7	6	14

	PD2N1		
	Measured	**Simulated**	**%D**
Anthesis day (dap)	70	70	-
Physiological maturity day (dap)	128	131	(2)
Yield at harvest maturity (kg [dm]/ha)	7,618	6,991	8
Number at maturity (no/m2)	2,164	2,173	(0)
Number at maturity (no/unit)	492	494	(0)
LAI	3.480	1.390	60
Tops weight at maturity (kg [dm]/ha)	10,527	10,790	(2)
Harvest index at maturity	0.72	0.65	10
Tops weight at anthesis (kg [dm]/ha)	4,307	2,619	39
Leaf number per stem at maturity	15	16	(4)
Emergence day (dap)	8	7	13

	PD3N1		
	Measured	**Simulated**	**%D**
Anthesis day (dap)	67	70	(4)
Physiological maturity day (dap)	132	134	(2)
Yield at harvest maturity (kg [dm]/ha)	7,965	5,667	29
Number at maturity (no/m2)	2,136	2,180	(2)
Number at maturity (no/unit)	486	496	(2)
LAI	3.05	1.33	56
Tops weight at maturity (kg [dm]/ha)	10,873	9,636	11
Harvest index at maturity	0.73	0.59	19
Tops weight at anthesis (kg [dm]/ha)	3,788	2,684	29
Leaf number per stem at maturity	14	16	(18)
Emergence day (dap)	6	6	-

%D = Deviation from the observed data

Table 12b: Calibration results for CERES-maize model using average performance data for each treatment

	PD1N2		
	Measured	**Simulated**	**% D**
Anthesis day (dap)	70	69	1
Physiological maturity day (dap)	133	127	5
Yield at harvest maturity (kg [dm]/ha)	10,720	8,249	23
Number at maturity (no/m2)	2,805	918	67
Number at maturity (no/unit)	638	473	26
LAI	4.66	1.58	66
Tops weight at maturity (kg [dm]/ha)	14,635	12,389	15
Harvest index at maturity	0.730	0.666	9
Tops weight at anthesis (kg [dm]/ha)	5,794	3,185	45
Leaf number per stem at maturity	14	16	(16)
Emergence day (dap)	7	6	14
	PD2N2		
	Measured	**Simulated**	**% D**
Anthesis day (dap)	70	70	-
Physiological maturity day (dap)	128	131	(2)
Yield at harvest maturity (kg [dm]/ha)	8,049	7,825	3
Number at maturity (no/m2)	2,413	2,241	7
Number at maturity (no/unit)	549	509	7
LAI	4.190	2.030	52
Tops weight at maturity (kg [dm]/ha)	11,213	11,788	(5)
Harvest index at maturity	0.72	0.66	8
Tops weight at anthesis (kg [dm]/ha)	4,750	2,765	42
Leaf number per stem at maturity	15	16	(4)
Emergence day (dap)	8	7	13
	PD3N2		
	Measured	**Simulated**	**% D**
Anthesis day (dap)	67	70	(4)
Physiological maturity day (dap)	132	134	(2)
Yield at harvest maturity (kg [dm]/ha)	7,049	6,402	9
Number at maturity (no/m2)	2,068	2,302	(11)
Number at maturity (no/unit)	470	523	(11)
LAI	4.68	1.49	68
Tops weight at maturity (kg [dm]/ha)	9,879	10,635	(8)
Harvest index at maturity	0.71	0.60	15
Tops weight at anthesis (kg [dm]/ha)	4,766	2,902	39
Leaf number per stem at maturity	14	16	(18)
Emergence day (dap)	6	6	-

%D = Deviation from the observed data

4.3.2 Evaluation of CERES-maize model's response to three planting dates and N application rate

After calibrating the CERES-maize model, the CSPs for ZMS606 were used to conduct the initial simulations for the three planting dates and N application rate using the management practices, soil data presented and discussed in Chapter 3 (Table 2). The CERES-maize model was evaluated using datasets comprised of anthesis day (dap), physiological maturity day (dap), yield at harvest maturity, grain number at maturity (no m^{-2}), grain number at maturity (no/unit), tops (aboveground biomass) weight at maturity, tops weight at anthesis, leaf number per stem and emergence day (dap) from the three planting dates as presented in Table 11 above.

4.3.2.1 Phenological stages

The number of leaves per stem at maturity was over predicted at all treatment levels while the differences between observed and simulated emergence, anthesis and physiological maturity days after planting were ±1, $\geq$-3$\leq$±1 and $\geq$-4$\leq$6 days, respectively. Soler *et al.* (2007) also reported close prediction of days to anthesis in maize by using CERES-maize model in different environments. The close agreement between the observed and simulated values for emergence and anthesis dates for PD1, PD2 and PD3 indicated that good phenological CSPs were assigned to ZMS606 cultivar used in this study. Emergence and anthesis day (dap) were accurately predicted by the CERES-maize model. Phenological development determination of the maize crop is generally influenced by the researcher experience and even a relatively small error in the stage description can greatly influence the overall statistical results and outputs of the simulation.

4.3.2.2 Grain yield

Comparisons between the observed and simulated grain yield are presented in Table 11 above. The model under-predicted grain yield at PD1N1, PD1N2, PD2N1, PD2N2, PD3N1 and PD3N2 by 2728, 2471, 627, 224, 2298 and 647 kg [dm]/ha, respectively. The overall grain yield RMSE and NRMSE were 1811.56 kg[dm]/ha and 21.35 %, respectively. According to Soler *et al.* (2007) the simulation of grain yield was fair. There were no significant differences between the observed and simulated grain yield for PD2N1, PD2N2 and PD3N2. Comparison of grain yield using standard error bars indicated that there was not significant difference between the observed and simulated output at PD2N1, PD2N2 and PD3N2. As presented in Figure 11 there was not significant differences between the observed and simulate grain yield for PD1N1, PD1N2 and PD3N1.

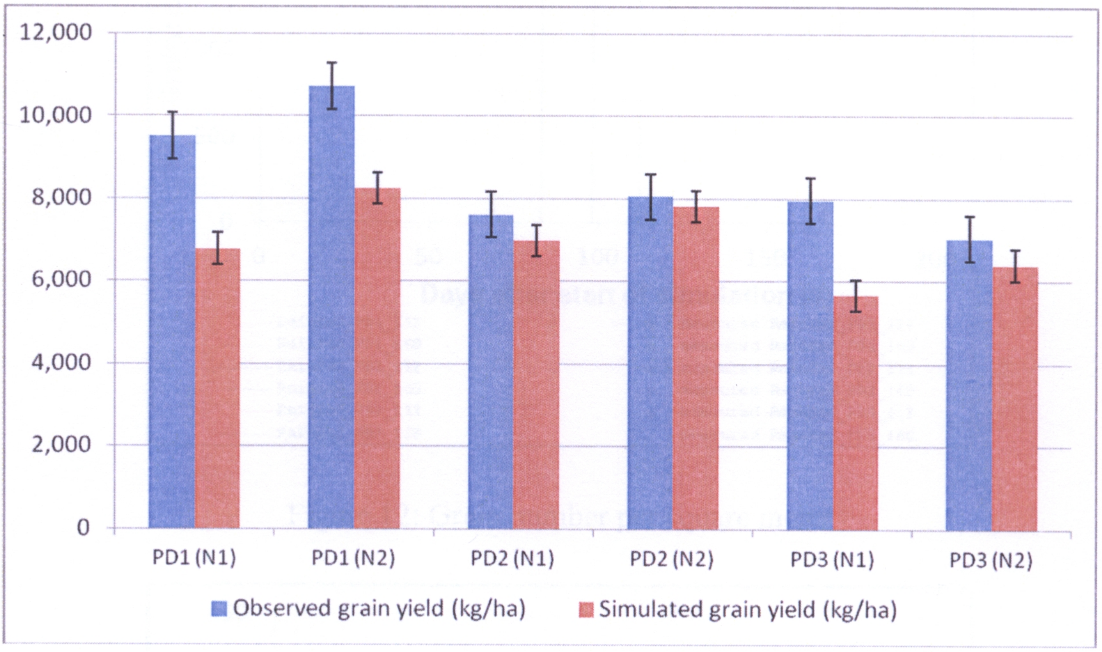

Figure 11: Observed vs Simulated grain yield

The model under predicted grain number at maturity (no m-2) and unit grain weight for PDN1, PD1N2 and PD2N2 as presented in Figure 12 and Figure 13. Grain number at maturity and unit grain weight was over-predicted at PD2N1, PD3N1 and PD3N2. The results of this study for PD1N1, PD1N2, and PD2N2 are supported by Mohamud (1998) who also found an under prediction for both grain number per plant and grain number per meter square.

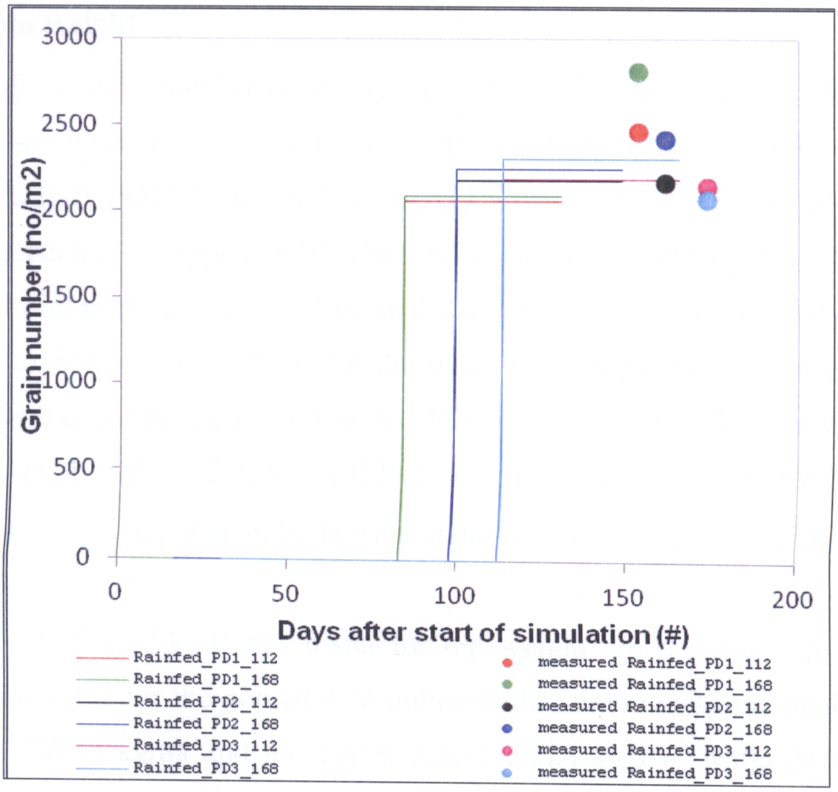

Figure 12: Grain number per square meter

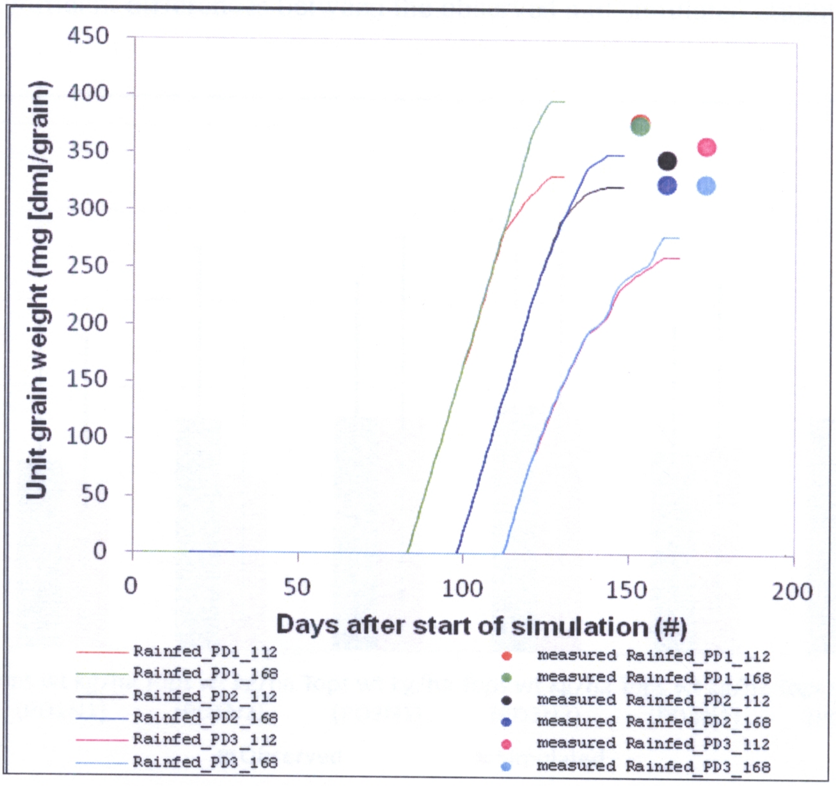

Figure 13: Unit grain weight (mg[dm]/grain)

4.3.2.3 Tops weight

The RMSE, d-stat, coefficient of determination (R^2) and NRMSE for all the treatments are presented in Table 11. The tops weight NRMSE for PD1N1, PD1N2, PD2N1, PD2N2, PD3N1 and PD3N2 were 15.52, 30.09, 29.27, 33.38, 37.78 and 36.99 % respectively (Appendix 9). The model's simulation of tops weight was good for PD1N1 and poor for PD1N2, PD2 and PD3 at all treatment levels (Appendix 9) according to Soler *et al.* (2007). On the other hand, tops weight at physiological maturity were under-predicted on PD1N1, PD1N2 and PD3N1 while the tops weight were over-predicted at PD2N1, PD2N2 and PD3N2 as shown in Figure 14. Additionally, tops weight at anthesis were under-predicted at all treatment levels.

The overall RMSE, EF, E and d-stat for top weight are presented in Figure 15 below. Mean error for the pooled data indicates that the model over-predicted tops weight by 726.58 kg/ha and its RMSE was 1135.24 kg ha^{-1} while its simulation (Figure 16) accuracy was good (d-stat=0.96, EF=0.86) as shown in Figure 15 and Figure 16. The presentation of standard error bar in Figure 14 indicated that they were no significant differences between the observed and simulated outputs.

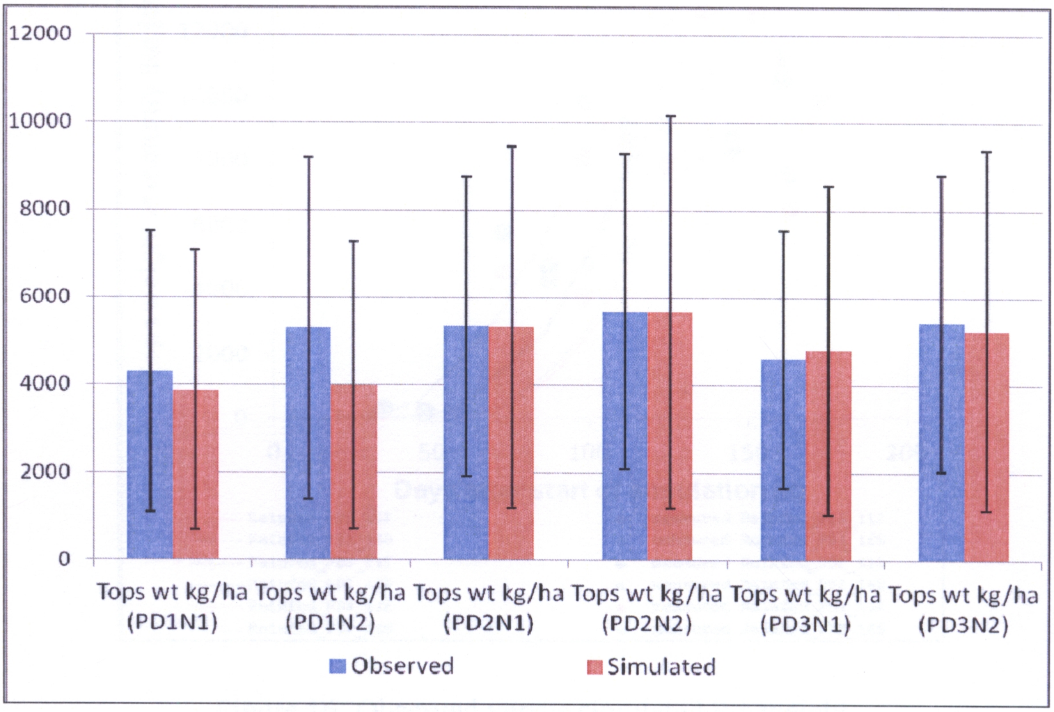

Figure 14: Tops weights

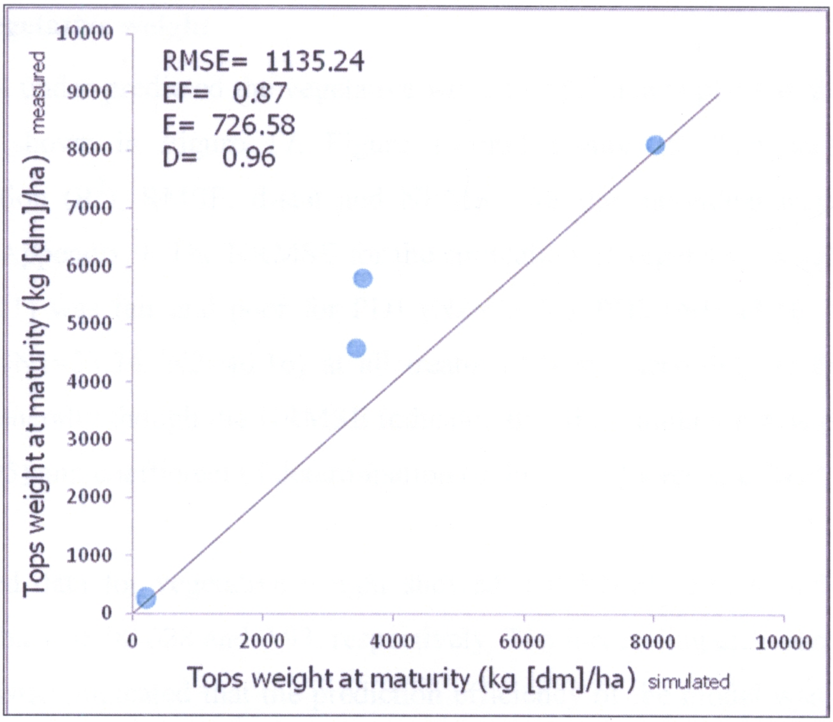

Figure 15: Observed versus simulated top weight

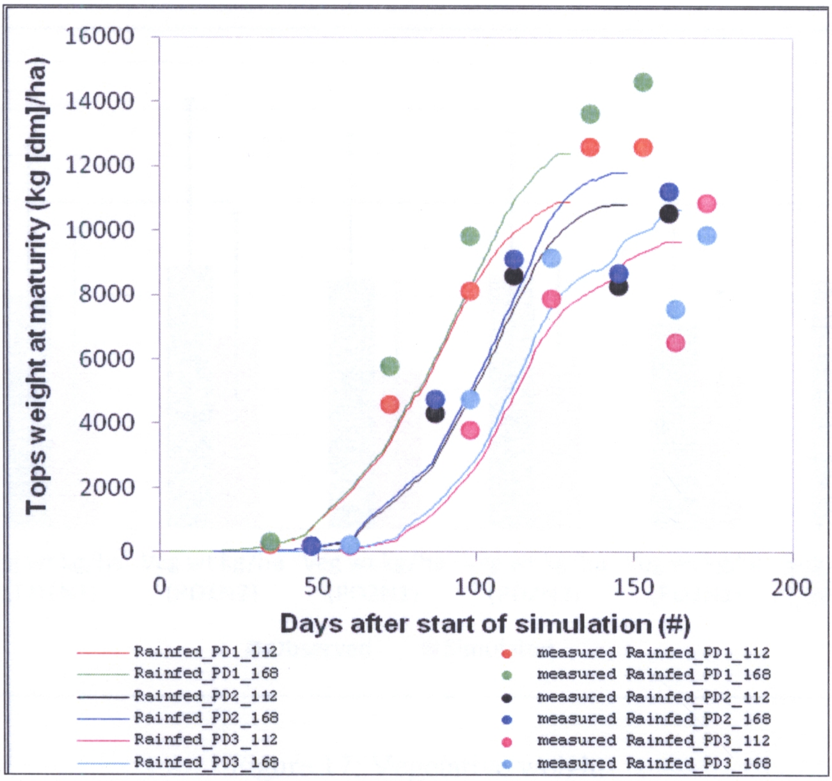

Figure 16: Observed versus simulated top weight

4.3.2.4 Vegetative weight

The model under-predicted the vegetative weight of the maize plant at all treatment levels as shown in Figure 17, Figure 18 and Figure 19. The coefficient of determination (R^2), RMSE, d-stat and NRMSE for the individual treatments are shown in Appendix 9. The NRMSE for the simulation of vegetative weight for PD1 (N1=225.21) was fair and poor for PD1 (N2=33.76), PD2 (N1=43.10, N2=38.09) and PD3 (N1=33.34, N2=40.16) at all treatment levels according to Soler *et al.* (2007). Generally though the NRMSE indicated that the simulation was poor, d-stat (0.83 - 0.95) and coefficient of determination (0.96 – 0.99) were excellent.

The pooled data for vegetative weight showed that RMSE, EF, E and d-stat are 82324 kg ha-1, 0.78, 628 and 0.93, respectively. The forecasting efficiency (EF) and d-stat statistics indicated that the prediction efficiency of the model was good. The standard error bars of observed and simulated vegetative weight indicated that they were no significant difference.

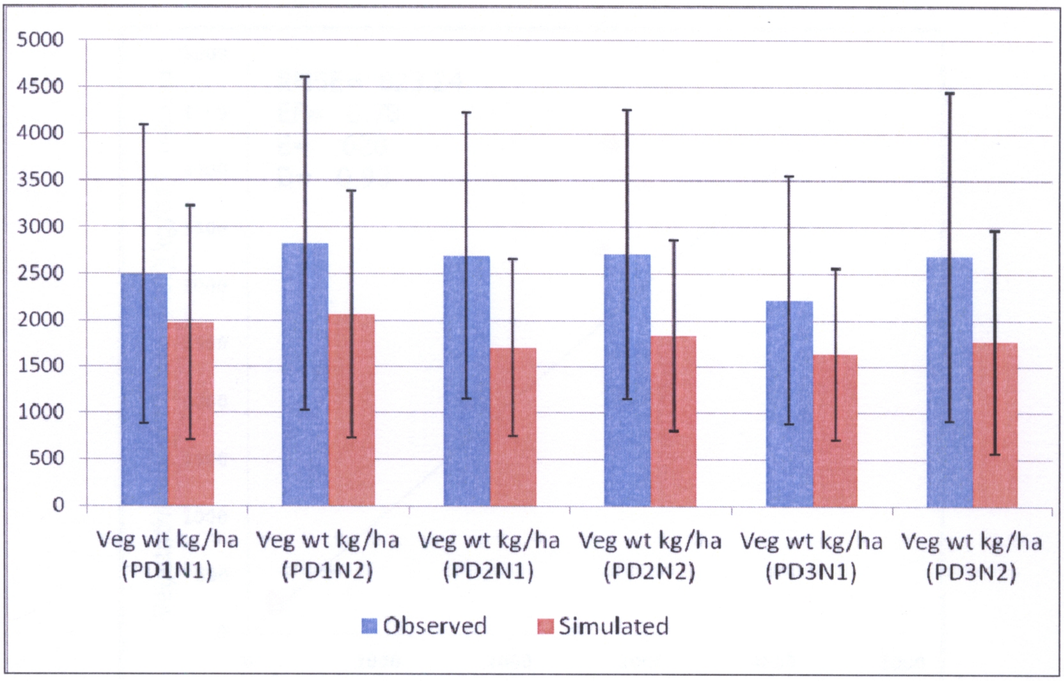

Figure 17: Vegetative weight

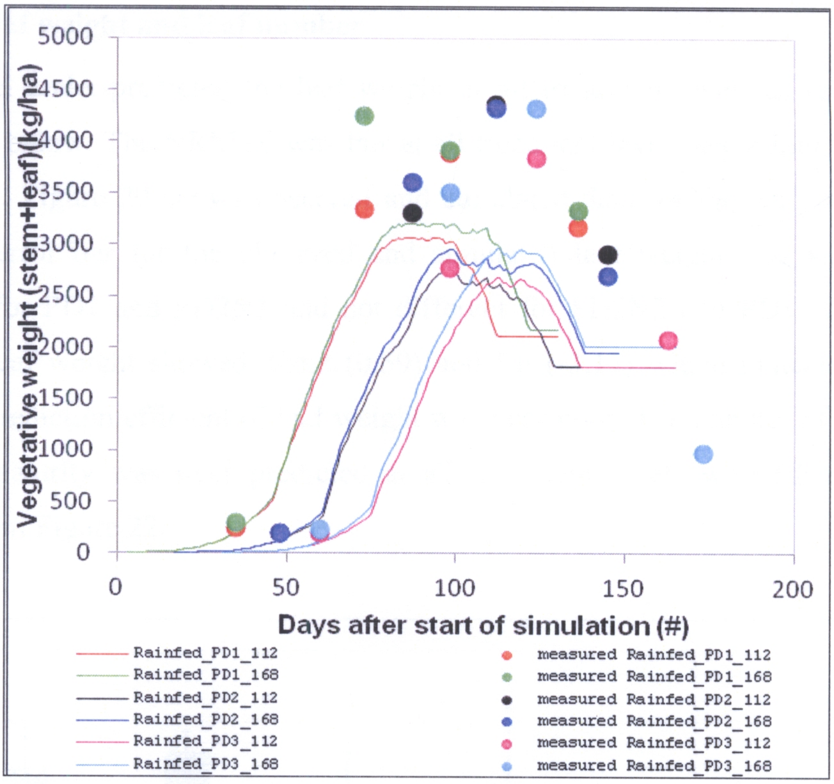

Figure 18: Simulation graph of observed and predicted vegetative weight

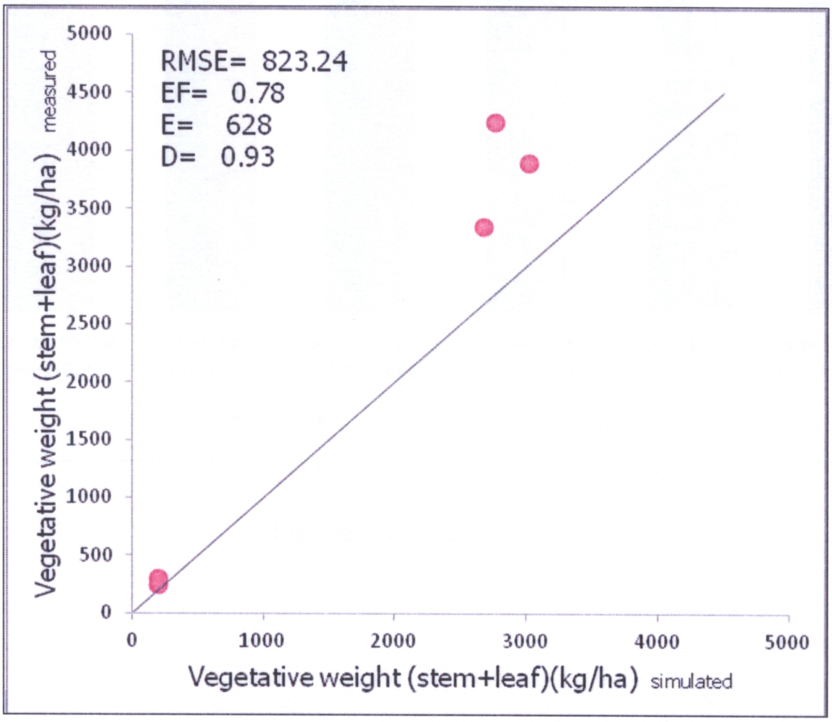

Figure 19: Observed versus Simulated vegetative weight

4.3.2.5 Leaf weight and leaf number

The model under-predicted the leaf weight at all treatment levels as presented in Figure 20 below. The NRMSE was fair at all treatment levels according to Soler *et al.* (2007). Figure 20 shows observed and simulated data for the leaf weight. The standard error bar for the observed and simulated leaf weight was significantly different for PD1 and PD2N1 and not different for PD2N2 and PD3. The pooled data for leaf weight showed d-stat (0.59) and EF (-3.17) which indicates that the model's prediction efficient of leaf weight was very poor. The number of leaves per stem at maturity was over predicted at all treatment levels with EF of 0.80 as presented in Figure 22.

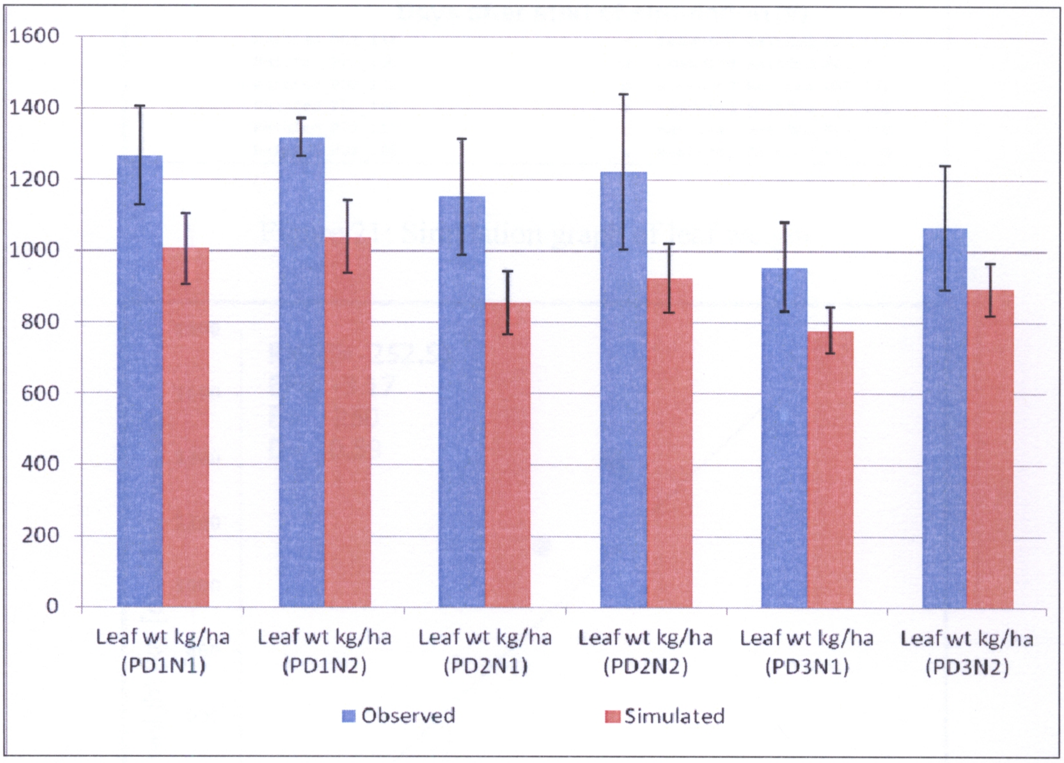

Figure 20: Leaf weight

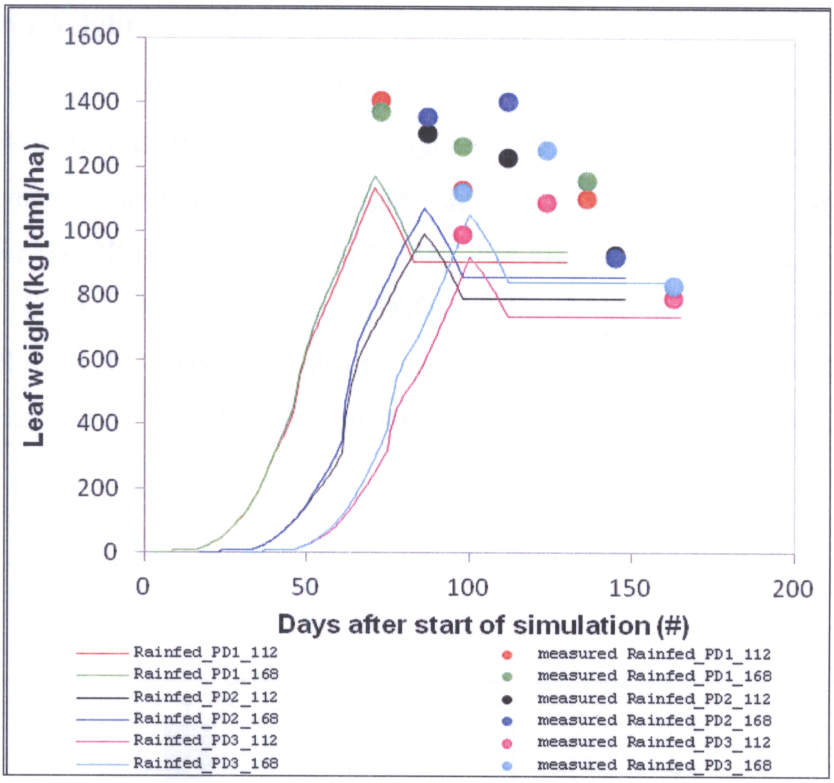

Figure 21: Simulation graph of leaf weight

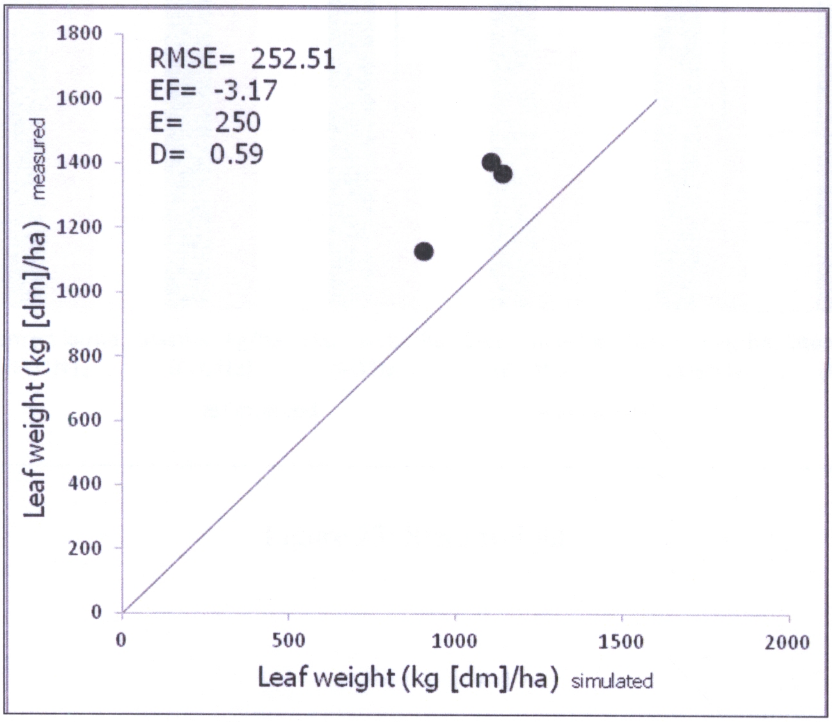

Figure 22: Observed versus simulated leaf weight

4.3.2.6 Stem weight

The CERES-maize model under-estimated stem weight at all treatment levels and the simulation results are presented in Figure 23, Figure 24 and Figure 25 below. The observed and simulated stem weight standard error bars were not significantly different for the PD1N1, PD3N1 and PD3N2 but different for PD1N2, PD2N1 and PD2N2 as shown in Figure 23. The NRMSE for stem weight was fair (PD1N1) and poor for PD1N2, PD2 and PD3 according to Soler *et al.* (2007). Overall statistics indicated that the EF (-2.84) was poor while the d-stat was 0.52 as shown in Figure 25 below.

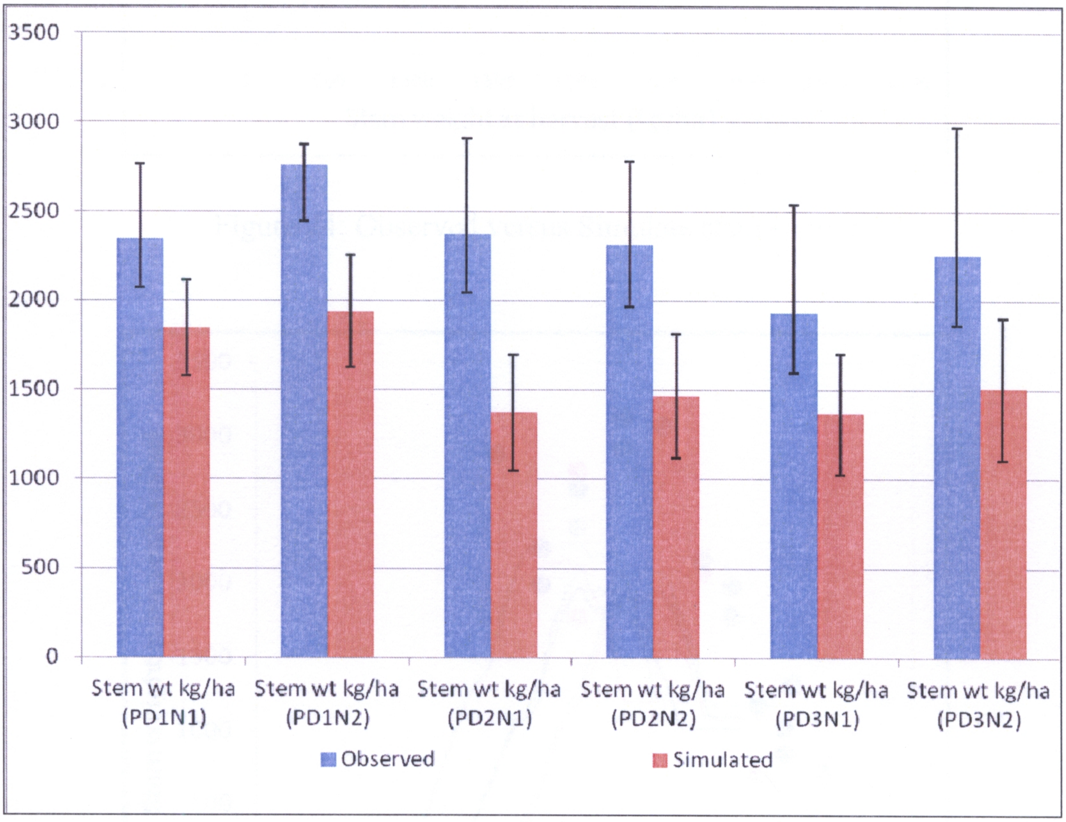

Figure 23: Stem weight

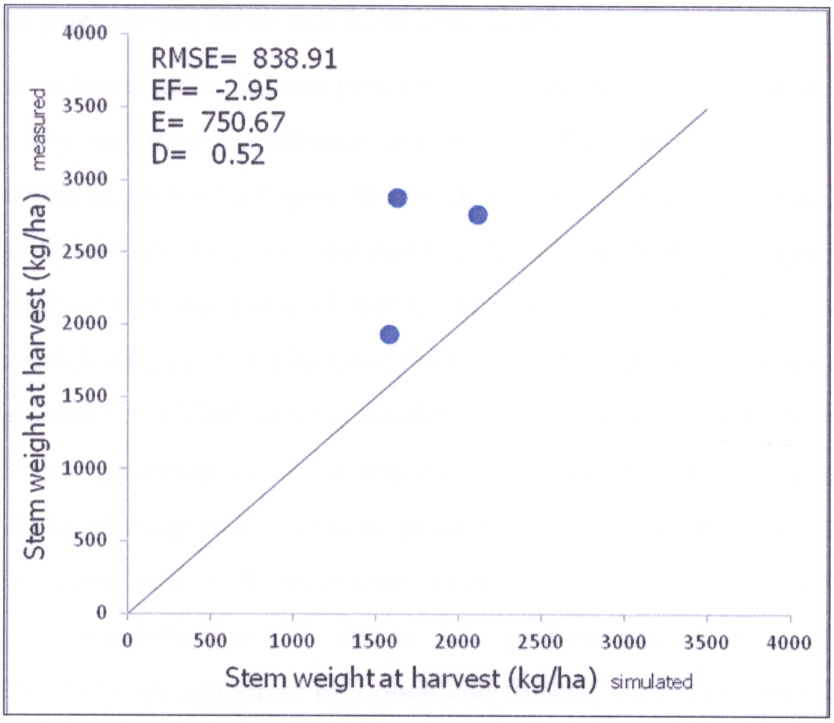

Figure 24: Observed versus Simulate stem weight

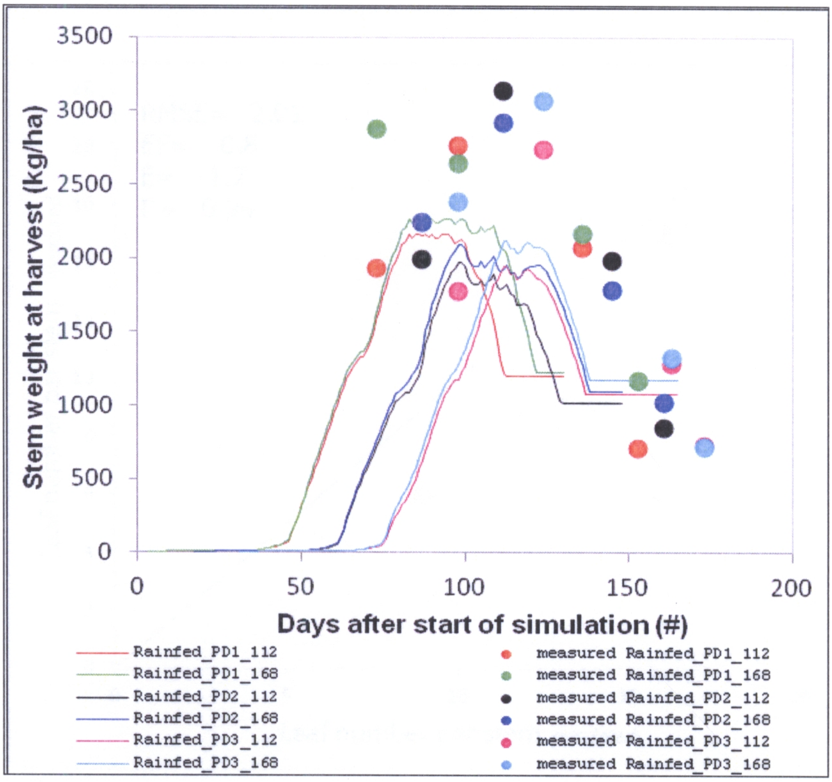

Figure 25: Observed versus Simulate stem weight

4.3.2.7 Leaf number per stem and Leaf area index

The number of leaves per stem was predicted with less accuracy as can be stem from Figure 26. The regression coefficient and the NRMSE statistics were poor at all treatment levels as shown in Figure 26 and Appendix 9. Leaf area index (LAI) was simulated with less accuracy. Overall statistics for LAI indicates that the forecasting efficiency (EF=-0.63) and d-stat (d-stat=0.54) were poor. The results do not agree with Jones and Kiniry (1986) who used the CERES-maize model. Jones and Kiniry (1986) evaluated the CERES-maize model using various data sets from different locations covering varying situations and it was observed that the simulated value of maximum LAI, aboveground biomass, grain number and grain yield were highly significantly correlated with measured values. The leaf area index had low coefficients of determination (R^2) due to poor performance of the model and the results of this study are supported by Lobell and Burke (2010) who reported that low coefficient of determination between predicted and observed values are due to poor performance by the model in representing crop yield responses to environmental factors.

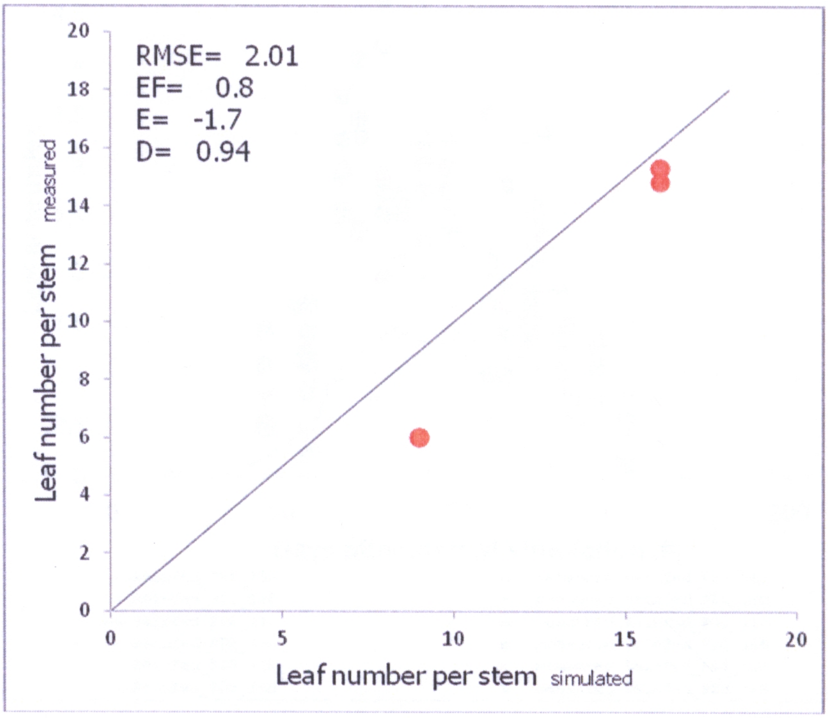

Figure 26: Observed vs Simulate leaf number per stem

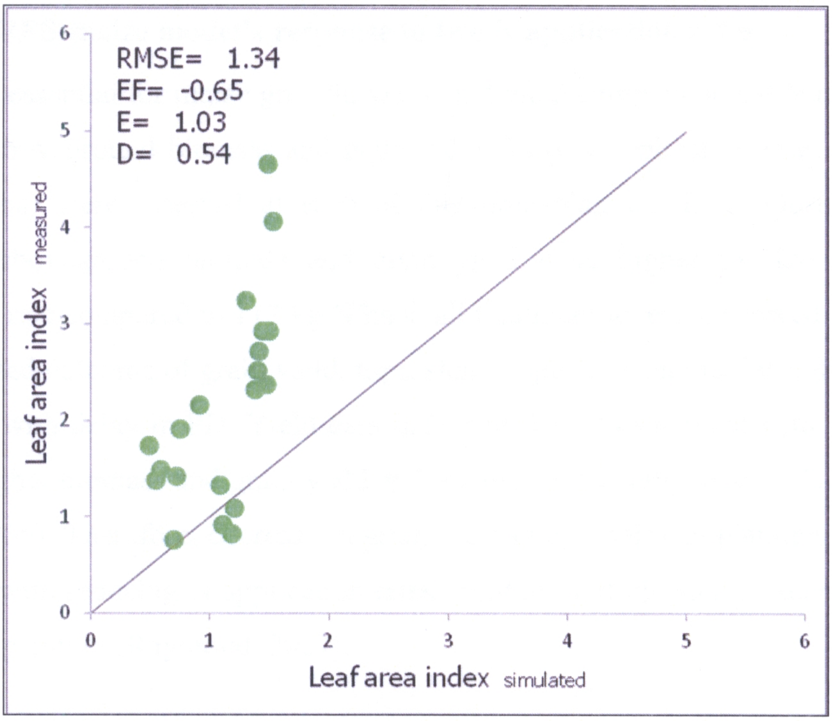

Figure 27: LAI evaluation statistics

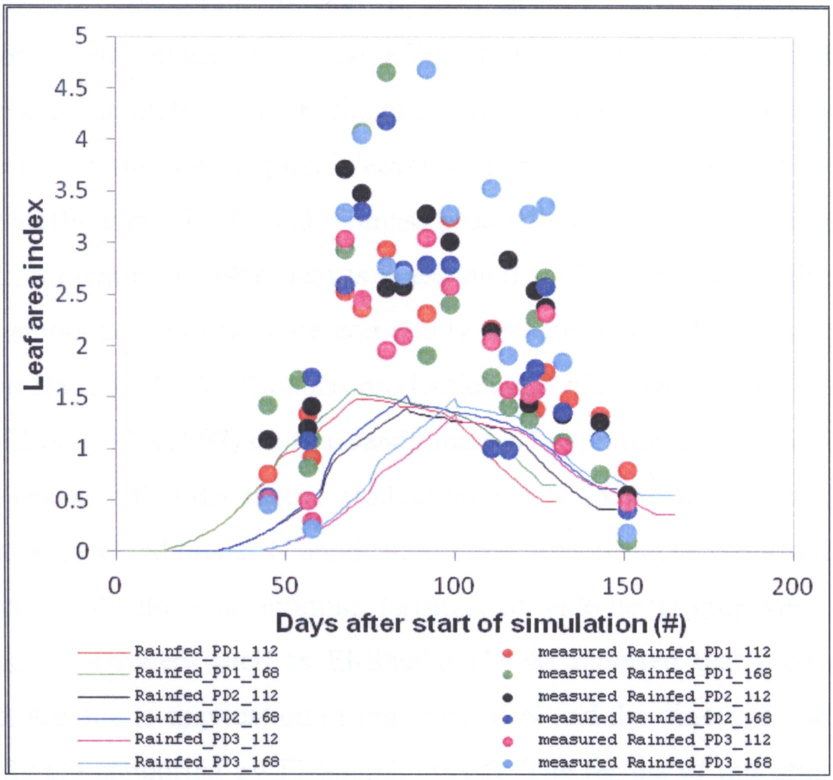

Figure 28: LAI evaluation graph

4.3.2.8 CERES-maize model's response to two N application rates

Nitrogen is essential for maize growth, yield, and yield component and N deficiency decreases aboveground biomass and grain yield. Two N application rates (112 and 168 N kg/ha) were assessed at each of the three planting dates. Observed and simulated aboveground biomass and grain yield were higher for 168 kg N/ha application rate compared to 112 kg N/ha at all treatment levels. Observed field data and simulated outcome of grain yield, tops, stem, vegetative and leaf weight showed a decrease with delay in PD. Yield data indicated that plots applied with 168 kg N ha^{-1} had higher biomass and grain yield and the results are supported by Fageria and Baliger (2005). Therefore, decrease in grain yield due to delay in planting would be associated with reducing N application rates, rainfall (soil moisture), solar radiation and air temperature (Raymond, 2007).

According to the simulation the N uptake during the maize growing season was 118 (PD1N1), 150 (PD1N2), 119 (PD2N1), 160 (PD2N2), 119 (PD3N1) and 153 (PD3N2) kg [N uptake]/ha as shown in Figure 29 and Appendix 7. The accumulation of dry matter was also affected by reduction in precipitation, air temperature and cumulative solar radiation. Fageria and Baliger (2005) reported that low nitrogen concentration in plants leaves is a factor that reduces the amount of radiation use efficiency (RUE) and biomass productivity. The accumulation of large amounts of nitrogen in the plant leaves is essential for high biomass and grain yield and higher amounts of nitrogen are commonly associated with high harvest indices (Fageria and Baliger, 2005). Biomass production and nitrogen uptake by maize was studied by Zhou et *al.* (1997) on fine sandy loam by applying 0, 180, 270 kg N ha^{-1}. The results revealed that dry matter production and N uptake were much higher for treatments that received higher N application rates. According to Workayehu (2000), various studies indicates that optimum fertilizer provide better crop yield and yield components. Researchers such as El-Sheikh (1998) reported that increased yield components are due to application of high rate of N and the observed values in this current study are supported by El-Sheikh (1998). The results of this study are also supported by Inamullah *et al.* (2011) who reported that there is an increase maize grain yield with increase in N application rate. Additionally, Muhammad *et al.*

(2010) reported that optimum fertilizer application provides better crop yield and yield components.

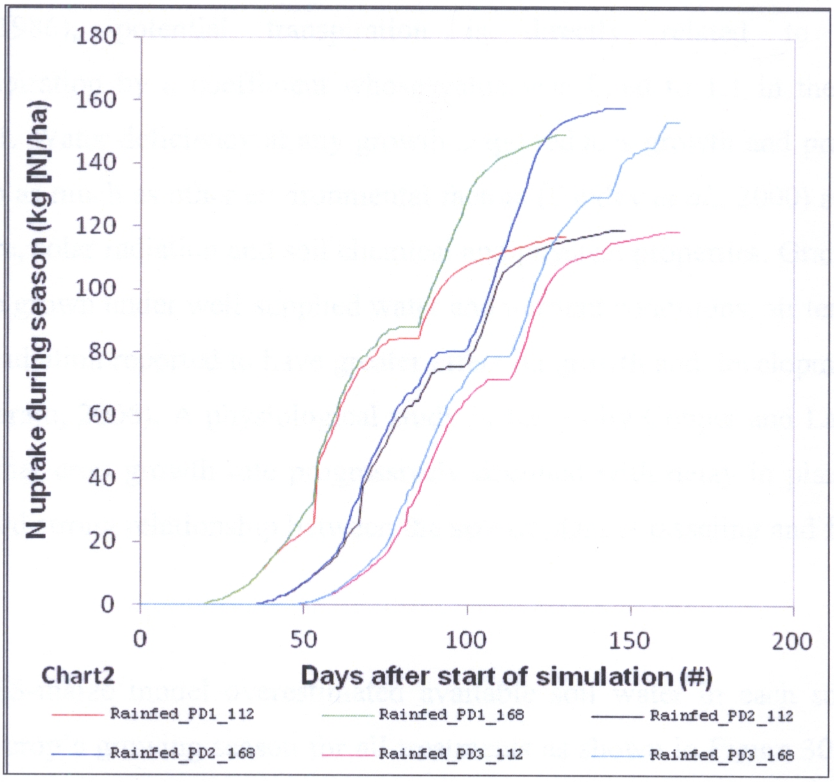

Figure 29: Simulated uptake of N during the growing season

4.4 Effect of soil water availability on maize growth, development and yield under three planting dates and two N application rate

The rate of water productivity was affected by the two N application rates on each of the three PDs. Water productivity increased with increasing rate of N application rate for both the observed and simulated results. The most important factors that affect maize growth and yield are N and water (soil moisture). The amount of N fertilizer required by maize crop varies depending on the yield potential and the amount of residual nitrogen in the soil prior to planting. In this study only 515.2, 498.8 and 476.8 mm of rainfall was received during PD1, PD2 and PD3 growing periods respectively. This indicated that maize yield and yield components were affected by the amount of rainfall received during the course of the growth period. Reddy (2006) noted that maize requires about 600-700 mm of water for optimum growth, yield and this also depends on climatic conditions.

The potential evapotranspiration in the CERES-maize model is calculated with the Priestley-Taylor relation (Priestley and Taylor, 1972). According to Jones and Kiniry (1986), potential transpiration is directly related to potential evapotranspiration by a coefficient whose value was fixed to 1.1 in the CERES-Maize v2.1. Water deficiency at any growth stage reduces growth and productivity of the crop as much as other environmental factors (Pandey *et al.*, 2000) such as air temperature, solar radiation and soil chemical and physical properties. Grain yield of maize crop grown under well-supplied water and nutrient conditions, air temperature and solar radiation reported to have greater effect on growth and development of the crop (Nagaraju, 2006). A physiological study in Kenya by Cooper and Law (1971) indicated that crop growth rate progressively declined with delay in planting date and obtained strong relationship between the size of plant at tasseling and final grain yield.

The CERES-maize model overestimated available soil water in each soil profile during the crop's growing season for all treatments as shown in Figure 30. The soil water content for the three PDs were simulated for soil layer 1 (d-stat=0.62), layer 2 (d-stat=0.55), layer 3 (d-stat=0.50) and layer 4 (d-stat=0.23). The CERES-maize model over-predicted the availability of soil water for the fourth soil layer.

Figure 31, Figure 32 and Figure 33 shows the amount of rainfall received during each maize growing period and the available soil water measurements taken with the Diviner probe. Simulated results indicated that as rainfall reduced the extractable soil water also reduced as shown in Figure 31, Figure 32 and Figure 33 below. Results from the evaluation graphs indicates that the amount of soil water available for plant growth decreased with reduced rainfall (Figure 34) and this had an impact on the aboveground biomass and grain yield for PD2 and PD3. Nangia *et al.* (2010) reported that soil profile layers of thickness 5-15, 15-30 and 30-45 cm are important for simulating correct plant water uptake and soil-water balance. The results are supported by Ollenburger (2012) who reported that water stress in maize increased with reducing rainfall and this contributed to grain yield reduction as the season progressed.

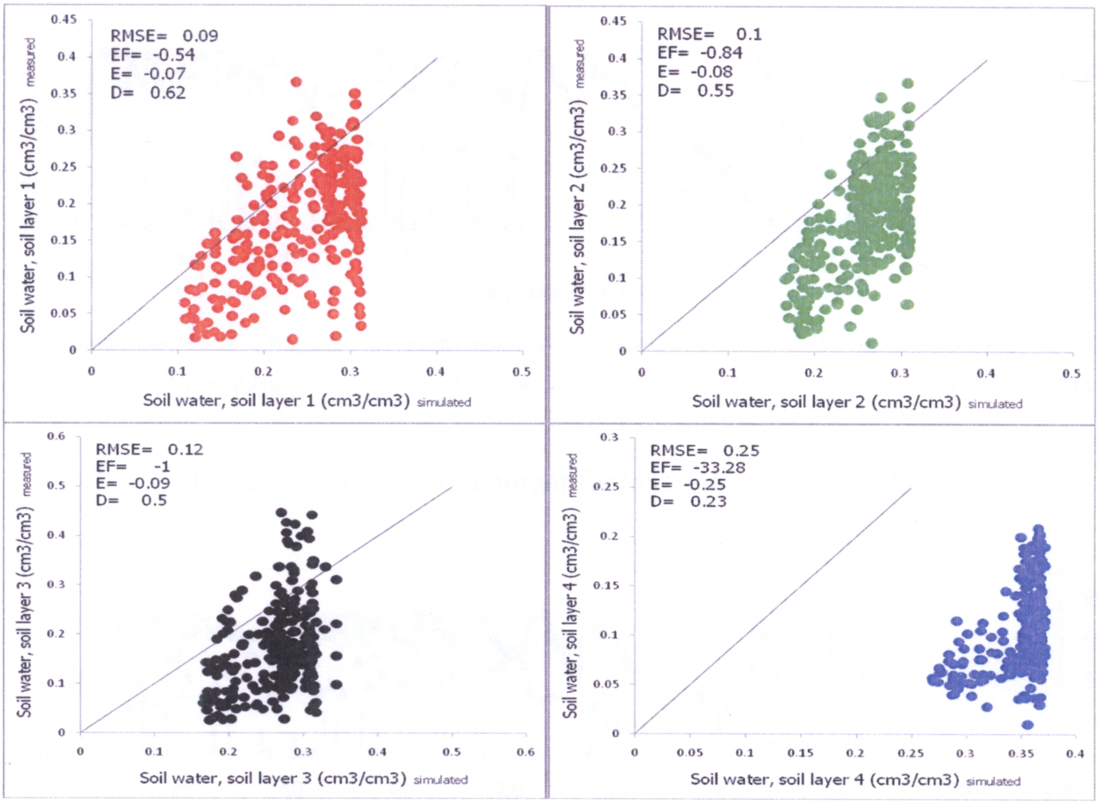

Figure 30: Evaluation statistics for soil water content (profile 1, 2, 3 and 4)

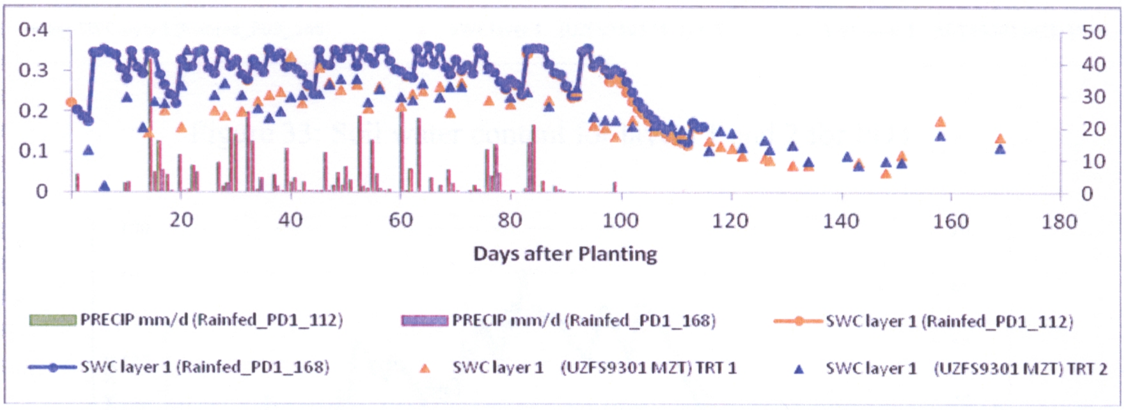

Figure 31: Soil water content for layers 1 and 2 for PD1

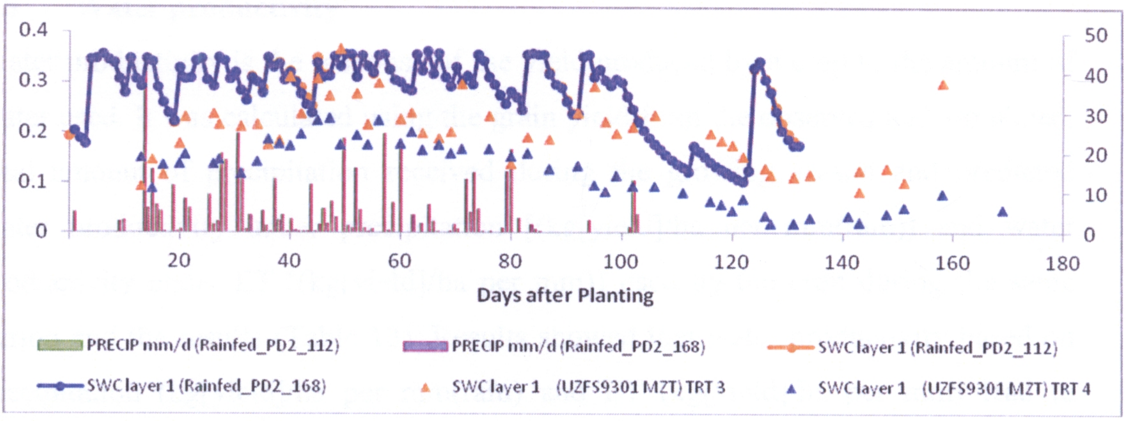

Figure 32: Soil water content for layers 1 and 2 for PD2

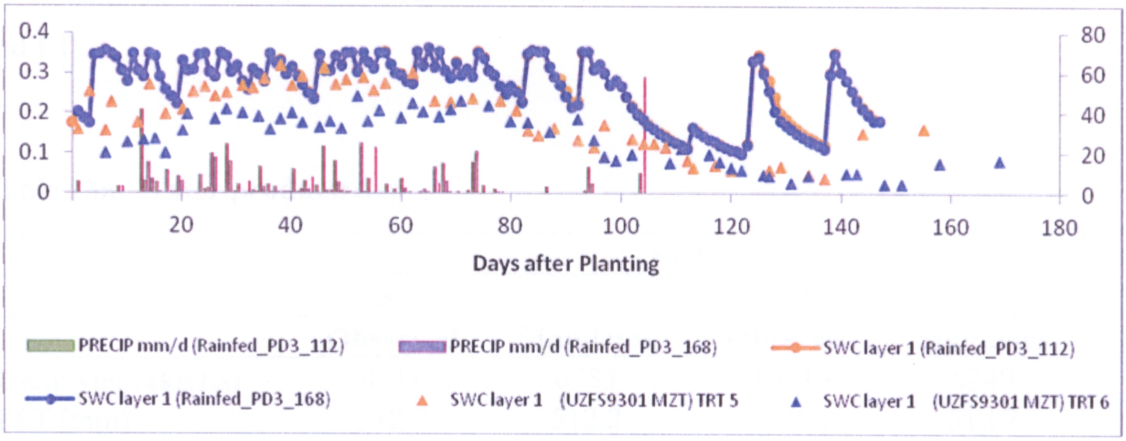

Figure 33: Soil water content for layers 1 and 2 for PD3

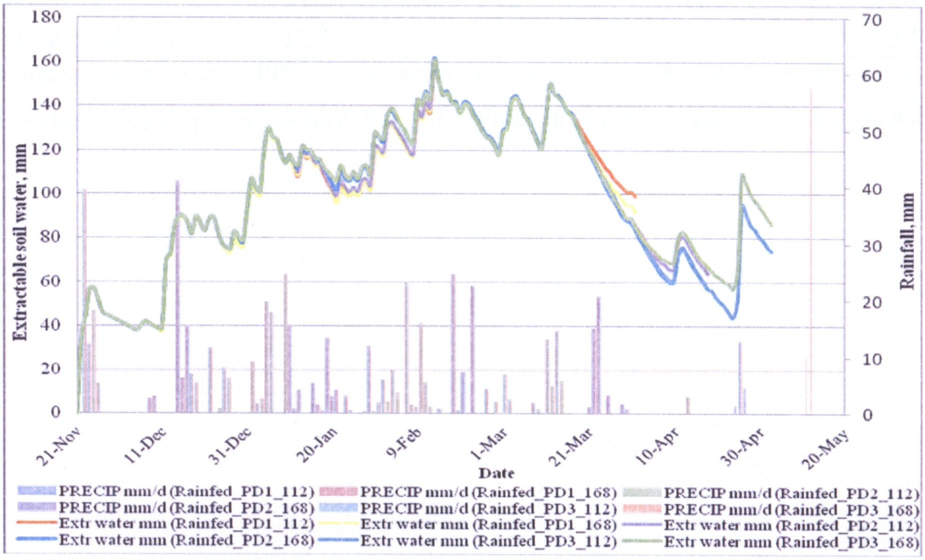

Figure 34: Extractable soil water content

4.5 Water productivity

Water productivity is the response of the yield produced by a crop to the amount of water used. It was calculated using the grain yield from the observed and simulated, total amount of precipitation received during the growing season and predicted water productivity under precipitation [(kg[yield]/ha per mm(rain)) and water productivity under ET [(kg[yield]/ha per mm)] used by the crop during the same period and the results (Table 13). Results showed that water productivity based on precipitation (kg[yield]/ha per mm(rain) and ET (kg[yield]/ha per mm) lead to increased grain yield with increased N application rate for both observed and predicted values for the exception of observed PD3N2. PD3N2 showed a decline in observed grain yield and therefore, reduced water productivity for both precipitation and ET.

Table 13a: Water productivity

	PD1			
	N1		**N2**	
	Observed	**Simulates**	**Observed**	**Simulates**
Grain yield (kg/ha)	9511	6783	10719	8249
PPT (mm)	512.2	512.2	512.2	512.2
ET (mm)	407.9	407.9	415.8	415.8
WP_PPT	18.57	13.24	20.93	16.11
WP_ET	23.32	16.63	25.78	19.84
N applied	112	112	168	168
Season length (days)	128	128	128	128

ET: Evapotranspiration (mm); PPT: Total precipitation (mm); WP: Water productivity under precipitation (kg[yield]/ha per mm(rain); WP_ET: Water productivity under ET (kg[yield]/ha per mm)

Table 14b: Water productivity

	PD2			
	N1		N2	
	Observed	**Simulates**	**Observed**	**Simulates**
Grain yield (kg/ha)	7618	6991	8049	7825
PPT (mm)	498.8	498.8	498.8	498.8
ET (mm)	409.1	409.1	409.1	409.1
WP_PPT	15.27	14.02	16.14	15.69
WP_ET	18.62	17.09	19.67	19.13
N applied	112	112	168	168
Season length (days)	131	131	131	131

Table 15c: Water productivity

	PD3			
	N1		N2	
	Observed	**Simulates**	**Observed**	**Simulates**
Grain yield (kg/ha)	7965	5667	7049	6402
PPT (mm)	476.6	476.6	476.6	476.6
ET (mm)	391.7	389.9	396.5	396.5
WP_PPT	16.71	11.89	14.79	13.43
WP_ET	20.33	14.53	17.78	16.15
N applied	112	112	168	168
Season length (days)	132	132	132	132

4.6 Sensitivity Analyses

A sensitivity analysis demonstrated that anthesis day, physiological maturity day, emergence day and tops at anthesis were not affected by varying the CSPs (G2 and G3) in this study and it is supported by Yang (2008). Variation in G2 from 596.8 to 595.8 showed that grain yield and tops weight at maturity also changed. There were changes in grain yield and tops weight for both: PD1N1 (-0.17, -0.12), PD1N2 (-0.15, -929) and PD2N1 (0.00, 0.00), PD2N2 (-1.93, -0.06), PD3N1 (-0.04, -0.01) and PD3N2 (0.00, 0.00) respectively. Changing the G2 from 592.8 to 597.8 lead to either an increase or decrease in grain yield and tops weight at maturity at all treatment levels. Changes in grain and tops yield were: PD1N1 (-1.13, -0.71), PD1N2 (0.13, -9.23) and PD2N1 (0.07, 0.05), PD2N2 (-1.80, 0.03), PD3N1 (0.04, 0.03) and PD3N2 (0.06, 0.04) respectively.

There were no changes in tops weight at anthesis by variation in G3 CSP at all treatment levels. Varying G3 from 13.79 to 12.79 showed that grain yield and tops weight at maturity also changed. There were changes in grain yield and tops weight for both PD1N1 (-0.49, -0.32), PD1N2 (-7.25, -10.78) and PD2N1 (-0.59, -0.40), PD2N2 (-4.15, -1.57), PD3N1 (-0.30, -0.18) and PD3N2 (-1.92, -1.15), respectively. Changing the G3 from 13.79 to 14.79 lead to either increase or decrease in grain yield and tops weight at maturity at all treatment levels. Increases in grain and tops weight were observed for: PD1N1 (-0.49, -0.31), PD1N2 (1.90, -8.18) and PD2N1 (-0.25, -0.17), PD2N2 (0.91, 1.86), PD3N1 (1.92, 1.12) and PD3N2 (2.31, 1.39) respectively. Changes in G2 and G3 values resulted in proportional change to simulated yield for the ZMS 606 maize cultivar.

Results on sensitivity analysis of precipitation (PPT) (±4 mm), solar radiation (SRAD) (±4 $MJ/m^2/day$), minimum and maximum air temperature (±2°C) are presented in Table 16, Table 17 and Table 18 respectively. The model had problems with PPT, SRAD and temperature simulation in sensitivity analysis. Increasing PPT from the base by 4 mm had higher sensitivity and this reduced grain yield for PD1 and PD2 as shown in Table 16. Grain yield was increased up to 27.32% for PD3 by increasing PPT up to 4 mm. Reducing PPT up to 4 mm reduced grain yield by 37.48%. Increasing SRAD up to $4MJ/m^2/day$ increased grain yield by 7.83% (PD1N1), 10.81% (PD1N2), 5.46% (PD2N1), 13.00% (PD2N2) and 3.12% (PD3N1). Grain yield reduced by 6.49% for PD3N2. Reducing SRAD at all treatment levels had a very high sensitivity and led to reduced yield of up to 29.63% (PD1N2) as presented in Table 17. The CERES-maize model was very sensitive to minimum and maximum temperature as presented in Table 18 and Table 19. The model sensitivity of grain yield to soil and climate data was investigated by Bert *et al.* (2007) using 31 years of historical weather data for a field in Argentine Pampas. The soil N content at sowing, soil organic matter content, soil water storage capacity, soil water content at sowing and daily solar radiation were examined and each variable varied within designed boundary. In spite of the model demonstrating sensitivities to soil variables, much higher sensitivity was reported to changes in daily SRAD and the findings of Bert *et al.* (2007) support this study.

Table 16: Changes in rainfall

Rainfall (mm)	PD1N1	PD1N2	PD2N1	PD2N2	PD3N1	PD3N2
4	-16.92	-21.65	-11.51	-10.38	9.00	16.90
2	-8.40	-8.85	-6.59	-0.81	18.02	27.32
0	0	0	0	0	0	0
-2	5.58	3.25	6.55	-6.42	-13.48	-25.26
-4	-8.25	-14.57	-20.79	-32.39	-23.63	-37.48

Table 17: Changes in solar radiation

SRAD (MJ/m^2/day)	PD1N1	PD1N2	PD2N1	PD2N2	PD3N1	PD3N2
4	7.83	10.81	5.46	13.00	3.12	-6.49
2	3.54	5.63	3.93	1.60	2.35	-4.57
0	0	0	0	0	0	0
-2	-6.51	-15.19	-5.26	-10.75	-5.33	-6.63
-4	-16.19	-29.63	-17.25	-21.02	-11.10	-14.26

Table 18: Changes in minimum temperature

Min Temperature (°C)	PD1N1	PD1N2	PD2N1	PD2N2	PD3N1	PD3N2
2	-1.37	-1.96	2.09	-2.85	1.83	-4.29
1	-1.73	-1.53	0.75	-2.82	-2.74	-5.94
0	0	0	0	0	0	0
-1	-1.92	-0.45	-2.49	-4.03	2.03	7.71
-2	2.45	6.06	-4.67	-5.23	5.07	13.26

Table 19: Changes in maximum temperature

Max temperature (°C)	PD1N1	PD1N2	PD2N1	PD2N2	PD3N1	PD3N2
2	-2.16	-4.65	3.80	-0.96	4.18	-0.96
1	0.74	0.28	1.12	-2.08	-1.24	-3.74
0	0	0	0	0	0	0
-1	-3.54	-2.84	-3.87	-4.82	2.31	8.62
-2	-2.79	-0.12	-5.60	-4.75	2.46	7.04

4.7 Seasonal Analysis

4.7.1 Biophysical analysis

According to one seasonal analysis simulation, the box plot produced using CERES-maize model is presented in Figure 35. On application of 112 kg N/ha (PD2N1), the maximum average harvest maturity yield obtainable was 7265.0 kg/ha. Similarly, 168 kg N/ha (PD1N2) gave a maximum average yield of 8311.0kg/ha. However, the best treatment that guaranteed higher maximum harvest maturity yield was 168 kg N/ha (PD1N2) was applied as presented in Figure 35 and Table 20.

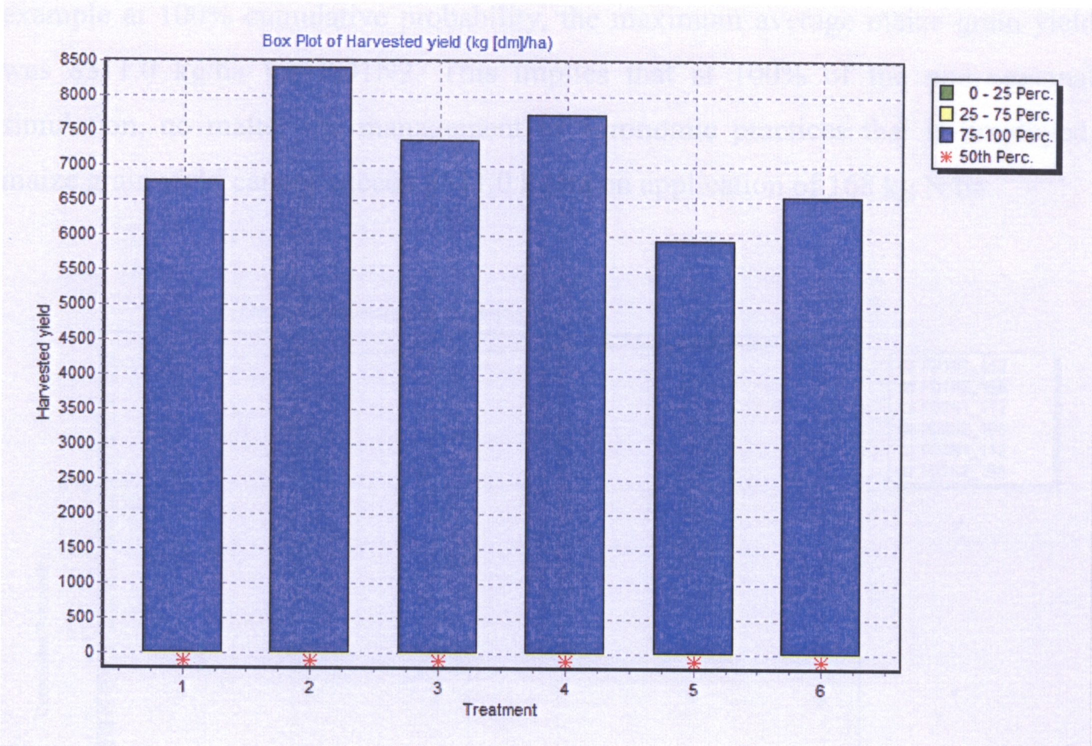

Figure 35: Seasonal analysis of simulated average yield at harvest maturity

Table 20: Seasonal analysis of yield kg/ha

Treatment	Mean	St.dev	Max
PD1N1	126.8	1236.9	6676.0
PD1N2	181.3	1535.4	8311.0
PD2N1	146.5	1344.5	7265.0
PD2N2	159.2	1414.0	7646.0
PD3N1	98.6	1082.3	5829.0
PD3N2	119.8	1198.6	6466.0

According to the seasonal analysis simulation for one season, Figure 36 shows result of cumulative probability of attaining harvest grain yield by specific treatment. For example at 100% cumulative probability, the maximum average maize grain yield was 8311.0 kg/ha for PD1N2. This implies that at 100% of the one seasonal simulation, no matter the management or agronomic practices that is employed, maize grain yield cannot exceed 8311.0 kg/ha on application of 168 kg N/ha.

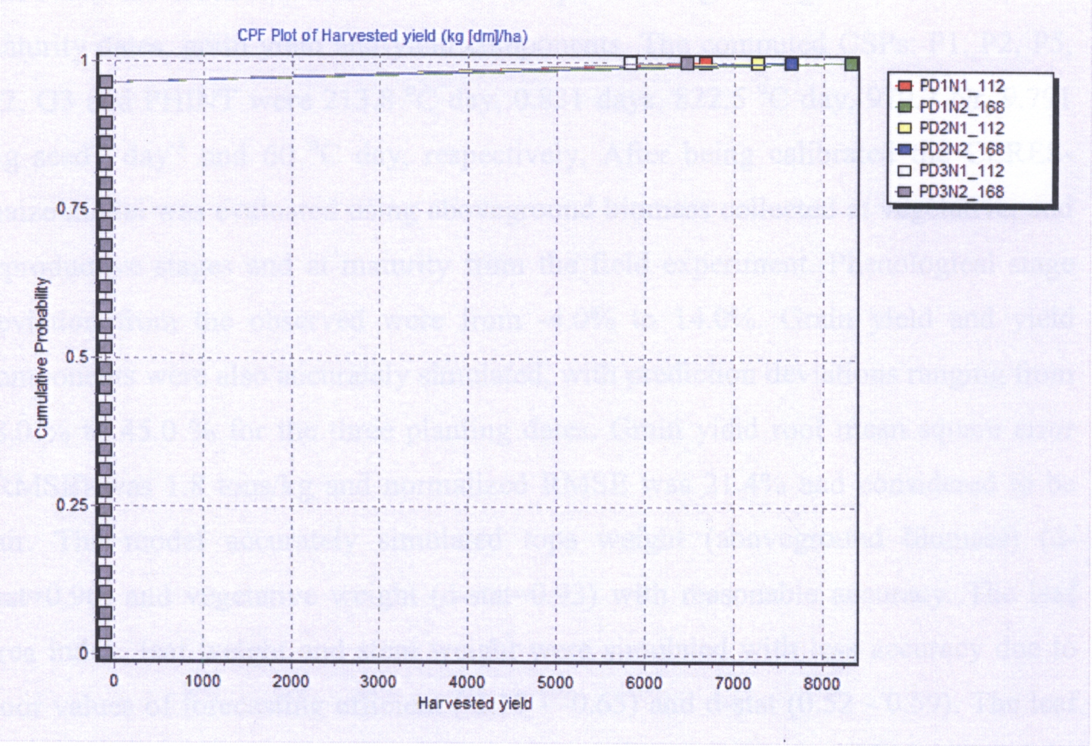

Figure 36: Cumulative probability function plot of grain yield at maturity for one season

CHAPTER FIVE: CONCLUSIONS AND PROPOSED FUTURE STUDIES

5.0 Conclusions

Using the analysis of variance, results showed that date of planting affected aboveground biomass and grain yield while nitrogen application rates of 168 kg N/ha gave higher grain yield and aboveground biomass compared to 112 kg N/ha. Planting date affected the aboveground biomass, stover, husks and grain yield at maturity ($P < 0.05$).

The minimum data sets required by the CERES-maize model as input were characterized. The amount of rainfall and temperature decreased with delay in planting date and ultimately these affected grain yield and yield components. The CSPs for the ZMS606 cultivar were computed using emergence, anthesis, and maturity dates, grain yield and yield components. The computed CSPs: P1, P2, P5, G2, G3 and PHINT were 213.8 ^{o}C day, 0.831 days, 822.5 ^{o}C day, 979.7 Nr, 9.791 mg seed^{-1} day^{-1} and 60 ^{o}C day, respectively. After being calibrated the CERES-maize model was evaluated using aboveground biomass collected at vegetative, and reproductive stages and at maturity from the field experiment. Phenological stage deviation from the observed were from -4.0% to 14.0%. Grain yield and yield components were also accurately simulated, with prediction deviations ranging from -8.0 % to 45.0 % for the three planting dates. Grain yield root mean square error (RMSE) was 1.8 tons/kg and normalized RMSE was 21.4% and considered to be fair. The model accurately simulated tops weight (aboveground biomass) (d-stat=0.96) and vegetative weight (d-stat=0.93) with reasonable accuracy. The leaf area index, leaf weight and stem weight were simulated with less accuracy due to poor values of forecasting efficient (-3.17 - -0.65) and d-stat (0.52 - 0.59). The leaf area index low coefficients of determination were due to poor performance of the model.

Simulation of soil root water availability demonstrated that substantial potential yield may have been lost due to water stress under rain-fed conditions especially for the second and third date of planting. On the other, water use efficiency increased with higher N application rates at all treatment levels.

The results from this study have shown that the model would be a very useful tool for determining the best planting date and crop management strategies. The model did not have a lot of variability across the planting dates and can accurately be used to study the effects of changes in management practices at a specific location. The model was very sensitive to changes in solar radiation, air temperature and rainfall. The use of system-based experiments can facilitate quicker agrotechnology transfer to farmers by using the CERES-maize model. From the analysis the stated alternative hypothesis was accepted meaning that there are significant differences between measured and simulated outputs on date of planting, nitrogen fertilizer application rates, root-zone soil water availability, and maize growth and yield using the CERES-maize model.

5.1 Future Studies and Recommendations

From the findings of this study, the following are the proposed future studies:

1. Based on the simulation results from this study the CERES-maize model appeared to be suitable for the agro-ecological region II of Zambia, however, the model's performance in simulation for a long term basis needs to be evaluated after being validated with independent ZMS606 cultivar emergence, anthesis, and physiological maturity dates, aboveground biomass and grain yield data;
2. Future studies should put more emphasis on modeling growth and yield of maize and other field crops under the three agro-ecological regions of Zambia;
3. A field trial is recommended for agro-ecological region II of Zambia since data on tops (aboveground biomass) N and grain N was not collected;
4. Teaching institutions may harness opportunities offered by crop simulation models as decision support tools to explore the potential of new cultivars for new areas before establishing costly and time consuming field trials and also to test different crop and fertilizer management strategies.

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Appendices

Appendix 1: Analysis of variance

Variate: HI

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Repl stratum	2	0.0025034	0.0012517	1.76	
Repl.plots stratum					
N_rate	1	0.0008170	0.0008170	1.15	0.309
PD	2	0.0023235	0.0011617	1.64	0.243
N_rate.PD	2	0.0004294	0.0002147	0.30	0.746
Residual	10	0.0070994	0.0007099		
Total	17	0.0131725			

Variate: Top_R4_kg[7]

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Repl stratum	2	37835896.	18917948.	1.74	
Repl.Blocks stratum					
N_rate	1	8362129.	8362129.	0.77	0.401
Planting_date	2	2534901.	1267450.	0.12	0.891
N_rate.Planting_date	2	11099306.	5549653.	0.51	0.615
Residual	10	108740441.	10874044.		
Total	**17**	**168572672.**			

Variate: Ear_shuck_R4_kg[10]

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Repl stratum	2	19036768.	9518384.	3.16	
Repl.Blocks stratum					
N_rate	1	5525781.	5525781.	1.84	0.205
Planting_date	2	5139215.	2569607.	0.85	0.455
N_rate.Planting_date	2	13033025.	6516513.	2.17	0.165
Residual	10	30089929.	3008993.		
Total	**17**	**72824718.**			

Variate: Aboveground_biomass

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Block stratum	2	170278.	85139.	9.44	
Block.plots stratum					
N_rate	1	15129.	15129.	1.68	0.224
PD	2	364341.	182170.	20.19	<.001
N_rate.PD	2	69671.	34836.	3.86	0.057
Residual	10	90214.	9021.		
Total	**17**	**709632.**			

Variate: Husk

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	76.3	38.2	0.34	
Block.plots stratum					
N_rate	1	100.1	100.1	0.89	0.368
PD	2	1926.1	963.0	8.56	0.007
N_rate.PD	2	538.0	269.0	2.39	0.142
Residual	10	1125.1	112.5		
Total	**17**	**3765.5**			

Variate: Stover

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Block stratum	2	8144.	4072.	2.67	
Block.plots stratum					
N_rate	1	5147.	5147.	3.38	0.096
PD	2	12598.	6299.	4.13	0.049
N_rate.PD	2	6483.	3242.	2.13	0.170
Residual	10	15242.	1524.		
Total	**17**	**47614.**			

Variate: cob

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Block stratum	2	970.0	485.0	3.95	
Block.plots stratum					
N_rate	1	115.7	115.7	0.94	0.355
PD	2	649.6	324.8	2.64	0.120
N_rate.PD	2	568.0	284.0	2.31	0.150
Residual	10	1228.5	122.9		
Total	**17**	**3531.8**			

Variate: leaf_blade

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Block stratum	2	184.23	92.12	3.85	
Block.plots stratum					
N_rate	1	26.13	26.13	1.09	0.321
PD	2	122.65	61.33	2.56	0.126
N_rate.PD	2	30.29	15.15	0.63	0.551
Residual	10	239.16	23.92		
Total	**17**	**602.47**			

Variate: leafsheath

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Block stratum	2	51.44	25.72	2.19	
Block.plots stratum					
N_rate	1	0.96	0.96	0.08	0.781
PD	2	80.79	40.39	3.44	0.073
N_rate.PD	2	0.03	0.01	0.00	0.999
Residual	10	117.30	11.73		
Total	**17**	**250.51**			

Variate: seed

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Block stratum	2	113304.	56652.	9.81	
Block.plots stratum					
N_rate	1	2627.	2627.	0.45	0.515
PD	2	242410.	121205.	20.99	<.001
N_rate.PD	2	34647.	17324.	3.00	0.095
Residual	10	57747.	5775.		
Total	**17**	**450735.**			

Variate: stem

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Block stratum	2	5739.	2869.	2.48	
Block.plots stratum					
N_rate	1	2015.	2015.	1.74	0.217
PD	2	1852.	926.	0.80	0.477
N_rate.PD	2	1664.	832.	0.72	0.511
Residual	10	11593.	1159.		
Total	**17**	**22862.**			

Appendix 2: Weather data used in DSSAT v4.5

Month	Precipitation (mm)	Solar Radiation (MJ m^{-2} d^{-1})	Temperature (°C) Max	Temperature (°C) Min	Relative humidity (%)
Jun-13	0.0	16.8	13.3	9.4	0.0
Jul-13	0.0	18.0	23.1	9.4	0.0
Aug-13	0.0	18.8	26.2	12.3	0.0
Sep-13	0.0	20.0	31.0	16.5	0.0
Oct-13	56.8	19.7	30.0	17.5	5.0
Nov-13	93.0	19.8	30.4	18.9	9.0
Dec-13	141.8	18.5	28.6	18.0	17.0
Jan-14	155.4	16.6	27.4	17.5	26.0
Feb-14	99.8	14.9	26.6	17.8	18.0
Mar-14	85.6	17.3	27.3	16.8	14.0
Apr-14	87.2	16.7	25.6	14.9	5.0
May-14	0.0	17.9	24.9	12.0	0.0

Appendix 3: Experimental file (FileX) used in DSSAT v4.5

```
*EXP.DETAILS: UZFS1301MZ CALIBRATION AND EVALUATION OF CERES-MAIZE MODEL

*GENERAL
@PEOPLE
Charles Bwalya Chisanga
@ADDRESS
University of Zambia, P. O. Box 37290, Lusaka, Zambia
@SITE
School of Agriculture, Agricultural Field Station
@ PAREA  PRNO  PLEN  PLDR  PLSP  PLAY HAREA  HRNO  HLEN  HARM.........
    -99   -99   -99   -99   -99   -99   -99   -99   -99   -99

*TREATMENTS                        -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
 1 1 1 0 Rainfed_PD1_112            1  1  1  1  1  0  1  0  0  0  0  0  1
 2 1 1 0 Rainfed_PD1_168            1  1  1  1  1  0  2  0  0  0  0  0  1
 3 1 1 0 Rainfed_PD2_112            1  1  1  2  2  0  3  0  0  0  0  0  1
 4 1 1 0 Rainfed_PD2_168            1  1  1  2  2  0  4  0  0  0  0  0  1
 5 1 1 0 Rainfed_PD3_112            1  1  1  3  3  0  5  0  0  0  0  0  1
 6 1 1 0 Rainfed_PD3_168            1  1  1  3  3  0  6  0  0  0  0  0  1

*CULTIVARS
@C CR INGENO CNAME
 1 MZ IB1170 ZMS 606

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX  SLDP  ID_SOIL    FLNAME
 1 UNZAFS01 UZ13       -99   -99 DR000   -99   -99   -99 L      -99  UZFS201301 -99
@L ...........XCRD ...........YCRD .....ELEV .............AREA .SLEN .FLWR .SLAS FLHST FHDUR
 1         28.39477        -15.3371      1261               -99   -99   -99   -99   -99   -99

*SOIL ANALYSIS
@A SADAT  SMHB  SMPX  SMKE  SANAME
 1 13324 SA011 SA002 SA015  Chemical analysis of composit sample
@A  SABL  SADM  SAOC  SANI SAPHW SAPHB  SAPX  SAKE  SASC
 1    20   1.7   .66   .06   6.5   6.2    33    .5   2.2
 1    40   1.7    .6   .04   6.7   6.5    19    .1   2.6
 1    60   1.7   .34   .02   6.9   6.2     8    .2   2.4
 1   100   1.7   .18   .01   6.9   6.4     3    .1     2

*INITIAL CONDITIONS
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID ICNAME
 1    FA 13324   -99   -99     1     1   -99   -99   -99   -99   -99   -99 Treatment 1 (PD1)
@C  ICBL  SH2O  SNH4  SNO3
 1    20  .142    .1     0
 1    40  .138     0     0
 1    60  .135     0     0
 1   100  .109     0     0
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID ICNAME
 2    FA 13324   -99   -99     1     1   -99   -99   -99   -99   -99   -99 Treatment 2 (PD2)
@C  ICBL  SH2O  SNH4  SNO3
 2    20  .155    .1     0
 2    40  .139     0     0
 2    60  .146     0     0
 2   100  .141     0     0
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID ICNAME
 3    FA 13324   -99   -99     1     1   -99   -99   -99   -99   -99   -99 Treatment 3 (PD3)
@C  ICBL  SH2O  SNH4  SNO3
 3    20  .161    .1     0
 3    40  .133     0     0
 3    60  .144     0     0
 3   100  .128     0     0

*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH  SPRL
PLNAME
 1 13328 13335   4.4   4.4     S     R    30   -99     6   -99   -99   -99   -99   -99                        PD1
 2 13342 13350   4.4   4.4     S     R    30   -99     6   -99   -99   -99   -99   -99                        PD2
 3 13356 13362   4.4   4.4     S     R    30   -99     6   -99   -99   -99   -99   -99                        PD3

*IRRIGATION AND WATER MANAGEMENT
@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 1     1    30    50   100 GS000 IR001    10 -99
@I IDATE  IROP IRVAL
 1 13326   -99   -99

*FERTILIZERS (INORGANIC)
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 1 13328 FE005 AP004    10    20     0     0   -99   -99   -99 PD1_112N kg/ha
 1 13328 FE013 AP004    10     0     9     0   -99   -99   -99 PD1_112N kg/ha
 1 13328 FE018 AP004    10     0     0     8   -99   -99   -99 PD1_112N kg/ha
 1 14013 FE005 AP003     5    92   -99   -99   -99   -99   -99 PD1_112N kg/ha
 2 13328 FE005 AP004    10    30     0     0   -99   -99   -99 PD1_168N kg/ha
 2 13328 FE013 AP004    10     0    17     0   -99   -99   -99 PD1_168N kg/ha
 2 13328 FE018 AP004    10     0     0    12   -99   -99   -99 PD1_168N kg/ha
 2 14013 FE005 AP003     5   138   -99   -99   -99   -99   -99 PD1_168N kg/ha
 3 13342 FE018 AP003    10     0     0     8   -99   -99   -99 PD2_112N kg/ha
 3 13342 FE013 AP003    10     0     9     0   -99   -99   -99 PD2_112N kg/ha
 3 13342 FE005 AP003    10    20     0     0   -99   -99   -99 PD2_112N kg/ha
 3 14027 FE005 AP003     5    92   -99   -99   -99   -99   -99 PD2_112N kg/ha
 4 13342 FE013 AP004    10     0    17     0   -99   -99   -99 PD2_168N kg/ha
 4 13342 FE005 AP004    10    30     0     0   -99   -99   -99 PD2_168N kg/ha
 4 13342 FE018 AP004    10     0     0    12   -99   -99   -99 PD2_168N kg/ha
 4 14027 FE005 AP003     5   138   -99   -99   -99   -99   -99 PD2_168N kg/ha
 5 13342 FE018 AP004    10     0     0     8   -99   -99   -99 PD3_112N kg/ha
 5 13342 FE013 AP004    10     0     9     0   -99   -99   -99 PD3_112N kg/ha
 5 13342 FE005 AP004    10    20     0     0   -99   -99   -99 PD3_112N kg/ha
```

```
 5 14041 FE005 AP003     5    92   -99   -99   -99   -99   -99 PD3_112N kg/ha
 6 13356 FE013 AP004    10     0    17     0   -99   -99   -99 PD3_168N kg/ha
 6 13356 FE005 AP004    10    30     0     0   -99   -99   -99 PD3_168N kg/ha
 6 13356 FE018 AP004    10     0     0    12   -99   -99   -99 PD3_168N kg/ha
 6 14041 FE005 AP003     5   138   -99   -99   -99   -99   -99 PD3_168N kg/ha

*RESIDUES AND ORGANIC FERTILIZER
@R RDATE  RCOD  RAMT  RESN  RESP  RESK  RINP  RDEP  RMET RENAME
 1 13326   -99   -99   -99   -99   -99   -99   -99   -99 -99

*CHEMICAL APPLICATIONS
@C CDATE CHCOD CHAMT  CHME CHDEP   CHT..CHNAME
 1 13326   -99   -99   -99   -99   -99  -99

*TILLAGE AND ROTATIONS
@T TDATE TIMPL  TDEP TNAME
 1 13326   -99   -99 -99

*ENVIRONMENT MODIFICATIONS
@E ODATE EDAY  ERAD  EMAX  EMIN  ERAIN ECO2  EDEW  EWIND ENVNAME
 1 13326 A   0 A   0 A   0 A   0 A 0.0 A   0 A   0 A   0

*HARVEST DETAILS
@H HDATE  HSTG  HCOM HSIZE   HPC  HBPC HNAME
 1 13326 GS000   -99   -99   -99   -99 Maize

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME.................... SMODEL
 1 GE              1     1     S 13326  2150 Simulation of PD1, PD2 &  MZCER
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES  CHEM  TILL   CO2
 1 OP              Y     Y     N     Y     N     N     N     N     M
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM MESEV MESOL
 1 ME              M     M     E     R     S     L     R     1     G     S     2
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              R     R     R     R     M
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT VBOSE CHOUT OPOUT
 1 OU              N     Y     Y     1     Y     Y     Y     Y     Y     N     A     N     Y

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL          12001 12001    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 1 IR             30    50   100 GS000 IR001    10     1
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI             30    50    25 FE001 GS000
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE            100     1    20
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA              0 01001   100     0
```

Appendix 4: SOILS: General DSSAT Soil Input File

```
*SOILS: General DSSAT Soil Input File

*UZFS201401  FAO          L     100 Haplic Lixisols
@SITE        COUNTRY        LAT     LONG SCS FAMILY
 UNZA Field  Zambia       -15.4   28.333 Paleausalf
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6    .6    73     1     1 IB001 IB001 IB001
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI  SLHW  SLHB  SCEC  SADC
    20    Ap  .164   .28  .376     1  1.32  1.65   .66  26.4  31.6   -99   .06   6.5   -99    12   -99
    40    Ah  .252  .368  .374  .549   .06  1.66    .6  42.4  33.6   -99   .04   6.7   -99    10   -99
    60     B   .24  .356   .37  .368   .06  1.67   .34  40.4  31.6   -99   .02   6.9   -99    15   -99
   100     C  .262   .37  .375  .202   .06  1.66     2  44.4  33.6   -99   .01   6.9   -99     8   -99
@  SLB  SLPX  SLPT  SLPO CACO3  SLAL  SLFE  SLMN  SLBS  SLPA  SLPB  SLKE  SLMG  SLNA  SLSU  SLEC  SLCA
    20   -99   -99   -99   -99   -99   -99   -99   -99   -99   -99    .4   -99   -99   -99   -99   3.7
    40   -99   -99   -99   -99   -99   -99   -99   -99   -99   -99    .1   -99   -99   -99   -99   1.4
    60   -99   -99   -99   -99   -99   -99   -99   -99   -99   -99    .2   -99   -99   -99   -99   2.8
   100   -99   -99   -99   -99   -99   -99   -99   -99   -99   -99    .1   -99   -99   -99   -99   1.1
```

Appendix 5: FileA: Average values of performance for the maize experiment

```
*EXP. DATA (A): UZFS1330lMZ Average yield and yield components of maize experiment obs

! File last edited on day 9/30/2014 at 5:37:03 PM
!!
!
!
@TRNO  HWAM  CWAM  ADAT  MDAT  CWAA  H#AM  EDAT  LAIX  HIAM  L#SM AMDAY  HDAP  L#SX  PDAT  SWAH  E#AM  EWAM  EWUM SRADA TMINA TMAXA  H#UM
    1  9511 12586 14033 14096  4597  2458 13335  3.24  0.76  14.3    63   150    17 13328 706.6   5.2 10782   245 17.02  16.9  27.6   558
    2 10720 14635 14033 14096  5794  2805 13335  4.66  0.73  14.2    63   150    18 13328  1168   5.8 12129   276 17.02  16.9  27.6   638
    3  7618 10527 14047 14105  4307  2164 13350  3.48  0.72  15.2    58   144    16 13342 844.8   4.5  8768   199 16.55  16.6    27   492
    4  8049 11213 14047 14105  4750  2413 13350  4.19  0.72  15.2    58   144    17 13342  1025   5.0  9322   212 16.55  16.6    27   549
    5  7965 10873 14058 14123  3788  2136 13362  3.05  0.73  13.5    67   144    15 13356 724.3   5.2  9232   210 16.73  16.2   268   486
    6  7049  9879 14058 14123  4766  2068 13362  4.68  0.71  13.7    67   144    15 13356 717.5   5.3  8208   187 16.73  16.2  26.8   470
```

Appendix 6: FileT: Time course data (averages) for the maize experiment

```
*EXP. DATA (T): uzfs9301MZ My Maize experiment observed (T) data

! File last edited on day 06/30/2014 at 7:10:54 PM
!
@TRNO   DATE  L#SD  LAID  LWAD  SWAD  GWAD  VWAD  CWAD  G#AD  GWGD  HIAD  CWPD  E#AD  EWAD LLAID  G#PD   DAP  SW1D  SW2D  SW3D  SW4D
     1 13335                                                                                          7
     1 13337                                                                                          9
     1 13339                                                                                         11 0.146 0.205 0.175 0.064
     1 13340
     1 13342                                                                                             0.201  0.23   0.2 0.082
     1 13345                                                                                             0.159 0.173  0.19 0.099
     1 13346                                                                                             0.351 0.367 0.337 0.171
     1 13351                                                                                             0.202 0.243 0.235 0.095
     1 13353                                                                                             0.188 0.172 0.139 0.091
     1 13356                                                                                               0.2 0.217 0.177 0.069
     1 13359                                                                                             0.224 0.207 0.191 0.069
     1 13360     6                         243.7 243.7                    5.48                           14
     1 13361                                                                                              0.24 0.234 0.179  0.09
     1 13363                                                                                             0.249 0.232 0.191 0.064
     1 13365                                                                                             0.336 0.255 0.163 0.079
     1 14002                                                                                              0.22   0.2 0.145 0.072
     1 14005        0.76                                                                                 0.307 0.285 0.178 0.089
     1 14007                                                                                             0.271 0.267 0.243   0.1
     1 14009                                                                                             0.254 0.182 0.217 0.107
     1 14012                                                                                             0.266 0.261 0.199 0.072
     1 14014                                                                                             0.206  0.18 0.137 0.068
     1 14015
     1 14016                                                                                             0.262  0.23 0.184 0.098
     1 14017        1.33
     1 14018        0.91
     1 14020                                                                                             0.213 0.257  0.22 0.098
     1 14022                                                                                             0.242 0.198 0.194 0.087
     1 14024                                                                                              0.25 0.285 0.226 0.092
     1 14027                                                                                             0.262 0.208 0.154 0.077
     1 14028        2.52
     1 14029                                                                                             0.197 0.167 0.126 0.079
     1 14031                                                                                         32 0.272 0.297 0.211 0.109
     1 14033 15.33  2.37  1406  1930        3337  4596                   103.4  8.07                     68
     1 14036                                                                                             0.226 0.251 0.245 0.083
     1 14040        2.93                                                                                 0.218 0.199 0.158 0.071
     1 14043                                                                                             0.247 0.175 0.159  0.07
     1 14045        2.71
     1 14046
     1 14047                                                                                             0.227 0.229 0.183 0.092
     1 14052        2.32                                                                                  0.25 0.226 0.181 0.076
     1 14055                                                                                             0.165 0.182 0.134 0.057
     1 14057                                                                                              0.16 0.148 0.125  0.06
     1 14058 14.83        1128  2763        3891  8107                   182.4   6.6                     70
     1 14059        3.24                                                                                 0.136 0.164 0.134 0.054
     1 14062                                                                                             0.177 0.154 0.095  0.04
     1 14066                                                                                             0.152 0.138  0.14 0.037
     1 14069                                                                                              0.14 0.138 0.106 0.037
     1 14071        2.16                                                                                 0.145 0.142  0.12 0.038
     1 14076        1.91                                                                                 0.126 0.147 0.092 0.047
     1 14078                                                                                             0.114 0.119 0.089 0.037
     1 14080                                                                                             0.108 0.115 0.085 0.036
     1 14082        1.48                                                                                 0.091 0.132 0.112 0.061
     1 14084        1.38
     1 14086                                                                                             0.086   0.1  0.09 0.028
     1 14087        1.74                                                                                 0.081 0.083 0.081 0.055
     1 14091                                                                                             0.068  0.07 0.084 0.039
     1 14094        1.49                                                                                 0.068 0.128 0.089  0.02
     1 14096 14.33        1101  2070        3172 13351                   300.4  7.33  7451               95
     1 14103        1.32                                                                                 0.074 0.069 0.057 0.022
     1 14108                                                                                              0.05 0.073 0.053 0.012
     1 14111        0.79                                                                                 0.092 0.095 0.088 0.035
     1 14113  14.3             706.6  9511       12586  2456   378  0.76 283.2  5.21 10782       558.3   133
     1 14118                                                                                             0.177 0.176 0.121 0.044
     1 14129                                                                                             0.137  0.14 0.105 0.044
     1 14148
     2 13328                                                                                             0.104 0.152 0.085  0.03
     2 13331                                                                                             0.015 0.012 0.028  0.01
     2 13335                                                                                          7 0.235 0.225 0.262 0.136
     2 13337                                                                                          9
     2 13338                                                                                              0.16 0.118 0.146 0.068
     2 13339                                                                                         11
     2 13340                                                                                             0.225  0.17 0.155 0.066
     2 13342                                                                                             0.219  0.17  0.17 0.069
     2 13345                                                                                             0.264 0.212 0.246 0.103
     2 13346                                                                                              0.35 0.224  0.21 0.088
     2 13351                                                                                             0.239 0.202 0.179 0.074
     2 13353                                                                                             0.269 0.176 0.204 0.082
     2 13356                                                                                             0.241 0.183  0.16 0.056
     2 13359                                                                                             0.207 0.171 0.194 0.075
     2 13360     6                         299.3 299.2                    6.73                           14
     2 13361                                                                                             0.183 0.197 0.167 0.072
     2 13363                                                                                             0.198 0.203 0.182 0.064
     2 13365                                                                                             0.234 0.208 0.166  0.07
     2 14002                                                                                             0.239 0.216 0.203 0.074
     2 14005        1.42                                                                                 0.242 0.247 0.188 0.079
     2 14007                                                                                             0.266 0.276 0.207  0.08
     2 14009                                                                                             0.279  0.25   0.2 0.087
     2 14012                                                                                             0.278 0.216   0.2 0.084
     2 14014                                                                                             0.221 0.205 0.182  0.07
     2 14015
     2 14016                                                                                             0.255 0.237 0.234 0.098
     2 14017        0.82
     2 14018        1.09
     2 14020                                                                                             0.235 0.198 0.177 0.072
     2 14022                                                                                             0.226 0.196 0.184 0.079
     2 14024                                                                                             0.269 0.182 0.178 0.087
     2 14027                                                                                             0.236 0.151 0.149 0.069
     2 14028        2.93
     2 14029                                                                                             0.261 0.155 0.164 0.071
     2 14031                                                                                         32 0.261 0.198   0.2 0.085
     2 14033 15.33  4.07  1371  2877        4249  5794                   130.3  8.43                     68
     2 14036                                                                                             0.304 0.195 0.167  0.09
     2 14040        4.66                                                                                 0.236 0.143 0.127 0.064
     2 14043                                                                                             0.247 0.166 0.138 0.066
     2 14014        1.67
     2 14046
     2 14047                                                                                             0.211 0.194 0.175 0.065
     2 14052        1.90                                                                                 0.257 0.178 0.165 0.068
     2 14055                                                                                             0.187 0.114 0.095  0.05
     2 14057                                                                                             0.177 0.119 0.103 0.037
     2 14058 14.83        1264  2643        3908  9818                   220.9   8.8                     70
     2 14059        2.40                                                                                 0.178 0.116 0.098 0.038
```

2	14062																0.162	0.112	0.077	0.046
2	14066																0.164	0.111	0.145	0.073
2	14068																			
2	14069																0.168	0.097	0.088	0.034
2	14071		1.69														0.155	0.119	0.096	0.035
2	14076		1.41														0.102	0.094	0.068	0.024
2	14078																0.151	0.093	0.075	0.036
2	14080																0.148	0.096	0.083	0.032
2	14082		1.29														0.112	0.085	0.074	0.039
2	14084		2.27																	
2	14086																0.128	0.078	0.069	0.041
2	14087		2.66														0.105	0.073	0.073	0.039
2	14091																0.115	0.079	0.081	0.04
2	14092		1.06																	
2	14094																0.078	0.078	0.074	0.042
2	14096	14.33		1156	2168		3325	13629				306.6	8.07	7415		95				
2	14101																0.091	0.065	0.07	0.037
2	14103		0.75														0.067	0.06	0.067	0.031
2	14108																0.077	0.047	0.044	0.027
2	14111		0.11														0.076	0.055	0.054	0.028
2	14113	14.2			1167	10719		14634	2805	375	0.73	329.2	5.78	12128	637.6	133				
2	14118																0.142	0.173	0.118	0.044
2	14129																0.112	0.184	0.138	0.049
2	14148																			
3	13338																0.092	0.172	0.171	0.106
3	13340																0.146	0.221	0.203	0.183
3	13342																0.116	0.216	0.174	0.094
3	13345																0.178	0.246	0.229	0.142
3	13346																0.23	0.251	0.221	0.115
3	13350															8				
3	13351																0.236	0.323	0.218	0.112
3	13352																0.215	0.263	0.176	0.123
3	13353															11				
3	13356															14	0.212	0.256	0.193	0.112
3	13359																0.216	0.26	0.186	0.15
3	13361																0.176	0.196	0.124	0.102
3	13363																0.183	0.275	0.226	0.16
3	13365																0.312	0.335	0.284	0.135
3	14002																0.237	0.267	0.248	0.156
3	14005		1.09														0.306	0.333	0.253	0.135
3	14007																0.273	0.316	0.288	0.17
3	14008	6					194.6	194.6				4.38				17				
3	14009																0.366	0.318	0.287	0.163
3	14012																0.278	0.322	0.299	0.2
3	14014																0.216	0.219	0.243	0.138
3	14016																0.298	0.347	0.33	0.179
3	14017		1.20																	
3	14018		1.41																	
3	14020																0.226	0.255	0.262	0.154
3	14022																0.238	0.268	0.272	0.174
3	14024																0.198	0.239	0.309	0.166
3	14027																0.189	0.234	0.252	0.146
3	14028		3.71																	
3	14029																0.201	0.262	0.263	0.156
3	14031																0.296	0.297	0.303	0.17
3	14033		3.48																	
3	14036																0.232	0.25	0.259	0.134
3	14040		2.56														0.137	0.195	0.183	0.12
3	14043																0.19	0.223	0.225	0.136
3	14045		2.58													29				
3	14046																			
3	14047	15.17		1304	1997		3301	4307				96.92	4.4			68	0.186	0.21	0.247	0.142
3	14052		3.28														0.239	0.267	0.274	0.168
3	14055																0.293	0.243	0.224	0.104
3	14057																0.222	0.202	0.208	0.099
3	14059		3.01														0.198	0.178	0.2	0.087
3	14062																0.212	0.185	0.16	0.083
3	14066																0.234	0.18	0.159	0.087
3	14069																			
3	14071		2.14																	
3	14072	14.7		1227	3135		4363	8598				193.4	8.8			70				
3	14076		2.83														0.198	0.16	0.151	0.078
3	14078																0.184	0.168	0.142	0.075
3	14080																0.176	0.188	0.176	0.082
3	14082		1.43														0.153	0.183	0.16	0.076
3	14084		2.54																	
3	14086																0.129	0.154	0.152	0.087
3	14087		2.38														0.117	0.141	0.139	0.071
3	14091																0.111	0.126	0.13	0.071
3	14092		1.34																	
3	14094																0.116	0.138	0.116	0.081
3	14103		1.26														0.124	0.105	0.13	0.067
3	14103																0.081	0.085	0.079	0.062
3	14105	15.5		927.4	1987		2914	8264				185.9	7.33	3904		95				
3	14108																0.128	0.078	0.083	0.054
3	14111		0.56														0.101	0.091	0.102	0.052
3	14118																0.3	0.241	0.209	0.079
3	14121	15.2			844.8	7617		10527	2164	345	0.72	236.8	4.53	8768	492	128				
3	14148																			
4	13338																0.149	0.136	0.14	0.096
4	13340																0.088	0.09	0.086	0.074
4	13342																0.135	0.094	0.116	0.072
4	13345																0.137	0.115	0.101	0.096
4	13346																0.157	0.14	0.098	0.125
4	13350															8				
4	13351																0.138	0.128	0.091	0.119
4	13352																0.146	0.122	0.093	0.117
4	13353															11				
4	13356															14	0.119	0.101	0.105	0.128
4	13359																0.141	0.124	0.108	0.111
4	13361																0.185	0.16	0.114	0.136
4	13363																0.178	0.161	0.111	0.13
4	13365																0.173	0.164	0.114	0.119
4	14002																0.197	0.146	0.12	0.137
4	14005		0.53														0.224	0.15	0.153	0.129
4	14007																0.229	0.158	0.141	0.152
4	14008	6					202.4	202.4				4.55				17				
4	14009																0.175	0.184	0.133	0.123
4	14012																0.194	0.17	0.116	0.133
4	14014																0.175	0.173	0.119	0.144
4	14016																0.225	0.18	0.144	0.173
4	14017		1.07																	
4	14018		1.70																	
4	14020																0.178	0.168	0.146	0.126
4	14022																0.201	0.149	0.127	0.139
4	14024																0.165	0.142	0.123	0.156
4	14027																0.176	0.142	0.116	0.125
4	14028		2.59																	
4	14029																0.158	0.12	0.093	0.108
4	14031																0.167	0.157	0.128	0.128
4	14033		3.31																	
4	14036																0.166	0.156	0.114	0.123
4	14040		4.19														0.153	0.134	0.1	0.144

4	14043																0.158	0.119	0.088	0.128
4	14045		2.74													29				
4	14046																			
4	14047	15.33		1354	2243		3597	4749				106.8	4.4			68	0.127	0.113	0.098	0.134
4	14052		2.78														0.133	0.14	0.104	0.123
4	14055																0.095	0.088	0.067	0.095
4	14057																0.083	0.082	0.054	0.083
4	14059		2.78														0.113	0.071	0.056	0.076
4	14062																0.092	0.065	0.041	0.075
4	14066																0.093	0.083	0.049	0.077
4	14069																			
4	14071		1														0.08	0.065	0.046	0.086
4	14072	15		1402	2920		4323	9124				205.3	8.8			70				
4	14076		0.99														0.064	0.058	0.048	0.072
4	14078																0.056	0.065	0.053	0.063
4	14080																0.044	0.058	0.049	0.068
4	14082		1.67														0.067	0.044	0.028	0.056
4	14084		1.78																	
4	14086																0.034	0.043	0.052	0.074
4	14087		2.57														0.018	0.027	0.027	0.052
4	14091																0.019	0.024	0.033	0.06
4	14092		1.36																	
4	14094																0.029	0.042	0.035	0.074
4	14101																0.034	0.038	0.031	0.063
4	14103		1.09														0.02	0.035	0.029	0.053
4	14105	15.17		917	1789		2702	8691				195.5	8.07	4842		95				
4	14108																0.038	0.032	0.025	0.057
4	14111		0.41														0.05	0.041	0.04	0.052
4	14118																0.078	0.074	0.039	0.078
4	14121	14.2			1025	8048		11212	2413	324	0.72	252.2	4.98	9321	548.5	128				
4	14129																0.045	0.038	0.031	0.062
4	14148																			
5	13335																0.083	0.117	0.104	0.072
5	13338																0.14	0.175	0.116	0.089
5	13340																0.158	0.175	0.149	0.082
5	13342																0.252	0.269	0.227	0.126
5	13345																0.157	0.207	0.159	0.084
5	13346																0.227	0.226	0.156	0.08
5	13351																0.177	0.25	0.138	0.095
5	13353																0.271	0.266	0.176	0.102
5	13356																0.196	0.234	0.156	0.114
5	13359																0.208	0.26	0.135	0.096
5	13361																0.252	0.248	0.144	0.097
5	13362															6				
5	13363																0.264	0.251	0.17	0.111
5	13364															8				
5	13365																0.24	0.266	0.169	0.101
5	14002															11	0.25	0.282	0.156	0.107
5	14005		0.51														0.267	0.309	0.175	0.116
5	14007																0.262	0.299	0.18	0.118
5	14009																0.286	0.294	0.187	0.129
5	14012																0.319	0.311	0.179	0.121
5	14014																0.268	0.265	0.15	0.11
5	14016																0.292	0.275	0.165	0.108
5	14017		0.5																	
5	14018		0.29																	
5	14020	6					193.2	193.1				4.35				14	0.313	0.313	0.195	0.121
5	14022																0.272	0.262	0.137	0.111
5	14024																0.283	0.264	0.158	0.107
5	14027																0.288	0.296	0.148	0.116
5	14028		3.03																	
5	14029																0.257	0.246	0.147	0.105
5	14031																0.275	0.266	0.162	0.112
5	14033		2.45																	
5	14036																0.299	0.319	0.172	0.115
5	14040		1.96														0.23	0.238	0.146	0.108
5	14043																0.227	0.246	0.133	0.094
5	14045		2.09																	
5	14046																			
5	14047																0.236	0.245	0.125	0.091
5	14052		3.05														0.229	0.252	0.119	0.101
5	14055																0.207	0.22	0.095	0.089
5	14056															26				
5	14057																0.156	0.168	0.072	0.079
5	14058	15		988.8	1779		2769	3784				85.15	8.07			65				
5	14059		2.57														0.144	0.164	0.073	0.07
5	14062																0.161	0.147	0.062	0.062
5	14066																0.132	0.16	0.071	0.069
5	14069																0.115	0.135	0.055	0.059
5	14071		2.04														0.169	0.155	0.057	0.063
5	14076		1.57														0.134	0.162	0.063	0.062
5	14078																0.122	0.143	0.058	0.062
5	14080																0.122	0.145	0.068	0.066
5	14082		1.54														0.114	0.143	0.06	0.061
5	14084	14.83	1.57	1090	2741		3832	7891				177.5	8.8			67				
5	14086																0.083	0.134	0.052	0.059
5	14087		2.32														0.065	0.114	0.062	0.061
5	14091																0.07	0.102	0.083	0.061
5	14092		1.03																	
5	14094																0.057	0.099	0.079	0.052
5	14101																0.059	0.088	0.062	0.059
5	14103		1.07														0.067	0.068	0.061	0.046
5	14108																0.047	0.061	0.045	0.041
5	14111		0.48														0.038	0.064	0.057	0.04
5	14118																0.15	0.15	0.105	0.058
5	14123	13.5		791.8	1283		2075	6539				147.1	5.13	3297		93				
5	14129																0.162	0.202	0.103	0.07
5	14133	14.3			724.4	7964		10872	2136	357.4	0.73	244.6	5.16	9231	485.6	135				
5	14148																			
6	13331																0.099	0.114	0.129	0.118
6	13335																0.126	0.14	0.169	0.153
6	13338																0.132	0.128	0.151	0.175
6	13340																0.136	0.159	0.235	0.189
6	13342																0.1	0.179	0.22	0.165
6	13345																0.157	0.202	0.283	0.156
6	13346																0.197	0.182	0.311	0.19
6	13351																0.184	0.184	0.237	0.177
6	13353																0.208	0.224	0.263	0.195
6	13356																0.199	0.188	0.251	0.194
6	13359																0.191	0.215	0.274	0.183
6	13361																0.159	0.184	0.224	0.113
6	13362															6				
6	13363																0.186	0.219	0.31	0.175
6	13364															8				
6	13365																0.201	0.252	0.349	0.202
6	14002															11	0.176	0.209	0.205	0.125
6	14005		0.46														0.165	0.173	0.342	0.185
6	14007																0.18	0.233	0.399	0.209
6	14009																0.161	0.202	0.406	0.192
6	14012																0.242	0.221	0.427	0.17
6	14014																0.178	0.197	0.442	0.203
6	14016																0.206	0.209	0.378	0.179
6	14018		0.22																	

6	14020	6					238	237.9				5.35				14	0.187	0.211	0.447	0.186
6	14022																0.222	0.228	0.423	0.199
6	14024																0.204	0.242	0.39	0.196
6	14027																0.192	0.192	0.408	0.175
6	14028		3.29																	
6	14029																0.21	0.198	0.337	0.195
6	14031																0.228	0.253	0.394	0.191
6	14033		4.05																	
6	14036																0.218	0.196	0.383	0.171
6	14040		2.77														0.178	0.175	0.295	0.167
6	14043																0.177	0.208	0.324	0.159
6	14045		2.68																	
6	14046																			
6	14047																0.152	0.17	0.337	0.176
6	14052		4.68														0.185	0.188	0.318	0.149
6	14055																0.133	0.166	0.289	0.159
6	14056															26				
6	14057																0.091	0.125	0.279	0.141
6	14058	15		1121	2379		3501	4766				107.2	8.8			65				
6	14059		3.28														0.082	0.121	0.249	0.145
6	14062																0.097	0.113	0.224	0.139
6	14066																			
6	14069																0.076	0.117	0.199	0.131
6	14071		3.53														0.111	0.116	0.195	0.117
6	14076		1.91														0.098	0.099	0.204	0.129
6	14078																0.08	0.121	0.139	0.118
6	14080																0.065	0.099	0.225	0.118
6	14082		3.28														0.058	0.098	0.232	0.12
6	14084	15	2.08	1250	3070		4321	9157				206	8.8			67				
6	14086																0.047	0.073	0.19	0.113
6	14087		3.35														0.043	0.078	0.148	0.105
6	14091																0.025	0.046	0.067	0.051
6	14092		1.84																	
6	14094																0.043	0.063	0.142	0.102
6	14101																0.049	0.053	0.124	0.094
6	14103		1.08														0.05	0.085	0.143	0.115
6	14108																0.022	0.029	0.071	0.056
6	14111		0.18														0.022	0.031	0.06	0.05
6	14118																0.075	0.077	0.098	0.063
6	14123	13.7		830.7	1325			7572				170.3	5.13	3738		93				
6	14129																0.083	0.108	0.138	0.082
6	14133	14.8			717.5	7049	979	9878	2068	323.9	0.71	222.2	5.3	8208	470.2	135				
6	14148																			

Appendix 7: Simulation Overview File

```
*SIMULATION OVERVIEW FILE

*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub         SEP 30, 2014; 19:30:40

*RUN  1         : Rainfed_PD1_112          MZCER045 UZFS9301    1
 MODEL          : MZCER045 - Maize
 EXPERIMENT     : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH      : C:\DSSAT45\maize\
 TREATMENT  1   : Rainfed_PD1_112          MZCER045


 CROP           : Maize             CULTIVAR : ZMS 606          ECOTYPE :IB0001
 STARTING DATE  : NOV 22  2013
 PLANTING DATE  : NOV 24  2013          PLANTS/m2 :  4.4     ROW SPACING :  30.cm
 WEATHER        : UZ93    2013
 SOIL           : UZFS201401     TEXTURE : L     - Haplic Lixisols
 SOIL INITIAL C : DEPTH:100cm EXTR. H2O:112.8mm  NO3:  0.0kg/ha  NH4:  0.0kg/ha
 WATER BALANCE  : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION     :        0 mm IN      0 APPLICATIONS
 NITROGEN BAL.  : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER   :      112 kg/ha IN     4 APPLICATIONS
 RESIDUE/MANURE : INITIAL :       0 kg/ha ;         0 kg/ha IN     0 APPLICATIONS
 ENVIRONM. OPT. : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= S  0.00
                  RAIN= A  0.00  CO2 = A   0.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT : WATER    :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                  PHOTO    :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                  CO2 358ppm   NSWIT   :1  EVAP :S  SOIL   :2
 MANAGEMENT OPT : PLANTING:R   IRRIG   :R  FERT :R  RESIDUE:R  HARVEST:M
                  WEATHER :M   TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3    cm3/cm3          g/cm3         ugN/g  ugN/g    %
--------------------------------------------------------------------------------
   0-  5 0.164 0.280 0.376 0.116 0.142   1.00   1.70   6.50   0.00   0.00   0.66
   5- 15 0.164 0.280 0.376 0.116 0.142   1.00   1.70   6.50   0.00   0.00   0.66
  15- 20 0.164 0.280 0.376 0.116 0.142   1.00   1.70   6.50   0.00   0.00   0.66
  20- 30 0.252 0.368 0.378 0.116 0.138   0.55   1.70   6.70   0.00   0.00   0.60
  30- 40 0.252 0.368 0.378 0.116 0.138   0.55   1.70   6.70   0.00   0.00   0.60
  40- 50 0.240 0.356 0.370 0.116 0.135   0.37   1.70   6.90   0.00   0.00   0.34
  50- 60 0.240 0.356 0.370 0.116 0.135   0.37   1.70   6.90   0.00   0.00   0.34
  60- 80 0.262 0.370 0.380 0.108 0.109   0.20   1.70   6.90   0.00   0.00   0.18
  80-100 0.262 0.370 0.380 0.108 0.109   0.20   1.70   6.90   0.00   0.00   0.18

 TOT-100  23.6  34.9  37.7  11.3  12.7  <--cm   -  kg/ha-->   0.0    0.0  66640
 SOIL ALBEDO    : 0.13      EVAPORATION LIMIT : 6.00        MIN. FACTOR  : 1.00
 RUNOFF CURVE # :73.00      DRAINAGE RATE     : 0.60        FERT. FACTOR : 1.00

  Maize      CULTIVAR :IB1170-ZMS 606             ECOTYPE :IB0001
  P1      : 213.80  P2      : 0.8310  P5      : 822.50
  G2      : 979.70  G3      :   9.791  PHINT  : 60.000

*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

 RUN NO.      1     Rainfed_PD1_112

              CROP GROWTH      BIOMASS           LEAF    CROP N      STRESS       STRESS
    DATE  AGE STAGE            kg/ha     LAI    NUM  kg/ha  %   H2O     N     P1     P2  RSTG
  ------ --- ----------       -----   -----   ----   ---  ---  ----  ----  ----  ----  ----
  22 NOV   0 Start Sim            0    0.00    0.0     0  0.0  0.00  0.00  0.00  0.00     7
  24 NOV   0 Sowing               0    0.00    0.0     0  0.0  0.00  0.00  0.00  0.00     8
  25 NOV   1 Germinate            0    0.00    0.0     0  0.0  0.00  0.00  0.00  0.00     9
  30 NOV   6 Emergence           18    0.00    1.9     1  4.4  0.00  0.01  0.00  0.00     1
  13 DEC  19 End Juveni          45    0.10    6.3     2  3.6  0.00  0.00  0.00  0.00     2
  19 DEC  25 Floral Ini          97    0.20    7.7     3  3.6  0.00  0.00  0.00  0.00     3
   1 FEB  69 75% Silkin        3247    1.48   16.4    60  1.8  0.00  0.04  0.00  0.00     4
  13 FEB  81 Beg Gr Fil        5235    1.41   16.4    63  1.2  0.00  0.00  0.00  0.00     5
  28 MAR 124 End Gr Fil       10877    0.49   16.4    94  0.9  0.03  0.49  0.00  0.00     6
  31 MAR 127 Maturity         10877    0.49   16.4    94  0.9  0.21  0.87  0.00  0.00    10
  31 MAR 127 Harvest          10877    0.49   16.4    94  0.9  0.00  0.00  0.00  0.00    10


*MAIN GROWTH AND DEVELOPMENT VARIABLES

 @    VARIABLE                                         SIMULATED    MEASURED
      --------                                         ---------    --------
      Anthesis day (dap)                                      69          70
      Physiological maturity day (dap)                       127         133
      Yield at harvest maturity (kg [dm]/ha)                6783        9511
      Number at maturity (no/m2)                            2052        2458
      Unit wt at maturity (g [dm]/unit)                   0.3305         -99
      Number at maturity (no/unit)                         466.4         558
      Tops weight at maturity (kg [dm]/ha)                 10877       12586
      By-product produced (stalk) at maturity (kg[dm]/ha    4120         -99
      Leaf area index, maximum                              1.48        3.24
      Harvest index at maturity                            0.624        0.76
      Grain N at maturity (kg/ha)                             83         -99
      Tops N at maturity (kg/ha)                              94         -99
      Stem N at maturity (kg/ha)                              11         -99
      Grain N at maturity (%)                                1.2         -99
      Tops weight at anthesis (kg [dm]/ha)                  3097        4597
      Tops N at anthesis (kg/ha)                              58         -99
      Leaf number per stem at maturity                     16.40        14.3
      Emergence day (dap)                                      6           7

*ENVIRONMENTAL AND STRESS FACTORS

 |-----Development Phase------|-------------Environment--------------|----------------Stress-----------------|
                              |--------Average--------|---Cumulative--|         (0=Min, 1=Max Stress)        |
                         Time  Temp  Temp Solar Photop         Evapo |----Water---|--Nitrogen--|--Phosphorus-|
                         Span   Max   Min   Rad  [day]   CO2   Rain  Trans  Photo         Photo         Photo
                         days    øC    øC MJ/m2     hr   ppm     mm     mm  synth Growth  synth Growth  synth Growth
--------------------------------------------------------------------------------------------------------------------
 Emergence-End Juvenile    13  30.7  18.2  22.6  12.87  357.6    5.8   15.4  0.000  0.000  0.002  0.006  0.000  0.000
 End Juvenil-Floral Init    6  26.7  17.0  13.6  12.91  357.7   75.6   21.6  0.000  0.000  0.001  0.002  0.000  0.000
 Floral Init-End Lf Grow   44  27.5  17.7  17.0  12.84  357.8  214.2  166.9  0.000  0.000  0.018  0.045  0.000  0.000
 End Lf Grth-Beg Grn Fil   12  26.4  17.8  13.3  12.62  357.9   59.4   38.3  0.000  0.000  0.000  0.000  0.000  0.000
 Grain Filling Phase       43  27.1  17.3  16.5  12.25  358.2  124.6  138.8  0.006  0.022  0.295  0.467  0.000  0.000

 Planting to Harvest      127  27.5  17.6  17.0  12.60  357.9  515.2  407.9  0.002  0.012  0.122  0.195  0.000  0.000
--------------------------------------------------------------------------------------------------------------------

*Resource Productivity
 Growing season length: 127 days
```

```
Precipitation during growing season       515.2 mm[rain]
  Dry Matter Productivity                  2.11 kg[DM]/m3[rain]           =    21.1 kg[DM]/ha per mm[rain]
  Yield Productivity                       1.32 kg[grain yield]/m3[rain] =    13.2 kg[yield]/ha per mm[rain]

Evapotranspiration during growing season  407.9 mm[ET]
  Dry Matter Productivity                  2.67 kg[DM]/m3[ET]             =    26.7 kg[DM]/ha per mm[ET]
  Yield Productivity                       1.66 kg[grain yield]/m3[ET]   =    16.6 kg[yield]/ha per mm[ET]

Transpiration during growing season       191.0 mm[EP]
  Dry Matter Productivity                  5.69 kg[DM]/m3[EP]             =    56.9 kg[DM]/ha per mm[EP]
  Yield Productivity                       3.55 kg[grain yield]/m3[EP]   =    35.5 kg[yield]/ha per mm[EP]

N applied during growing season            112. kg[N applied]/ha
  Dry Matter Productivity                  97.1 kg[DM]/kg[N applied]
  Yield Productivity                       60.6 kg[yield]/kg[N applied]

N uptake during growing season              117 kg[N uptake]/ha
  Dry Matter Productivity                  93.0 kg[DM]/kg[N uptake]
  Yield Productivity                       58.0 kg[yield]/kg[N uptake]

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                     Maize YIELD :     6783 kg/ha    [Dry weight]

******************************************************************************************************************

*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub         SEP 30, 2014; 19:30:41

*RUN   2         : Rainfed_PD1_168           MZCER045 UZFS9301    2
 MODEL           : MZCER045 - Maize
 EXPERIMENT      : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH       : C:\DSSAT45\maize\
 TREATMENT  2    : Rainfed_PD1_168           MZCER045


 CROP            : Maize            CULTIVAR : ZMS 606           ECOTYPE :IB0001
 STARTING DATE   : NOV 22  2013
 PLANTING DATE   : NOV 24  2013         PLANTS/m2 :  4.4     ROW SPACING :  30.cm
 WEATHER         : UZ93    2013
 SOIL            : UZFS201401     TEXTURE : L      - Haplic Lixisols
 SOIL INITIAL C  : DEPTH:100cm EXTR. H2O:112.8mm  NO3:  0.0kg/ha  NH4:  0.0kg/ha
 WATER BALANCE   : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION      :        0 mm IN     0 APPLICATIONS
 NITROGEN BAL.   : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER    :       168 kg/ha IN     4 APPLICATIONS
 RESIDUE/MANURE  : INITIAL :      0 kg/ha ;         0 kg/ha IN      0 APPLICATIONS
 ENVIRONM. OPT.  : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= S  0.00
                   RAIN= A  0.00  CO2 = A   0.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT  : WATER    :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS   :N
                   PHOTO    :C  ET      :R  INFIL:S  HYDROL :R  SOM     :G
                   CO2 358ppm  NSWIT    :1  EVAP :S  SOIL   :2
 MANAGEMENT OPT  : PLANTING:R  IRRIG    :R  FERT :R  RESIDUE:R  HARVEST:M
                   WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3     NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3    cm3/cm3          g/cm3          ugN/g  ugN/g     %
--------------------------------------------------------------------------------
   0-  5 0.164 0.280 0.376 0.116 0.142   1.00   1.70   6.50   0.00   0.00   0.66
   5- 15 0.164 0.280 0.376 0.116 0.142   1.00   1.70   6.50   0.00   0.00   0.66
  15- 20 0.164 0.280 0.376 0.116 0.142   1.00   1.70   6.50   0.00   0.00   0.66
  20- 30 0.252 0.368 0.378 0.116 0.138   0.55   1.70   6.70   0.00   0.00   0.60
  30- 40 0.252 0.368 0.378 0.116 0.138   0.55   1.70   6.70   0.00   0.00   0.60
  40- 50 0.240 0.356 0.370 0.116 0.135   0.37   1.70   6.90   0.00   0.00   0.34
  50- 60 0.240 0.356 0.370 0.116 0.135   0.37   1.70   6.90   0.00   0.00   0.34
  60- 80 0.262 0.370 0.380 0.108 0.109   0.20   1.70   6.90   0.00   0.00   0.18
  80-100 0.262 0.370 0.380 0.108 0.109   0.20   1.70   6.90   0.00   0.00   0.18

TOT-100   23.6   34.9   37.7   11.3   12.7  <--cm    -  kg/ha-->    0.0     0.0  66640
SOIL ALBEDO     : 0.13       EVAPORATION LIMIT : 6.00          MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00        DRAINAGE RATE     : 0.60          FERT. FACTOR : 1.00

 Maize       CULTIVAR :IB1170-ZMS 606            ECOTYPE :IB0001
 P1       : 213.80  P2      : 0.8310  P5      : 822.50
 G2       : 979.70  G3      :   9.791  PHINT   : 60.000

*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

 RUN NO.     2     Rainfed_PD1_168

        CROP GROWTH      BIOMASS          LEAF   CROP N      STRESS       STRESS
  DATE  AGE STAGE          kg/ha    LAI    NUM  kg/ha  %   H2O    N     P1    P2   RSTG
 ------ --- ----------     -----  -----   ----   --- ---  ----  ----  ----  ----   ----
 22 NOV   0 Start Sim          0   0.00    0.0     0  0.0  0.00  0.00  0.00  0.00      7
 24 NOV   0 Sowing             0   0.00    0.0     0  0.0  0.00  0.00  0.00  0.00      8
 25 NOV   1 Germinate          0   0.00    0.0     0  0.0  0.00  0.00  0.00  0.00      9
 30 NOV   6 Emergence         18   0.00    1.9     1  4.4  0.00  0.01  0.00  0.00      1
 13 DEC  19 End Juveni        45   0.10    6.3     2  3.6  0.00  0.00  0.00  0.00      2
 19 DEC  25 Floral Ini        97   0.20    7.7     3  3.6  0.00  0.00  0.00  0.00      3
  1 FEB  69 75% Silkin      3340   1.54   16.4    62  1.8  0.00  0.02  0.00  0.00      4
 13 FEB  81 Beg Gr Fil      5356   1.45   16.4    65  1.2  0.00  0.00  0.00  0.00      5
 28 MAR 124 End Gr Fil     12389   0.65   16.4   126  1.0  0.03  0.30  0.00  0.00      6
 31 MAR 127 Maturity       12389   0.65   16.4   126  1.0  0.26  0.80  0.00  0.00     10
 31 MAR 127 Harvest        12389   0.65   16.4   126  1.0  0.00  0.00  0.00  0.00     10

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@     VARIABLE                                            SIMULATED     MEASURED
      --------                                            ---------     --------
      Anthesis day (dap)                                         69           70
      Physiological maturity day (dap)                          127          133
      Yield at harvest maturity (kg [dm]/ha)                   8249        10720
      Number at maturity (no/m2)                               2082         2805
      Unit wt at maturity (g [dm]/unit)                      0.3962          -99
      Number at maturity (no/unit)                            473.2          638
      Tops weight at maturity (kg [dm]/ha)                    12389        14635
      By-product produced (stalk) at maturity (kg[dm]/ha       4165          -99
      Leaf area index, maximum                                 1.58         4.66
      Harvest index at maturity                               0.666         0.73
      Grain N at maturity (kg/ha)                               113          -99
      Tops N at maturity (kg/ha)                                126          -99
      Stem N at maturity (kg/ha)                                 12          -99
      Grain N at maturity (%)                                   1.4          -99
      Tops weight at anthesis (kg [dm]/ha)                     3185         5794
      Tops N at anthesis (kg/ha)                                 59          -99
      Leaf number per stem at maturity                        16.40         14.2
      Emergence day (dap)                                         6            7

*ENVIRONMENTAL AND STRESS FACTORS
```

```
|-----Development Phase------|-----------------Environment-----------------|----------------Stress-----------------|
                             |-----------Average-----------|---Cumulative--|         (0=Min, 1=Max Stress)          |
                        Time  Temp  Temp Solar Photop           Evapo |----Water---|--Nitrogen--|--Phosphorus-|
                        Span   Max   Min   Rad  [day]     CO2   Rain  Trans  Photo           Photo           Photo
                        days    øC    øC MJ/m2     hr     ppm     mm     mm  synth Growth  synth Growth  synth Growth
--------------------------------------------------------------------------------------------------------------------
Emergence-End Juvenile    13  30.7  18.2  22.6  12.87   357.6    5.8   15.4  0.000  0.000  0.002  0.006  0.000  0.000
End Juvenil-Floral Init    6  26.7  17.0  13.6  12.91   357.7   75.6   21.6  0.000  0.000  0.001  0.002  0.000  0.000
Floral Init-End Lf Grow   44  27.5  17.7  17.0  12.84   357.8  214.2  168.2  0.000  0.000  0.006  0.016  0.000  0.000
End Lf Grth-Beg Grn Fil   12  26.4  17.8  13.3  12.62   357.9   59.4   38.3  0.000  0.000  0.000  0.000  0.000  0.000
Grain Filling Phase       43  27.1  17.3  16.5  12.25   358.2  124.6  144.5  0.000  0.028  0.164  0.281  0.000  0.000

Planting to Harvest      127  27.5  17.6  17.0  12.60   357.9  515.2  415.8  0.000  0.015  0.071  0.120  0.000  0.000
--------------------------------------------------------------------------------------------------------------------

*Resource Productivity
 Growing season length: 127 days

 Precipitation during growing season        515.2 mm[rain]
   Dry Matter Productivity                   2.40 kg[DM]/m3[rain]          =   24.0 kg[DM]/ha per mm[rain]
   Yield Productivity                        1.60 kg[grain yield]/m3[rain] =   16.0 kg[yield]/ha per mm[rain]

 Evapotranspiration during growing season  415.8 mm[ET]
   Dry Matter Productivity                   2.98 kg[DM]/m3[ET]            =   29.8 kg[DM]/ha per mm[ET]
   Yield Productivity                        1.98 kg[grain yield]/m3[ET]   =   19.8 kg[yield]/ha per mm[ET]

 Transpiration during growing season        202.9 mm[EP]
   Dry Matter Productivity                   6.11 kg[DM]/m3[EP]            =   61.1 kg[DM]/ha per mm[EP]
   Yield Productivity                        4.07 kg[grain yield]/m3[EP]   =   40.7 kg[yield]/ha per mm[EP]

 N applied during growing season             168. kg[N applied]/ha
   Dry Matter Productivity                   73.7 kg[DM]/kg[N applied]
   Yield Productivity                        49.1 kg[yield]/kg[N applied]

 N uptake during growing season               149 kg[N uptake]/ha
   Dry Matter Productivity                   83.1 kg[DM]/kg[N uptake]
   Yield Productivity                        55.4 kg[yield]/kg[N uptake]

------------------------------------------------------------------------------------------------------------

                     Maize YIELD :     8249 kg/ha    [Dry weight]

************************************************************************************************************

*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub         SEP 30, 2014; 19:30:41

*RUN   3         : Rainfed_PD2_112             MZCER045 UZFS9301    3
 MODEL           : MZCER045 - Maize
 EXPERIMENT      : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH       : C:\DSSAT45\maize\
 TREATMENT  3    : Rainfed_PD2_112             MZCER045


 CROP            : Maize             CULTIVAR : ZMS 606          ECOTYPE :IB0001
 STARTING DATE   : NOV 22  2013
 PLANTING DATE   : DEC  8  2013          PLANTS/m2 :  4.4     ROW SPACING :  30.cm
 WEATHER         : UZ93    2013
 SOIL            : UZFS201401     TEXTURE : L      - Haplic Lixisols
 SOIL INITIAL C  : DEPTH:100cm EXTR. H2O:112.8mm  NO3:  0.0kg/ha  NH4:  0.0kg/ha
 WATER BALANCE   : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION      :        0 mm IN      0 APPLICATIONS
 NITROGEN BAL.   : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER    :      112 kg/ha IN      4 APPLICATIONS
 RESIDUE/MANURE  : INITIAL :      0 kg/ha ;        0 kg/ha IN      0 APPLICATIONS
 ENVIRONM. OPT.  : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= S  0.00
                   RAIN= A  0.00  CO2  = A   0.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT  : WATER   :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                   PHOTO   :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                   CO2 358ppm  NSWIT   :1  EVAP :S  SOIL   :2
 MANAGEMENT OPT  : PLANTING:R  IRRIG   :R  FERT :R  RESIDUE:R  HARVEST:M
                   WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3    cm3/cm3          g/cm3         ugN/g  ugN/g    %
--------------------------------------------------------------------------------
   0-  5 0.164 0.280 0.376 0.116 0.155   1.00   1.70   6.50   0.00   0.00   0.66
   5- 15 0.164 0.280 0.376 0.116 0.155   1.00   1.70   6.50   0.00   0.00   0.66
  15- 20 0.164 0.280 0.376 0.116 0.155   1.00   1.70   6.50   0.00   0.00   0.66
  20- 30 0.252 0.368 0.378 0.116 0.139   0.55   1.70   6.70   0.00   0.00   0.60
  30- 40 0.252 0.368 0.378 0.116 0.139   0.55   1.70   6.70   0.00   0.00   0.60
  40- 50 0.240 0.356 0.370 0.116 0.146   0.37   1.70   6.90   0.00   0.00   0.34
  50- 60 0.240 0.356 0.370 0.116 0.146   0.37   1.70   6.90   0.00   0.00   0.34
  60- 80 0.262 0.370 0.380 0.108 0.141   0.20   1.70   6.90   0.00   0.00   0.18
  80-100 0.262 0.370 0.380 0.108 0.141   0.20   1.70   6.90   0.00   0.00   0.18

 TOT-100  23.6  34.9  37.7  11.3  14.4  <--cm   -  kg/ha-->    0.0    0.0  66640
 SOIL ALBEDO     : 0.13      EVAPORATION LIMIT : 6.00         MIN. FACTOR  : 1.00
 RUNOFF CURVE # :73.00      DRAINAGE RATE     : 0.60         FERT. FACTOR : 1.00

  Maize      CULTIVAR :IB1170-ZMS 606               ECOTYPE :IB0001
  P1      : 213.80  P2      : 0.8310  P5      : 822.50
  G2      : 979.70  G3      :   9.791  PHINT   : 60.000


 *SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

  RUN NO.     3     Rainfed_PD2_112

          CROP GROWTH      BIOMASS          LEAF   CROP N     STRESS      STRESS
   DATE   AGE STAGE          kg/ha     LAI   NUM  kg/ha  %   H2O     N    P1    P2   RSTG
  ------  --- ----------     -----   -----  ----   ---  ---  ----  ----  ----  ----   ----
  22 NOV    0 Start Sim          0    0.00   0.0     0  0.0  0.00  0.00  0.00  0.00      7
   8 DEC    0 Sowing             0    0.00   0.0     0  0.0  0.00  0.00  0.00  0.00      8
   9 DEC    1 Germinate          0    0.00   0.0     0  0.0  0.00  0.00  0.00  0.00      9
  15 DEC    7 Emergence         18    0.00   1.9     1  4.4  0.00  0.01  0.00  0.00      1
  28 DEC   20 End Juveni        36    0.08   5.9     1  3.5  0.00  0.00  0.00  0.00      2
   3 JAN   26 Floral Ini        78    0.16   7.4     3  3.6  0.00  0.00  0.00  0.00      3
  16 FEB   70 75% Silkin      2786    1.35  15.8    53  1.9  0.00  0.01  0.00  0.00      4
  28 FEB   82 Beg Gr Fil      4960    1.27  15.8    58  1.2  0.00  0.00  0.00  0.00      5
  14 APR  127 End Gr Fil     10790    0.41  15.8   100  0.9  0.26  0.48  0.00  0.00      6
  18 APR  131 Maturity       10790    0.41  15.8   100  0.9  0.16  0.86  0.00  0.00     10
  18 APR  131 Harvest        10790    0.41  15.8   100  0.9  0.00  0.00  0.00  0.00     10

 *MAIN GROWTH AND DEVELOPMENT VARIABLES

 @      VARIABLE                                          SIMULATED     MEASURED
        --------                                          ---------     --------
        Anthesis day (dap)                                       70           70
        Physiological maturity day (dap)                        131          128
        Yield at harvest maturity (kg [dm]/ha)                 6991         7618
```

```
     Number at maturity (no/m2)                                 2173           2164
     Unit wt at maturity (g [dm]/unit)                        0.3217            -99
     Number at maturity (no/unit)                              493.8            492
     Tops weight at maturity (kg [dm]/ha)                      10790          10527
     By-product produced (stalk) at maturity (kg[dm]/ha         3821            -99
     Leaf area index, maximum                                   1.39           3.48
     Harvest index at maturity                                 0.648           0.72
     Grain N at maturity (kg/ha)                                  91            -99
     Tops N at maturity (kg/ha)                                  100            -99
     Stem N at maturity (kg/ha)                                   10            -99
     Grain N at maturity (%)                                     1.3            -99
     Tops weight at anthesis (kg [dm]/ha)                       2619           4307
     Tops N at anthesis (kg/ha)                                   50            -99
     Leaf number per stem at maturity                          15.77           15.2
     Emergence day (dap)                                           7              8

*ENVIRONMENTAL AND STRESS FACTORS

 |-----Development Phase------|-----------------Environment------------------|----------------Stress-----------------|
                              |-----------Average-----------|---Cumulative--|        (0=Min, 1=Max Stress)           |
                         Time  Temp  Temp Solar Photop                   Evapo |----Water---|--Nitrogen--|--Phosphorus-|
                         Span   Max   Min   Rad  [day]     CO2    Rain  Trans  Photo         Photo         Photo
                         days    øC    øC MJ/m2     hr     ppm      mm     mm  synth Growth  synth Growth  synth Growth
--------------------------------------------------------------------------------------------------------------------
 Emergence-End Juvenile    13  27.1  18.0  16.2  12.91  357.8    55.2   50.5  0.000  0.000  0.002  0.005  0.000  0.000
 End Juvenil-Floral Init    6  27.7  18.1  16.4  12.90  357.8    51.4   21.2  0.000  0.000  0.000  0.000  0.000  0.000
 Floral Init-End Lf Grow   44  27.1  17.6  15.8  12.74  357.9   217.8  159.8  0.000  0.000  0.005  0.013  0.000  0.000
 End Lf Grth-Beg Grn Fil   12  26.6  17.8  15.5  12.43  358.1    18.6   40.1  0.000  0.000  0.000  0.000  0.000  0.000
 Grain Filling Phase       45  26.8  16.4  16.9  12.02  358.2   105.4  114.3  0.181  0.263  0.310  0.464  0.000  0.000

 Planting to Harvest      131  27.0  17.2  16.5  12.46  358.0   498.8  410.0  0.062  0.093  0.128  0.191  0.000  0.000
--------------------------------------------------------------------------------------------------------------------

*Resource Productivity
 Growing season length: 131 days

 Precipitation during growing season     498.8 mm[rain]
   Dry Matter Productivity                2.16 kg[DM]/m3[rain]          =   21.6 kg[DM]/ha per mm[rain]
   Yield Productivity                     1.40 kg[grain yield]/m3[rain] =   14.0 kg[yield]/ha per mm[rain]

 Evapotranspiration during growing season 410.0 mm[ET]
   Dry Matter Productivity                2.63 kg[DM]/m3[ET]            =   26.3 kg[DM]/ha per mm[ET]
   Yield Productivity                     1.71 kg[grain yield]/m3[ET]   =   17.1 kg[yield]/ha per mm[ET]

 Transpiration during growing season     167.3 mm[EP]
   Dry Matter Productivity                6.45 kg[DM]/m3[EP]            =   64.5 kg[DM]/ha per mm[EP]
   Yield Productivity                     4.18 kg[grain yield]/m3[EP]   =   41.8 kg[yield]/ha per mm[EP]

 N applied during growing season          112. kg[N applied]/ha
   Dry Matter Productivity                96.3 kg[DM]/kg[N applied]
   Yield Productivity                     62.4 kg[yield]/kg[N applied]

 N uptake during growing season            119 kg[N uptake]/ha
   Dry Matter Productivity                90.7 kg[DM]/kg[N uptake]
   Yield Productivity                     58.7 kg[yield]/kg[N uptake]

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                          Maize YIELD :      6991 kg/ha    [Dry weight]

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*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub          SEP 30, 2014; 19:30:42

*RUN   4          : Rainfed_PD2_168            MZCER045 UZFS9301    4
 MODEL            : MZCER045 - Maize
 EXPERIMENT       : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH        : C:\DSSAT45\maize\
 TREATMENT  4     : Rainfed_PD2_168            MZCER045


 CROP             : Maize            CULTIVAR : ZMS 606          ECOTYPE :IB0001
 STARTING DATE    : NOV 22  2013
 PLANTING DATE    : DEC  8  2013        PLANTS/m2 :  4.4     ROW SPACING :  30.cm
 WEATHER          : UZ93    2013
 SOIL             : UZFS201401     TEXTURE : L     - Haplic Lixisols
 SOIL INITIAL C   : DEPTH:100cm EXTR. H2O:112.8mm  NO3:  0.0kg/ha  NH4:  0.0kg/ha
 WATER BALANCE    : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION       :        0 mm IN      0 APPLICATIONS
 NITROGEN BAL.    : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER     :      168 kg/ha IN     4 APPLICATIONS
 RESIDUE/MANURE   : INITIAL :      0 kg/ha ;         0 kg/ha IN      0 APPLICATIONS
 ENVIRONM. OPT.   : DAYL= A  0.00  SRAD= A  0.00  TMAX= A  0.00  TMIN= S  0.00
                    RAIN= A  0.00  CO2 = A   0.0  DEW =A  0.00  WIND=A  0.00
 SIMULATION OPT   : WATER    :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS   :N
                    PHOTO    :C  ET      :R  INFIL:S  HYDROL :R  SOM     :G
                    CO2 358ppm   NSWIT   :1  EVAP :S  SOIL   :2
 MANAGEMENT OPT   : PLANTING:R   IRRIG   :R  FERT :R  RESIDUE:R  HARVEST:M
                    WEATHER :M   TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3    cm3/cm3          g/cm3         ugN/g  ugN/g    %
--------------------------------------------------------------------------------
   0-  5 0.164 0.280 0.376 0.116 0.155   1.00   1.70   6.50   0.00   0.00   0.66
   5- 15 0.164 0.280 0.376 0.116 0.155   1.00   1.70   6.50   0.00   0.00   0.66
  15- 20 0.164 0.280 0.376 0.116 0.155   1.00   1.70   6.50   0.00   0.00   0.66
  20- 30 0.252 0.368 0.378 0.116 0.139   0.55   1.70   6.70   0.00   0.00   0.60
  30- 40 0.252 0.368 0.378 0.116 0.139   0.55   1.70   6.70   0.00   0.00   0.60
  40- 50 0.240 0.356 0.370 0.116 0.146   0.37   1.70   6.90   0.00   0.00   0.34
  50- 60 0.240 0.356 0.370 0.116 0.146   0.37   1.70   6.90   0.00   0.00   0.34
  60- 80 0.262 0.370 0.380 0.108 0.141   0.20   1.70   6.90   0.00   0.00   0.18
  80-100 0.262 0.370 0.380 0.108 0.141   0.20   1.70   6.90   0.00   0.00   0.18

 TOT-100   23.6   34.9   37.7   11.3   14.4  <--cm    -  kg/ha-->    0.0    0.0  66640
 SOIL ALBEDO     : 0.13       EVAPORATION LIMIT : 6.00         MIN. FACTOR  : 1.00
 RUNOFF CURVE # :73.00        DRAINAGE RATE     : 0.60         FERT. FACTOR : 1.00

  Maize       CULTIVAR :IB1170-ZMS 606              ECOTYPE :IB0001
  P1      : 213.80   P2      : 0.8310   P5      : 822.50
  G2      : 979.70   G3      :   9.791  PHINT   : 60.000


*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

  RUN NO.      4     Rainfed_PD2_168

              CROP GROWTH       BIOMASS         LEAF   CROP N      STRESS       STRESS
    DATE  AGE STAGE              kg/ha    LAI   NUM  kg/ha  %   H2O    N     P1    P2   RSTG
  ------  --- ----------         -----  -----  ----  ---  ---  ----  ----  ----  ----  ----
  22 NOV    0 Start Sim              0   0.00   0.0    0  0.0  0.00  0.00  0.00  0.00     7
```

```
  8 DEC    0 Sowing             0   0.00   0.0    0  0.0  0.00  0.00  0.00  0.00      8
  9 DEC    1 Germinate          0   0.00   0.0    0  0.0  0.00  0.00  0.00  0.00      9
 15 DEC    7 Emergence         18   0.00   1.9    1  4.4  0.00  0.01  0.00  0.00      1
 28 DEC   20 End Juveni        36   0.08   5.9    1  3.5  0.00  0.00  0.00  0.00      2
  3 JAN   26 Floral Ini        79   0.17   7.4    3  3.6  0.00  0.00  0.00  0.00      3
 16 FEB   70 75% Silkin      2939   1.43  15.8   56  1.9  0.00  0.00  0.00  0.00      4
 28 FEB   82 Beg Gr Fil      5180   1.35  15.8   62  1.2  0.00  0.00  0.00  0.00      5
 14 APR  127 End Gr Fil     11788   0.61  15.8  136  1.2  0.30  0.22  0.00  0.00      6
 18 APR  131 Maturity       11788   0.61  15.8  136  1.2  0.43  0.66  0.00  0.00     10
 18 APR  131 Harvest        11788   0.61  15.8  136  1.2  0.00  0.00  0.00  0.00     10

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@      VARIABLE                                             SIMULATED     MEASURED
       --------                                             ---------     --------
       Anthesis day (dap)                                          70           70
       Physiological maturity day (dap)                           131          128
       Yield at harvest maturity (kg [dm]/ha)                    7825         8049
       Number at maturity (no/m2)                                2241         2413
       Unit wt at maturity (g [dm]/unit)                       0.3492          -99
       Number at maturity (no/unit)                             509.3          549
       Tops weight at maturity (kg [dm]/ha)                     11788        11213
       By-product produced (stalk) at maturity (kg[dm]/ha        3986          -99
       Leaf area index, maximum                                  1.51         4.19
       Harvest index at maturity                                0.664         0.72
       Grain N at maturity (kg/ha)                                123          -99
       Tops N at maturity (kg/ha)                                 136          -99
       Stem N at maturity (kg/ha)                                  12          -99
       Grain N at maturity (%)                                    1.6          -99
       Tops weight at anthesis (kg [dm]/ha)                      2765         4750
       Tops N at anthesis (kg/ha)                                  54          -99
       Leaf number per stem at maturity                         15.77         15.2
       Emergence day (dap)                                          7            8

*ENVIRONMENTAL AND STRESS FACTORS

 |-----Development Phase------|-------------Environment--------------|----------------Stress-----------------|
                              |--------Average-------|---Cumulative--|       (0=Min, 1=Max Stress)           |
                         Time  Temp  Temp Solar Photop         Evapo |----Water---|--Nitrogen--|--Phosphorus-|
                         Span   Max   Min   Rad  [day]   CO2   Rain  Trans  Photo         Photo         Photo
                         days    øC    øC MJ/m2     hr   ppm     mm     mm  synth Growth  synth Growth  synth Growth
--------------------------------------------------------------------------------------------------------------------
 Emergence-End Juvenile    13  27.1  18.0  16.2  12.91  357.8   55.2   50.5  0.000  0.000  0.002  0.005  0.000  0.000
 End Juvenil-Floral Init    6  27.7  18.1  16.4  12.90  357.8   51.4   21.2  0.000  0.000  0.000  0.000  0.000  0.000
 Floral Init-End Lf Grow   44  27.1  17.6  15.8  12.74  357.9  217.8  157.5  0.000  0.000  0.000  0.000  0.000  0.000
 End Lf Grth-Beg Grn Fil   12  26.6  17.8  15.5  12.43  358.1   18.6   40.5  0.000  0.000  0.000  0.000  0.000  0.000
 Grain Filling Phase       45  26.8  16.4  16.9  12.02  358.2  105.4  115.0  0.222  0.302  0.106  0.205  0.000  0.000

 Planting to Harvest      131  27.0  17.2  16.5  12.46  358.0  498.8  409.1  0.081  0.112  0.049  0.091  0.000  0.000
--------------------------------------------------------------------------------------------------------------------

*Resource Productivity
 Growing season length: 131 days

 Precipitation during growing season       498.8 mm[rain]
   Dry Matter Productivity                  2.36 kg[DM]/m3[rain]          =   23.6 kg[DM]/ha per mm[rain]
   Yield Productivity                       1.57 kg[grain yield]/m3[rain] =   15.7 kg[yield]/ha per mm[rain]

 Evapotranspiration during growing season  409.1 mm[ET]
   Dry Matter Productivity                  2.88 kg[DM]/m3[ET]            =   28.8 kg[DM]/ha per mm[ET]
   Yield Productivity                       1.91 kg[grain yield]/m3[ET]   =   19.1 kg[yield]/ha per mm[ET]

 Transpiration during growing season       174.2 mm[EP]
   Dry Matter Productivity                  6.77 kg[DM]/m3[EP]            =   67.7 kg[DM]/ha per mm[EP]
   Yield Productivity                       4.49 kg[grain yield]/m3[EP]   =   44.9 kg[yield]/ha per mm[EP]

 N applied during growing season            168. kg[N applied]/ha
   Dry Matter Productivity                  70.2 kg[DM]/kg[N applied]
   Yield Productivity                       46.6 kg[yield]/kg[N applied]

 N uptake during growing season              158 kg[N uptake]/ha
   Dry Matter Productivity                  74.6 kg[DM]/kg[N uptake]
   Yield Productivity                       49.5 kg[yield]/kg[N uptake]

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                        Maize YIELD :      7825 kg/ha    [Dry weight]

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*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub          SEP 30, 2014; 19:30:42

*RUN   5        : Rainfed_PD3_112             MZCER045 UZFS9301    5
 MODEL          : MZCER045 - Maize
 EXPERIMENT     : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH      : C:\DSSAT45\maize\
 TREATMENT  5   : Rainfed_PD3_112             MZCER045


 CROP           : Maize             CULTIVAR : ZMS 606          ECOTYPE :IB0001
 STARTING DATE  : NOV 22  2013
 PLANTING DATE  : DEC 22  2013        PLANTS/m2 :  4.4     ROW SPACING :  30.cm
 WEATHER        : UZ93    2013
 SOIL           : UZFS201401     TEXTURE : L     - Haplic Lixisols
 SOIL INITIAL C : DEPTH:100cm EXTR. H2O:112.8mm  NO3:  0.0kg/ha  NH4:  0.0kg/ha
 WATER BALANCE  : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION     :        0 mm IN      0 APPLICATIONS
 NITROGEN BAL.  : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER   :      112 kg/ha IN     4 APPLICATIONS
 RESIDUE/MANURE : INITIAL :      0 kg/ha ;        0 kg/ha IN     0 APPLICATIONS
 ENVIRONM. OPT. : DAYL= A   0.00  SRAD= A   0.00  TMAX= A   0.00  TMIN= S   0.00
                  RAIN= A   0.00  CO2  = A    0.0  DEW  =A   0.00  WIND=A   0.00
 SIMULATION OPT : WATER    :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                  PHOTO    :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                  CO2 358ppm   NSWIT   :1  EVAP :S  SOIL   :2
 MANAGEMENT OPT : PLANTING:R   IRRIG   :R  FERT :R  RESIDUE:R  HARVEST:M
                  WEATHER :M   TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK     pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                          C
   cm   cm3/cm3    cm3/cm3   cm3/cm3          g/cm3          ugN/g  ugN/g    %
--------------------------------------------------------------------------------
    0-  5 0.164 0.280 0.376 0.116 0.161   1.00   1.70   6.50   0.00   0.00   0.66
    5- 15 0.164 0.280 0.376 0.116 0.161   1.00   1.70   6.50   0.00   0.00   0.66
   15- 20 0.164 0.280 0.376 0.116 0.161   1.00   1.70   6.50   0.00   0.00   0.66
   20- 30 0.252 0.368 0.378 0.116 0.133   0.55   1.70   6.70   0.00   0.00   0.60
   30- 40 0.252 0.368 0.378 0.116 0.133   0.55   1.70   6.70   0.00   0.00   0.60
   40- 50 0.240 0.356 0.370 0.116 0.144   0.37   1.70   6.90   0.00   0.00   0.34
   50- 60 0.240 0.356 0.370 0.116 0.144   0.37   1.70   6.90   0.00   0.00   0.34
   60- 80 0.262 0.370 0.380 0.108 0.128   0.20   1.70   6.90   0.00   0.00   0.18
   80-100 0.262 0.370 0.380 0.108 0.128   0.20   1.70   6.90   0.00   0.00   0.18
```

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TOT-100  23.6  34.9  37.7  11.3  13.9  <--cm   -  kg/ha-->    0.0     0.0  66640
SOIL ALBEDO     : 0.13        EVAPORATION LIMIT : 6.00         MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00         DRAINAGE RATE     : 0.60         FERT. FACTOR : 1.00

 Maize       CULTIVAR :IB1170-ZMS 606              ECOTYPE :IB0001
 P1      : 213.80  P2       : 0.8310  P5      : 822.50
 G2      : 979.70  G3       :  9.791  PHINT   : 60.000

*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

 RUN NO.     5     Rainfed_PD3_112

          CROP GROWTH       BIOMASS           LEAF   CROP N      STRESS       STRESS
   DATE  AGE STAGE           kg/ha    LAI    NUM  kg/ha  %   H2O     N     P1    P2    RSTG
 ------  --- ----------      -----   -----   ----   ---  ---  ----  ----  ----  ----   ----
 22 NOV    0 Start Sim          0    0.00    0.0     0  0.0  0.00  0.00  0.00  0.00      7
 22 DEC    0 Sowing             0    0.00    0.0     0  0.0  0.00  0.00  0.00  0.00      8
 23 DEC    1 Germinate          0    0.00    0.0     0  0.0  0.00  0.00  0.00  0.00      9
 28 DEC    6 Emergence         18    0.00    1.9     1  4.4  0.00  0.01  0.00  0.00      1
 11 JAN   20 End Juveni        38    0.08    6.1     1  3.5  0.00  0.00  0.00  0.00      2
 17 JAN   26 Floral Ini        74    0.16    7.5     3  3.6  0.00  0.00  0.00  0.00      3
  2 MAR   70 75% Silkin      2809    1.27   16.0    52  1.8  0.00  0.00  0.00  0.00      4
 14 MAR   82 Beg Gr Fil      5048    1.20   16.0    57  1.1  0.00  0.00  0.00  0.00      5
  1 MAY  130 End Gr Fil      9636    0.36   16.0   100  1.0  0.45  0.30  0.00  0.00      6
  5 MAY  134 Maturity        9636    0.36   16.0   100  1.0  0.00  0.79  0.00  0.00     10
  5 MAY  134 Harvest         9636    0.36   16.0   100  1.0  0.00  0.00  0.00  0.00     10


*MAIN GROWTH AND DEVELOPMENT VARIABLES

@       VARIABLE                                          SIMULATED     MEASURED
        --------                                          ---------     --------
        Anthesis day (dap)                                       70           67
        Physiological maturity day (dap)                        134          132
        Yield at harvest maturity (kg [dm]/ha)                 5667         7965
        Number at maturity (no/m2)                             2180         2136
        Unit wt at maturity (g [dm]/unit)                    0.2599          -99
        Number at maturity (no/unit)                          495.5          486
        Tops weight at maturity (kg [dm]/ha)                   9636        10873
        By-product produced (stalk) at maturity (kg[dm]/ha     3990          -99
        Leaf area index, maximum                               1.33         3.05
        Harvest index at maturity                             0.588         0.73
        Grain N at maturity (kg/ha)                              90          -99
        Tops N at maturity (kg/ha)                              100          -99
        Stem N at maturity (kg/ha)                               10          -99
        Grain N at maturity (%)                                 1.6          -99
        Tops weight at anthesis (kg [dm]/ha)                   2684         3788
        Tops N at anthesis (kg/ha)                               50          -99
        Leaf number per stem at maturity                      15.99         13.5
        Emergence day (dap)                                       6            6

*ENVIRONMENTAL AND STRESS FACTORS

 |-----Development Phase------|-----------------Environment-----------------|----------------Stress-----------------|
                              |-----------Average-----------|---Cumulative--|        (0=Min, 1=Max Stress)           |
                              Time  Temp  Temp Solar Photop              Evapo |----Water---|--Nitrogen--|--Phosphorus-|
                              Span   Max   Min   Rad  [day]    CO2   Rain  Trans  Photo         Photo         Photo
                              days    øC    øC MJ/m2     hr    ppm     mm     mm  synth Growth  synth Growth  synth Growth
--------------------------------------------------------------------------------------------------------------------------
 Emergence-End Juvenile        14  27.7  17.9  16.8  12.89  357.8   96.8   52.0  0.000  0.000  0.002  0.006  0.000  0.000
 End Juvenil-Floral Init        6  26.9  18.0  17.4  12.84  357.8   28.0   24.4  0.000  0.000  0.000  0.001  0.000  0.000
 Floral Init-End Lf Grow       44  26.9  17.5  15.4  12.59  358.0  163.8  146.7  0.000  0.000  0.001  0.003  0.000  0.000
 End Lf Grth-Beg Grn Fil       12  27.5  17.8  15.4  12.23  358.1   76.4   42.2  0.000  0.003  0.000  0.000  0.000  0.000
 Grain Filling Phase           48  26.3  15.4  17.4  11.79  358.3   96.4   94.6  0.337  0.445  0.162  0.279  0.000  0.000

 Planting to Harvest          134  26.8  16.8  16.6  12.30  358.1  476.6  389.9  0.121  0.160  0.075  0.125  0.000  0.000
--------------------------------------------------------------------------------------------------------------------------

*Resource Productivity
 Growing season length: 134 days

 Precipitation during growing season        476.6 mm[rain]
   Dry Matter Productivity                   2.02 kg[DM]/m3[rain]            =   20.2 kg[DM]/ha per mm[rain]
   Yield Productivity                        1.19 kg[grain yield]/m3[rain]   =   11.9 kg[yield]/ha per mm[rain]

 Evapotranspiration during growing season   389.9 mm[ET]
   Dry Matter Productivity                   2.47 kg[DM]/m3[ET]              =   24.7 kg[DM]/ha per mm[ET]
   Yield Productivity                        1.45 kg[grain yield]/m3[ET]     =   14.5 kg[yield]/ha per mm[ET]

 Transpiration during growing season        144.4 mm[EP]
   Dry Matter Productivity                   6.67 kg[DM]/m3[EP]              =   66.7 kg[DM]/ha per mm[EP]
   Yield Productivity                        3.92 kg[grain yield]/m3[EP]     =   39.2 kg[yield]/ha per mm[EP]

 N applied during growing season             112. kg[N applied]/ha
   Dry Matter Productivity                   86.0 kg[DM]/kg[N applied]
   Yield Productivity                        50.6 kg[yield]/kg[N applied]

 N uptake during growing season               118 kg[N uptake]/ha
   Dry Matter Productivity                   81.7 kg[DM]/kg[N uptake]
   Yield Productivity                        48.0 kg[yield]/kg[N uptake]

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                    Maize YIELD :      5667 kg/ha    [Dry weight]

************************************************************************************************************

*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub          SEP 30, 2014; 19:30:42

*RUN   6          : Rainfed_PD3_168            MZCER045 UZFS9301    6
 MODEL            : MZCER045 - Maize
 EXPERIMENT       : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH        : C:\DSSAT45\maize\
 TREATMENT  6     : Rainfed_PD3_168            MZCER045


 CROP             : Maize               CULTIVAR : ZMS 606          ECOTYPE :IB0001
 STARTING DATE    : NOV 22  2013
 PLANTING DATE    : DEC 22  2013          PLANTS/m2 :  4.4     ROW SPACING :  30.cm
 WEATHER          : UZ93    2013
 SOIL             : UZFS201401     TEXTURE : L      - Haplic Lixisols
 SOIL INITIAL C   : DEPTH:100cm EXTR. H2O:112.8mm  NO3:   0.0kg/ha  NH4:   0.0kg/ha
 WATER BALANCE    : IRRIGATE ON REPORTED DATE(S)
 IRRIGATION       :          0 mm IN      0 APPLICATIONS
 NITROGEN BAL.    : SOIL-N & N-UPTAKE SIMULATION; NO N-FIXATION
 N-FERTILIZER     :        168 kg/ha IN     4 APPLICATIONS
 RESIDUE/MANURE   : INITIAL :        0 kg/ha ;          0 kg/ha IN       0 APPLICATIONS
 ENVIRONM. OPT.   : DAYL= A   0.00  SRAD= A   0.00  TMAX= A   0.00  TMIN= S   0.00
                    RAIN= A   0.00  CO2  = A    0.0  DEW  =A   0.00  WIND=A   0.00
 SIMULATION OPT   : WATER    :Y  NITROGEN:Y  N-FIX:N  PHOSPH :N  PESTS  :N
                    PHOTO    :C  ET      :R  INFIL:S  HYDROL :R  SOM    :G
                    CO2 358ppm   NSWIT   :1  EVAP :S  SOIL   :2
```

```
 MANAGEMENT OPT : PLANTING:R  IRRIG   :R  FERT :R  RESIDUE:R  HARVEST:M
                  WEATHER :M  TILLAGE :N

*SUMMARY OF SOIL AND GENETIC INPUT PARAMETERS

   SOIL LOWER UPPER   SAT  EXTR  INIT   ROOT   BULK      pH    NO3    NH4    ORG
  DEPTH LIMIT LIMIT    SW    SW    SW   DIST   DENS                           C
   cm   cm3/cm3    cm3/cm3    cm3/cm3          g/cm3          ugN/g  ugN/g    %
--------------------------------------------------------------------------------
  0-  5 0.164 0.280 0.376 0.116 0.161   1.00   1.70    6.50   0.00   0.00   0.66
  5- 15 0.164 0.280 0.376 0.116 0.161   1.00   1.70    6.50   0.00   0.00   0.66
 15- 20 0.164 0.280 0.376 0.116 0.161   1.00   1.70    6.50   0.00   0.00   0.66
 20- 30 0.252 0.368 0.378 0.116 0.133   0.55   1.70    6.70   0.00   0.00   0.60
 30- 40 0.252 0.368 0.378 0.116 0.133   0.55   1.70    6.70   0.00   0.00   0.60
 40- 50 0.240 0.356 0.370 0.116 0.144   0.37   1.70    6.90   0.00   0.00   0.34
 50- 60 0.240 0.356 0.370 0.116 0.144   0.37   1.70    6.90   0.00   0.00   0.34
 60- 80 0.262 0.370 0.380 0.108 0.128   0.20   1.70    6.90   0.00   0.00   0.18
 80-100 0.262 0.370 0.380 0.108 0.128   0.20   1.70    6.90   0.00   0.00   0.18

TOT-100  23.6  34.9  37.7  11.3  13.9  <--cm   -  kg/ha-->   0.0    0.0  66640
SOIL ALBEDO     : 0.13      EVAPORATION LIMIT : 6.00         MIN. FACTOR  : 1.00
RUNOFF CURVE # :73.00       DRAINAGE RATE     : 0.60         FERT. FACTOR : 1.00

 Maize       CULTIVAR :IB1170-ZMS 606            ECOTYPE :IB0001
 P1      : 213.80  P2      : 0.8310  P5      : 822.50
 G2      : 979.70  G3      :  9.791  PHINT   : 60.000


*SIMULATED CROP AND SOIL STATUS AT MAIN DEVELOPMENT STAGES

 RUN NO.     6     Rainfed_PD3_168

        CROP GROWTH      BIOMASS          LEAF   CROP N      STRESS       STRESS
  DATE  AGE STAGE          kg/ha     LAI   NUM  kg/ha  %    H2O     N     P1    P2    RSTG
 ------ --- ----------    -----   -----  ----   ---  ---  ----   ----   ----  ----   ----
 22 NOV   0 Start Sim         0    0.00   0.0     0  0.0  0.00   0.00   0.00  0.00      7
 22 DEC   0 Sowing            0    0.00   0.0     0  0.0  0.00   0.00   0.00  0.00      8
 23 DEC   1 Germinate         0    0.00   0.0     0  0.0  0.00   0.00   0.00  0.00      9
 28 DEC   6 Emergence        18    0.00   1.9     1  4.4  0.00   0.01   0.00  0.00      1
 11 JAN  20 End Juveni       39    0.09   6.1     1  3.5  0.00   0.00   0.00  0.00      2
 17 JAN  26 Floral Ini       80    0.17   7.5     3  3.6  0.00   0.00   0.00  0.00      3
  2 MAR  70 75% Silkin     3035    1.42  16.0    57  1.9  0.00   0.00   0.00  0.00      4
 14 MAR  82 Beg Gr Fil     5402    1.33  16.0    62  1.2  0.00   0.00   0.00  0.00      5
  1 MAY 130 End Gr Fil    10635    0.55  16.0   135  1.3  0.46   0.00   0.00  0.00      6
  5 MAY 134 Maturity      10635    0.55  16.0   135  1.3  0.00   0.00   0.00  0.00     10
  5 MAY 134 Harvest       10635    0.55  16.0   135  1.3  0.00   0.00   0.00  0.00     10

*MAIN GROWTH AND DEVELOPMENT VARIABLES

@      VARIABLE                                             SIMULATED     MEASURED
       --------                                             ---------     --------
       Anthesis day (dap)                                          70           67
       Physiological maturity day (dap)                           134          132
       Yield at harvest maturity (kg [dm]/ha)                    6402         7049
       Number at maturity (no/m2)                                2302         2068
       Unit wt at maturity (g [dm]/unit)                       0.2781          -99
       Number at maturity (no/unit)                             523.2          470
       Tops weight at maturity (kg [dm]/ha)                     10635         9879
       By-product produced (stalk) at maturity (kg[dm]/ha        4256          -99
       Leaf area index, maximum                                  1.49         4.68
       Harvest index at maturity                                0.602         0.71
       Grain N at maturity (kg/ha)                                114          -99
       Tops N at maturity (kg/ha)                                 135          -99
       Stem N at maturity (kg/ha)                                  21          -99
       Grain N at maturity (%)                                    1.8          -99
       Tops weight at anthesis (kg [dm]/ha)                      2902         4766
       Tops N at anthesis (kg/ha)                                  56          -99
       Leaf number per stem at maturity                         15.99         13.7
       Emergence day (dap)                                          6            6

*ENVIRONMENTAL AND STRESS FACTORS

 |-----Development Phase------|-----------------Environment-----------------|----------------Stress-----------------|
                              |-----------Average-----------|---Cumulative--|         (0=Min, 1=Max Stress)         |
                          Time  Temp  Temp Solar Photop                Evapo |----Water---|--Nitrogen--|--Phosphorus-|
                          Span   Max   Min   Rad  [day]     CO2   Rain Trans  Photo        Photo        Photo
                          days    øC    øC MJ/m2     hr     ppm     mm    mm  synth Growth synth Growth synth Growth
--------------------------------------------------------------------------------------------------------------------
 Emergence-End Juvenile     14  27.7  17.9  16.8  12.89  357.8   96.8  52.0  0.000  0.000  0.002  0.006  0.000  0.000
 End Juvenil-Floral Init     6  26.9  18.0  17.4  12.84  357.8   28.0  24.4  0.000  0.000  0.000  0.001  0.000  0.000
 Floral Init-End Lf Grow    44  26.9  17.5  15.4  12.59  358.0  163.8 148.3  0.000  0.000  0.000  0.000  0.000  0.000
 End Lf Grth-Beg Grn Fil    12  27.5  17.8  15.4  12.23  358.1   76.4  42.4  0.000  0.000  0.000  0.000  0.000  0.000
 Grain Filling Phase        48  26.3  15.4  17.4  11.79  358.3   96.4  97.6  0.359  0.464  0.000  0.000  0.000  0.000

 Planting to Harvest       134  26.8  16.8  16.6  12.30  358.1  476.6 396.5  0.129  0.166  0.000  0.001  0.000  0.000
--------------------------------------------------------------------------------------------------------------------

*Resource Productivity
 Growing season length: 134 days

 Precipitation during growing season      476.6 mm[rain]
   Dry Matter Productivity                 2.23 kg[DM]/m3[rain]        =    22.3 kg[DM]/ha per mm[rain]
   Yield Productivity                      1.34 kg[grain yield]/m3[rain] =  13.4 kg[yield]/ha per mm[rain]

 Evapotranspiration during growing season 396.5 mm[ET]
   Dry Matter Productivity                 2.68 kg[DM]/m3[ET]          =    26.8 kg[DM]/ha per mm[ET]
   Yield Productivity                      1.61 kg[grain yield]/m3[ET]  =   16.1 kg[yield]/ha per mm[ET]

 Transpiration during growing season      157.9 mm[EP]
   Dry Matter Productivity                 6.73 kg[DM]/m3[EP]          =    67.3 kg[DM]/ha per mm[EP]
   Yield Productivity                      4.05 kg[grain yield]/m3[EP]  =   40.5 kg[yield]/ha per mm[EP]

 N applied during growing season          168. kg[N applied]/ha
   Dry Matter Productivity                63.3 kg[DM]/kg[N applied]
   Yield Productivity                     38.1 kg[yield]/kg[N applied]

 N uptake during growing season            153 kg[N uptake]/ha
   Dry Matter Productivity                69.5 kg[DM]/kg[N uptake]
   Yield Productivity                     41.8 kg[yield]/kg[N uptake]

------------------------------------------------------------------------------------------------------------

                        Maize YIELD :       6402 kg/ha    [Dry weight]

************************************************************************************************************
```

Appendix 8: Water balance for the three planting dates

```
*WATER BALANCE OUTPUT FILE

*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub         AUG 27, 2014; 06:30:42

*RUN   1         : Rainfed_PD1_112             MZCER045 UZFS9301      1
 MODEL           : MZCER045 - Maize
 EXPERIMENT      : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH       : C:\DSSAT45\maize\
 TREATMENT  1    : Rainfed_PD1_112             MZCER045


!      WATER BALANCE PARAMETERS
!      ========================                    --mm--

!      Soil H20 (start) on Year/day 2013/326      236.00
!      Soil H20 (final) on Year/day 2014/091      307.94
!      Effective Irrigation                          0.00
!      Precipitation                               557.80
!      Water added with new mulch                    0.00
!      Drainage                                     44.47
!      Tiledrain flow                                0.00
!      Runoff                                       22.96
!      Mulch evaporation                             0.00
!      Soil Evaporation                            223.87
!      Transpiration                               194.56
!      Potential ET                                554.42

!      Initial mulch water content                   0.00
!      Final mulch water content                     0.00

!      Final Balance                                0.003

*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub         AUG 27, 2014; 06:30:42

*RUN   2         : Rainfed_PD1_168             MZCER045 UZFS9301      2
 MODEL           : MZCER045 - Maize
 EXPERIMENT      : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH       : C:\DSSAT45\maize\
 TREATMENT  2    : Rainfed_PD1_168             MZCER045


!      WATER BALANCE PARAMETERS
!      ========================                    --mm--

!      Soil H20 (start) on Year/day 2013/326      236.00
!      Soil H20 (final) on Year/day 2014/091      301.81
!      Effective Irrigation                          0.00
!      Precipitation                               557.80
!      Water added with new mulch                    0.00
!      Drainage                                     42.40
!      Tiledrain flow                                0.00
!      Runoff                                       23.12
!      Mulch evaporation                             0.00
!      Soil Evaporation                            220.48
!      Transpiration                               205.99
!      Potential ET                                552.58

!      Initial mulch water content                   0.00
!      Final mulch water content                     0.00

!      Final Balance                                0.003

*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub         AUG 27, 2014; 06:30:42

*RUN   3         : Rainfed_PD2_112             MZCER045 UZFS9301      3
 MODEL           : MZCER045 - Maize
 EXPERIMENT      : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH       : C:\DSSAT45\maize\
 TREATMENT  3    : Rainfed_PD2_112             MZCER045
```

```
!     WATER BALANCE PARAMETERS
!     ========================                      --mm--

!     Soil H20 (start) on Year/day 2013/326    236.00
!     Soil H20 (final) on Year/day 2014/109    295.29
!     Effective Irrigation                        0.00
!     Precipitation                             576.80
!     Water added with new mulch                  0.00
!     Drainage                                   47.65
!     Tiledrain flow                              0.00
!     Runoff                                     23.30
!     Mulch evaporation                           0.00
!     Soil Evaporation                          277.78
!     Transpiration                             168.77
!     Potential ET                              628.09

!     Initial mulch water content                 0.00
!     Final mulch water content                   0.00

!     Final Balance                              0.004


*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub          AUG 27, 2014; 06:30:43

*RUN   4         : Rainfed_PD2_168           MZCER045 UZFS9301     4
 MODEL           : MZCER045 - Maize
 EXPERIMENT      : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH       : C:\DSSAT45\maize\
 TREATMENT  4    : Rainfed_PD2_168           MZCER045


!     WATER BALANCE PARAMETERS
!     ========================                      --mm--

!     Soil H20 (start) on Year/day 2013/326    236.00
!     Soil H20 (final) on Year/day 2014/109    290.32
!     Effective Irrigation                        0.00
!     Precipitation                             576.80
!     Water added with new mulch                  0.00
!     Drainage                                   49.37
!     Tiledrain flow                              0.00
!     Runoff                                     23.30
!     Mulch evaporation                           0.00
!     Soil Evaporation                          269.88
!     Transpiration                             179.94
!     Potential ET                              625.69

!     Initial mulch water content                 0.00
!     Final mulch water content                   0.00

!     Final Balance                              0.004


*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub          AUG 27, 2014; 06:30:43

*RUN   5         : Rainfed_PD3_112           MZCER045 UZFS9301     5
 MODEL           : MZCER045 - Maize
 EXPERIMENT      : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH       : C:\DSSAT45\maize\
 TREATMENT  5    : Rainfed_PD3_112           MZCER045


!     WATER BALANCE PARAMETERS
!     ========================                      --mm--

!     Soil H20 (start) on Year/day 2013/326    236.00
!     Soil H20 (final) on Year/day 2014/126    324.15
!     Effective Irrigation                        0.00
!     Precipitation                             645.00
!     Water added with new mulch                  0.00
!     Drainage                                   51.73
!     Tiledrain flow                              0.00
!     Runoff                                     37.66
!     Mulch evaporation                           0.00
!     Soil Evaporation                          321.98
!     Transpiration                             145.48
!     Potential ET                              708.26
```

```
!     Initial mulch water content                 0.00
!     Final mulch water content                   0.00

!     Final Balance                              0.000


*DSSAT Cropping System Model Ver. 4.5.1.023 -Stub         AUG 27, 2014; 06:30:43

*RUN   6         : Rainfed_PD3_168            MZCER045 UZFS9301    6
 MODEL           : MZCER045 - Maize
 EXPERIMENT      : UZFS9301 MZ CALIBRATION AND EVALUATION OF CSM-CERES-MAIZE MODE
 DATA PATH       : C:\DSSAT45\maize\
 TREATMENT  6    : Rainfed_PD3_168            MZCER045


!     WATER BALANCE PARAMETERS
!     ========================                  --mm--

!     Soil H20 (start) on Year/day 2013/326    236.00
!     Soil H20 (final) on Year/day 2014/126    319.54
!     Effective Irrigation                        0.00
!     Precipitation                             645.00
!     Water added with new mulch                  0.00
!     Drainage                                   50.08
!     Tiledrain flow                              0.00
!     Runoff                                     37.54
!     Mulch evaporation                           0.00
!     Soil Evaporation                          315.65
!     Transpiration                             158.18
!     Potential ET                              705.52

!     Initial mulch water content                 0.00
!     Final mulch water content                   0.00

!     Final Balance                              0.002
```

Appendix 9: Evaluation statistics at all treatment levels

				PD1				
		N1				N2		
Crop characteristics	**RMSE**	**d-stat**	**R^2**	**NRMSE**	**RMSE**	**d-stat**	**R^2**	**RRMSE**
Tops weight (kg/ha)	669.63	0.98	0.97	15.52	1595.77	0.95	0.97	30.09
Stem weigh (kg/ha)	521.44	0.70	1.00	22.23	926.63	0.12	1.00	33.57
Leaf weight (kg/ha)	263.48	0.59	1.00	20.80	281.71	0.34	1.00	21.37
Veg weight (kg/ha)	628.02	0.95	0.99	25.21	951.60	0.91	0.96	33.76
LAI	1.09	0.55	0.45	55.05	1.41	0.49	0.24	65.46
Leaf number	1.90	0.94	1.00	15.80	1.90	0.94	1.00	15.80
				PD2				
		N1				N2		
Tops weight (kg/ha)	1,563.15	0.96	0.87	29.27	1,900.15	0.94	0.83	33.38
Stem weigh (kg/ha)	1,032.73	0.54	0.86	43.52	856.16	0.57	1.00	36.95
Leaf weight (kg/ha)	322.10	0.51	0.43	27.94	358.63	0.54	0.18	29.30
Veg weight (kg/ha)	1,160.61	0.83	0.98	43.10	1,030.76	0.86	0.99	38.09
LAI	0.54	0.55	0.73	56.50	0.62	0.49	0.66	62.10
Leaf number	1.49	0.54	0.58	65.64	1.27	0.57	0.41	63.18
				PD3				
		N1				N2		
Tops weight (kg/ha)	1,738.47	0.93	0.80	37.78	2,009.81	0.92	0.77	36.99
Stem weigh (kg/ha)	636.71	0.65	1.00	32.92	861.81	0.69	0.88	38.17
Leaf weight (kg/ha)	220.04	0.50	0.03	22.99	245.58	0.54	0.05	23.02
Veg weight (kg/ha)	739.24	0.90	0.96	33.34	1,079.01	0.88	0.99	40.16
LAI	0.39	0.71	0.71	43.10	0.51	0.55	0.21	54.50
Leaf number	1.15	0.59	0.31	69.70	1.89	0.55	0.34	78.22