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Field and Modelled Maize *(Zea Mays)* Response to Water Stress at Different Growth Stages

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Abstract

Water is becoming scarce in arid, drought prone and even high rainfall areas due to rainfall variability and uneven distribution resulting from changing climate. Therefore, sustainable and innovative management of agricultural water resources are urgently required. This study was undertaken to determine how efficiently water can be managed in irrigated maize cultivation under scarce water conditions in the tropics. The study involved planting maize in the field to evaluate the growth and yield response to water stress at different growth stages. Also the crop model DSSATv4 was used to evaluate maize yield response to water stress at the different growth stages (i.e. seedling, knee-height, tasseling-silking and grain filling) by imposing water stress for a period of 14 days. Randomised complete block design with four replicates were used for the field experiment. The effect of water stress at these stages of development on plant height, girth, leaf surface area, number of kernels, grain yield were evaluated. Results were analysed statistically using Analysis of Variance (ANOVA) at 95% confidence interval. Results of the study showed that most of the vegetative and yield parameters were affected to varying degrees by water deficits in the soil profile during the various monitored stages. The highest yield was observed from the unstressed plots which had water throughout the growth period of the maize. Short duration (14 days) water stress during the tasseling-silking caused the highest grain yield reduction of 5 and 27% for the model and field experiments respectively.

***Keywords*:** DSSAT; Maize; Model; Growth stages; Water stress

Introduction

Maize (*Zea mays* L.) is largely used as livestock feed and as industrial raw material in industrialized countries (Onuh *et. al*., 2008). In developing countries, it is the main source of food for human consumption (Omemu *et al*., 2008), supplying carbohydrate, protein, iron, vitamin B, and minerals (Omemu *et al*., 2008; M'mboyi *et al*. 2010). Unfortunately, to promote maize production, water deficit is one of the most common environmental stresses that affect growth and development of the crop (Ghassemi-Golezani *et al*. 2009), especially in developing countries (Seghatoleslami *et al*., 2008). Maize susceptibility to drought is due to the plant's water requirement for cell elongation and its' inability to delay vegetative growth. This implies that there is always the danger of yield loss regardless of the timing of dry weather (Sangoi and Salvador, 1998). Though, the amount of yield loss in dry periods is most pronounced at flowering stage (Guelloubi *et al*., 2005) the magnitude and the timing of water deficit on growth stage are of major importance in scheduling limited water (Doorenbos and Kassam, 1979).

It is possible to maintain relatively high yields if water deficit is limited to periods other than around flowering stage. A field experiment conducted on a silty-loam soil in Turkey by Cakir (2004) showed that water deficit during the rapid vegetative growth stage decreased plant height. On loam soil in northeast Spain deficit irrigation at flowering led to significant yield penalties (Farre and Faci, 2009). Therefore, deciding on the stage to allocate scarce water resources in maize production is mandatory in achieving high grain yield.

Crop models are increasingly becoming valuable tools in assisting with decision making at both the farm and regional level (Wilkerson *et al*., 2002) by integrating the current state-of-the art scientific knowledge from many different agricultural disciplines (Jintrawet and Hoogenboom, 1995; Hoogenboom, 2010). The Decision Support System for Agrotechnology Transfer (DSSAT) is a crop simulation model for more than 25 crops, in terms crop growth, development and yield, soil and plant water, nitrogen,carbon balances, on-farm and precision management to regional impact assessments of the impact of climate change and variability. Kpongor et al., (2006) successfully modelled and applied sorghum yield in response to mineral fertilizer in semi-arid Ghana using DSSAT.

In many countries like Ghana, where maize production is key to the economy, the growing season for crops is often characterized by long temporal and wide spatial variations in water supply (Ritchie, 1989).This makes water deficit an important constraint for maize production. The objectives of the study were (a) to determine site hydraulic properties and its effect on drying cycle of the rooting zone (b) evaluate the effect of water stress at different developmental stages under field conditions to determine its effect on growth and yield of maize and (c) compare maize yield in (b) to yield from modelled conditions using DSSAT. The results of this study is helpful in policy planning regarding irrigation management for maximizing net financial returns from limited water resources for maize production.

Materials and methods

Field experiment

Experimental Site

A field experiment was conducted at the Mechanization site of the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi during the major growing season in 2010 from April to August. The purpose was to evaluate the effect of moisture stress at different developmental stages of maize on its growth and yield under rain-fed conditions. The moisture stress was imposed on the field by using rain shelter. The site was located at latitudes 6°40' N and longitude 1°33' W with an altitude of 261 m above mean sea level. The mean annual rainfall in the region was 1350 mm and the average temperature was 26.5 °C. The soil of the experimental site was predominantly sandy loam to a depth of 45 cm.

Experimental Setup

The field had 5 treatments and 4 replicates, each with area of 4.8 m by 2.8 m with 1.5 m spacing between treatments and replications. The test crop was 'Obatanpa' maize variety, sown at 2 seeds per hill. Each plot was planted with 6 rows and 7 hills per row with crop spacing of 0.80 m x 0.40 m. The experimental design was Randomized Complete Block Design (RCBD).

NPK 15-15-15 fertilizer at a recommended rate of 250 kg ha^{-1} (on 22nd May, 2010, 3 weeks after the planting, WAP by point placement at 5 cm depth and 5 – 10 cm away from the plant for both the field and model experiments. Also Ammonium nitrate was applied by point placement about 5 – 10 cm away from the plants and beneath the soil surface at a depth of about 5 cm at a rate of 75 kg Nha^{-1} (on 17th June, 2010, 6 WAP) before the flowering stage of the plant. Weeding was carried out at 2 WAP and 6 WAP.

Water stress treatments and measurements

Rain shelters were constructed for imposition of water stress treatments on the plots as and when necessary. Aluminium roofing sheets of 0.5 m height were placed up to a soil depth of 0.3 m to enclose each stressed plot to prevent lateral flow of water (moisture) from surrounding plots into the stressed plots. The remaining 0.2 m above ground surface prevents run-off from entering the stressed plots. A shed of height 2.5 m and a roof slope of 10 ° (to the horizontal) was mounted on the stress plot. A transparent polythene rubber sheet was then used to form removable roofing (rain-shelter) for the top and sides of the stressed plots to prevent rain (moisture) from getting into contact with a stressed plot. Adequate aeration was ensured by creating holes on the sides of the rain shelter structure. The transparent polythenes were then held in place to the structure by means of ropes tied to the poles of the structure.

Water stress was imposed at four critical growth stages of maize as identified by Ikisan (2000) (Seedling stage – establishment phase (SD), Knee-height stage (K-H), Tasseling and Silking stage (T-S) and Grain filling stage (G-F)). The stress treatment was imposed when about 50% of the plants have reached a particular stage. During the stress periods, rain shelters were constructed over the stress treatment plots. The period of water stress imposition was 14 days for the different stages.

Field data collection

Two plants per plot from the boarder rows were cut at ground level at the end of each stress treatment, oven dried for about 48 hours at 70 °C to a constant weight to obtain the total dry matter (TDM).

Soil moisture contents of the plots were monitored for layers 0 – 15 and 15 – 30 cm by gravimetric methods. This was done at three days intervals for the period of water stress imposition for all the stressed and unstressed plots. The soil moisture was determined by gravimetric method.

Three plants in the middle rows were tagged and used for plant height, leaf surface area and stem girth data collection at two weeks intervals. Leaf surface area was determined on the most developed leaf by measuring the length and breadth of the leaf and multiplying these by a factor of 0.75 (Yang and Alley, 2005). Stem girth was measured at a height of 5 cm from the ground surface for the tagged plants.

Maize ears were harvested from the 3 middle rows of the plots on 120 days after sowing (DAS). After drying the ears under open-air conditions, the maize cobs were threshed, manually winnowed; weighed, and sub samples per plot were weighed fresh, oven-dried to constant weight at 70 °C and re-weighed to determine the moisture content. The maize yield was calculated.

Crop Model

Data requirements and procedure for building the DSSAT model

A profile was dug up to 1.5 m depth at the experimental site. Soil samples were taken at depths of 0 – 10 cm, 10 – 20 cm, 20 – 30 cm, 30 – 45 cm, 45 – 60 cm and > 60 cm. The soils were analysed for organic carbon (using Walkley and Black Method), pH in water, Aluminium saturation, total Nitrogen, total Phosphorous (using Brays Solution), total Potassium, clay, silt and sand content and gravels. The particle size distribution of sand, silt and clay was used to characterise soil texture based on USDA textural triangle. Management data used for the model were principally obtained from the field experiment carried out at the Mechanization site of KNUST. These included cultivar ('*Obaatanpa*'), planting date (3rd May, 2010) and plant spacing (80 × 40 cm). The plants were monitored and phenological data which included date of emergence (9th May, 2010), date of flowering (29th June, 2010), date of maturity (31st August, 2010) noted. Planting method, fertilizer amounts (as was done for the field experiment) were included in the model.

Table 1: Part of weather data used in building the weather file for the model

Calender Day	Tmax, °C	Tmin, °C	Rainfall, mm	Sunshine Hours	Radiation, $MJm^{-2} day^{-1}$
131	34.00	24.20	21.30	5.20	27.11
132	33.00	21.80	23.80	5.90	28.75
133	33.00	22.60	0.00	7.80	33.26
134	32.50	24.20	0.50	0.00	14.62
135	33.00	24.30	41.10	6.10	29.13
136	33.00	21.60	0.00	7.60	32.67
137	32.50	23.60	0.00	6.30	29.54
138	34.00	23.20	16.50	7.80	33.07
139	33.00	23.30	1.40	6.20	29.24
140	34.50	23.60	0.00	9.50	37.01
141	34.50	23.80	0.00	8.40	34.37
142	34.50	24.20	0.00	7.50	32.20
143	34.00	24.30	0.00	5.40	27.22
144	33.00	23.20	0.00	4.20	24.36
145	33.50	23.20	3.90	8.10	33.50
146	33.00	22.80	TR	6.40	29.47
147	33.00	24.20	1.50	5.10	26.39
148	33.00	21.60	0.00	8.40	34.08
149	33.00	23.60	0.00	8.40	34.04
150	33.00	23.80	0.00	6.90	30.50
151	33.00	23.60	8.30	3.10	21.61

Table 2: Physical and some chemical properties of the soil at the experimental site

	Horizon	Particle size distribution			Texture	pH 1:1	Org. C	Total N	Org. M	Exchangeable cmol/kg			Cations
	(cm)	Sand %	Silt %	Clay %		H_2O	%	%	%	Ca	Mg	K	Na
BP	10 – 15	8.4	31.6	0.0	SL	5.20	1.19	0.11	2.05	2.94	1.07	0.31	0.05
P	15 – 30	57.1	26.9	16.0	SL	5.20	0.93	0.08	1.60	3.57	1.10	0.21	0.05
AP_1	0 - 10	63.6	26.4	10.0	SL	4.80	1.19	0.10	2.05	2.14	0.53	0.22	0.04
AP_2	10 – 20	61.3	26.7	12.0	SL	4.90	1.12	0.09	1.93	1.87	0.53	0.19	0.04
B_1	20 – 30	60.4	25.6	14.1	SL	4.80	1.04	0.08	1.79	1.34	1.07	0.19	0.03
B_2	30 – 45	57.7	26.3	16.0	SL	4.90	0.93	0.08	1.60	1.07	0.27	0.13	0.05
C_1	45 – 60	54.9	27.1	8.0	L	4.80	0.76	0.06	1.31	0.53	0.27	0.08	0.02
C_2	>60	32.6	31.4	36.0	CL	4.40	0.46	0.04	0.79	1.07	0.80	0.09	0.03

BP – Field soil analysis before planting, AP_1 – C_2 – Soil profile analysis, SL – Sandy loam, L – Loam, CL – Clayey loam

Model water stress treatments

A weather file was created from weather data (daily rainfall, temperature (minimum and maximum) and sunshine hours converted to solar radiation were obtained from the KNUST Agro-meteorological Station located 400 m from the experimental site. These data covered the period of the experiment. A seasonal analysis was run for the experiment based on a weather file. Other information included; latitude, longitude and elevation. The "weatherman" was used to create 5 different weather files for the new weather station. These files were then edited to correspond to the imposed stress treatments by putting zero rainfall amounts for each 2-week imposed treatment corresponding to when the stresses were imposed on the field.

Results and discussion

The effect of water stress on growth and biomass accumulation of maize

Plant height

For all treatments there was an increase in plant height until the 8 – 9 WAP when a maximum height was reached for the different treatments (Figure 1). At the end of the seedling stage, significant difference were observed for treatments SD and K-H on one hand and T-S, G-F and UnS on the other hand. At the end of the knee-height, tasseling/silking, grain filling-stage and at harvest, no significant difference was observed for all the treatments (Table 3). This could be attributed to the fact that by the end of the knee-height stage, treatment SD may have recovered from the deficit experienced during the SD stage as reported by Sipaseuth *et al.*, (2007).

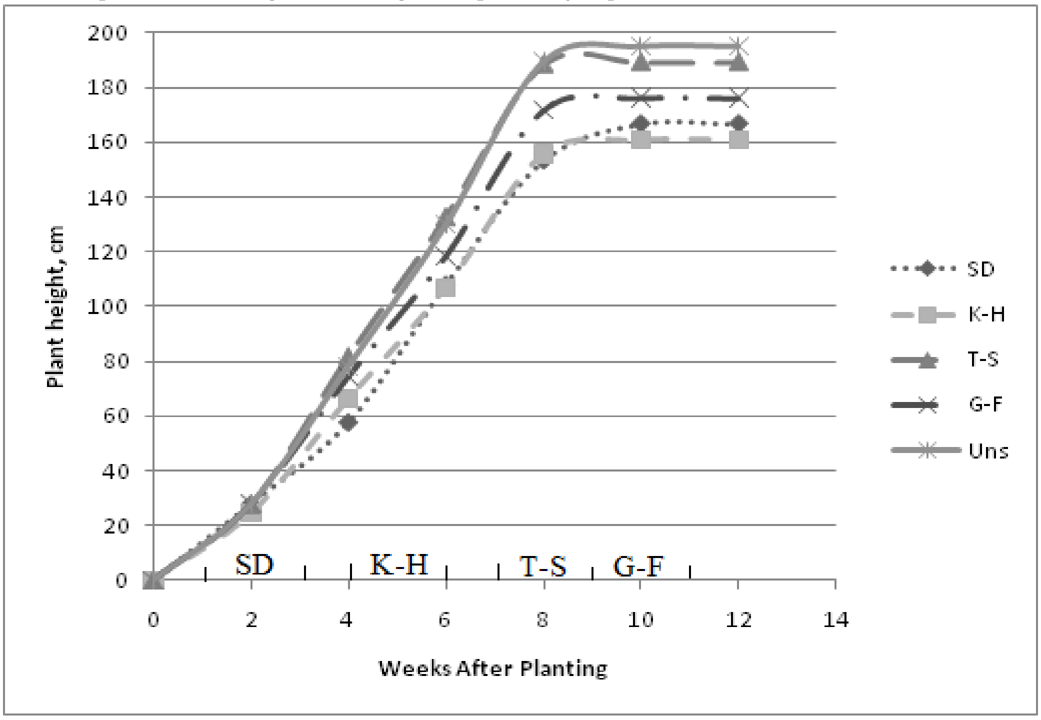

Figure 1: Plant height of maize exposed to water stress treatments during seedling (SD = 0-2weeks), knee-height (K-H = 4-6 weeks), tasseling-silking (T-S = 7-9weeks) and grain-filling (G-F = 9-11 weeks) stages and unstressed (UnS) maize in field experiment

Table 3: Plant height at the end of different growth stages of field experiment

Stress treatment	Plant Height (cm)	
	At end of SD treatment	At harvest
SD	44 a	167
K-h	50 a	161
T-S	61 b	189
G-F	56 ab	176
UnS	60 b	195
LSD (0.05)	13.2	NS

* Means within the same column not followed by the same letter are significantly different at $P < 0.05$ level by Duncan's multiple range test.

Stem girth

Maize girth increased with time until the maximum was reached 4 – 6 WAP. At this stage, it was observed that the seedling and knee-height treatments were affected by water stress as compared to the others. All subsequent measurements after this stage showed no changes since the plant reached their maximum girth by the 6^{th} WAP (Figure 2). Hence the treatments of Tasseling-Silking and Grain-filling did not have any influence on the plant girth 6 WAP. ANOVA at harvest gave significant difference in girth. The SD water stress resulted in significantly smaller girth compared to T-S, G-F and UnS treatments at harvest.

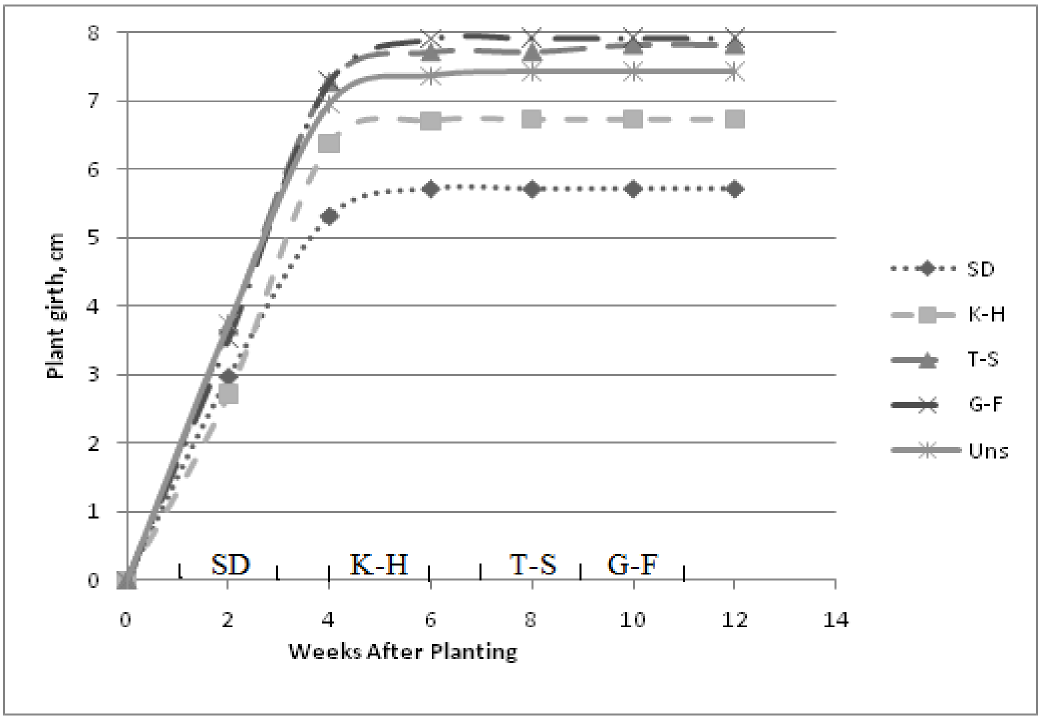

Figure 2: Plant girth of maize exposed to water stress treatments during seedling (SD), knee-height (K-H), tasseling-silking (T-S) and grain-filling (G-F) stages and unstressed (UnS) in field experiment

Leaf surface area

Leaf surface area increases with time for the period of the experiment. SD was significantly affected by water stress compared to the other treatments at harvest (Figure 3).

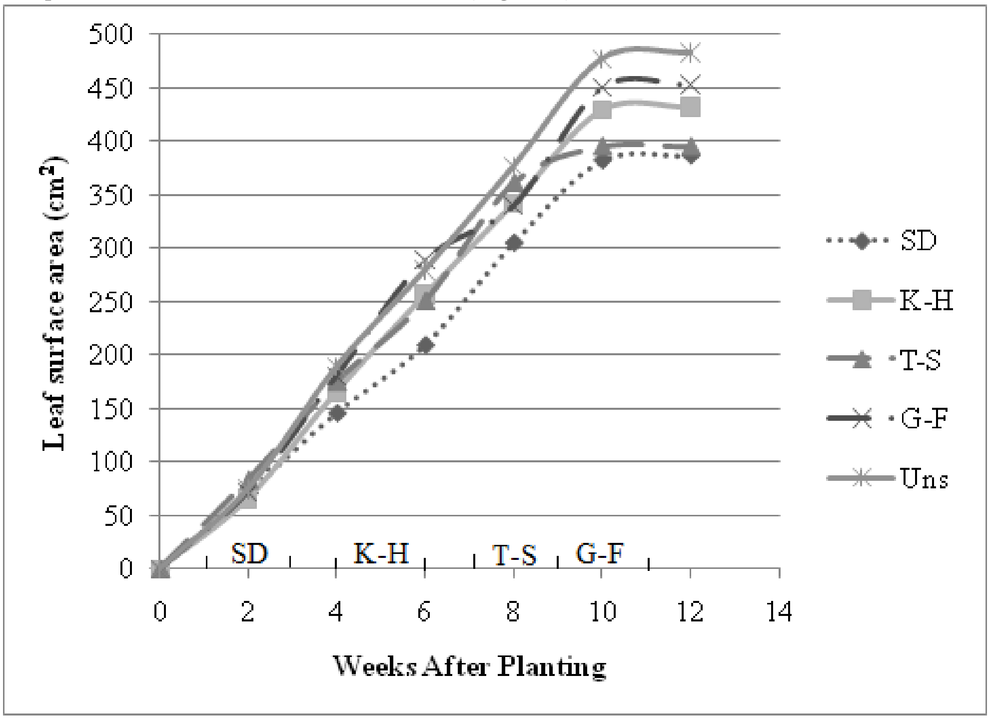

Figure 3: Leaf surface area of maize exposed to water stress treatments during seedling (SD), knee-height (K-H), tasseling-silking (T-S) and grain-filling (G-F) stages and unstressed maize in field experiment

Biomass accumulation during field and modelled experiment

Total dry matter accumulation was not significantly affected by water stress based on results from field experiment (Table 4). Analysis of biomass at the end of all the considered stages showed that the unstressed treatments gave higher TDM compared to the stressed treatments. However the biomass accumulated was not significantly different for the different treatments. Total dry matter accumulation at different stage of the field and modelled experiments showed that vegetative stages (SD and K-H) were the most affected by the imposed treatments. TDM losses were in the range of 2 – 10 % for the two different experiments (i.e. field and model).

Table 4: Total Dry Matter accumulation at different stages of the field experiment and model

Stress treatment	Total dry matter (kgha^{-1}) after									
	Seedling stage		Knee-height stage		Tasseling-Silking stage		Grain-filling stage		At Harvest	
	Field	Model	Field	Model	Field	Model	Field	Model	Field	Model
SD	270	808	2342	2607	3509	3777	3840	5100	3786	6496
K-H	274	820	2386	2623	3643	3817	3876	5136	3781	6488
T-S	275	820	2302	2636	3643	3809	3831	5123	3720	6505
G-F	279	837	2290	2679	3580	3854	3830	5217	3734	6596
UnS	279	837	2275	2679	3578	3854	3910	5218	3901	6641

Water stress effect on yield and yield components

Number of kernels per ear for plants with ears

Counting of number of kernels per ear for plants that have ears are summarised in Table 5. Results obtained showed that kernel number per ear was significantly (*P* < 0.05) affected by water stress treatment. Number of kernels per ear from treatments G-F and T-S were significantly lower than the UnS treatment. The results were similar to that of Farre´ and Faci (2009) and Sah and Zamora (2005) when they studied the impact of water stress on number of kernels per ear.

Table 5: Mean number of kernels per ear for plants with ears under water stress treatments

Stress treatment	Number of kernels per ear
SD	419 a b c *
K-H	428 b c
T-S	358 a b
G-F	348 a
UnS	480 c
LSD (0.05)	72

* Means within the same column not followed by the same letter are significantly different at P < 0.05 level by Duncan's multiple range test.

Grain yield for field and model experiments

Grain yield was not significantly affected by water stress (Table 6). The yields of treatments exposed to water stress were lower than the control treatment (unstressed). The most affected treatment was the T-S, followed by K-H, G-F and SD with decreasing impact of water stress. There were 3 – 5 % and 11 – 27 % (for the model and field experiments respectively) yield reductions resulting from the water stress. Similar to results of study by Cakir (2004), yield of the maize is dependent on the moisture stress and their timing during the crop cycle. Moisture stress in the sensitive stages (tasseling and silking or grain filling) resulted in highest grain yield reduction. Relatively higher yields were obtained for treatments with stress occurring at the vegetative stages prior to tasseling showing relative tolerance of maize to short duration water stress during these stages as stated by NeSmith and Ritchie (1992). Grain yield was related to the kernel number per ear for the field experiment. Pandey *et al.*, (2000a) stated that kernel number can be reduced by 20 – 50 % due to water stress based on results they obtained from experiment. NeSmith and Ritchie (1992) indicated that yield reduction in maize was attributable to a reduction in the number of well developed kernels. This reduction in yield is primarily associated with decrease in kernel number and secondarily with weight per kernel when water stress was imposed during vegetative and reproductive phases of growth (Pandey et al., 2000b).

Table 6: Grain yield obtained from field and model experiment under water stress and control treatments.

Stress treatment	Average grain yield from field (kgha^{-1})	Crop Model Grain yield (kgha^{-1})	% Overestimation of yield by model
SD	2280	2787	22.24
K-H	1995	2773	39.00
T-S	1860	2766	48.71
G-F	2130	2808	31.10
UnS	2550	2908	14.04

Since models are ideal representations of the real occurrences and interactions in the environment, the crop model DSSAT which takes into account the various soil, water and management data, tends to oversimplify some of the inputted data and in its simplification overestimate yield in all the water stress treatments. The grain yield of the crop model for the UnS was for instance over estimated by about 40% compared to the UnS for the field experiment. However, if an appropriate fertility factor is identified, grain yield can be accurately predicted.

Conclusion

Results from the study generally showed that growth and yield is affected by water stress to varying degrees depending on the timing of the stress period. The highest grain yield was obtained when maize plants were not stressed for the entire growth period (unstressed treatment).

In terms of growth, the seedling stage (establishment phase) was the most affected. Thus the plant stressed at this stage is still able to recover and give better yield if no further water stress occurs.

Yield components such as kernel number per plant for the field experiment were affected by water stress thereby influencing the yield. Based on the modelled experiments, it can be concluded that the most sensitive stage in terms of yield and yield components of maize plant in response to water stress is the tasseling and silking stage with reduction in yield of 5 % and 27 % respectively

The study also showed that it is possible to implement deficit irrigation strategies for reduced agricultural water use by increasing the interval between irrigations during the periods other than around flowering based on the results. For irrigation scheduling purposes in situations of limited water, the most critical stage that water must be applied is the tasseling and silking stages. Finally, results obtained from the modelled experiments indicated that grain yield in response to different water stress treatment applications could be reasonably predicted by the DSSAT-CSM. Hence it is concluded that the DSSAT can be used in the country with little or no modification to the program (paying particular attention to the fertility factor used for the newly built soil model or the adapted soil model) to estimate and predict maize yield in response to drought.

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