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Modeling the Effect of Different Stress Conditions on Maize Productivity Using Yield-Stress Model

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Abstract

Two field experiments were conducted in 2005 and 2006 growing seasons at El-Kalubia Governorate, Egypt to collect data on maize yield of three cultivars to be used to validate Yield-Stress model. The objectives of this research were to use Yield-Stress model to predict maize yield: (i) under deducting 20% of the total irrigation. (ii) under saline water irrigation with EC=2 dS/m. (iii) under deducting 20% of the total irrigation with EC=2 dS/m. (iv) under heat stress. The model prediction gave a good agreement with measured yield and water consumptive use. Results also indicated that potential maize yield could be reduced by 4.29 and 4.87% in 2005 and 2006 growing seasons, respectively if the amount of total irrigation was reduced by 20%. Under salinity conditions (EC=2dS/m), the potential maize yield could be reduced by 3.29 and 4.21% in 2005 and 2006 growing seasons, respectively. Using deficit saline irrigation could reduce yield by 6.80 and 7.84% for the 1st and the 2nd season, respectively. Finally, if current temperature would increase by 1.5 ºC, the potential maize yield could be reduced by up to 9.5%. Therefore, defeating these stresses conditions could improve maize growth environment and improve final yield.

Key words: water stress, salinity stress, deficit saline water irrigation, heat stress, water consumptive use.

INTRODUCTION

Increasing maize productivity under different stress conditions pose as a great challenge to agricultural scientists. Stress conditions could be water stress, salinity stress, the combined effect of both water and salinity stresses and heat stress. Modeling maize yield under these previously mentioned situations could be very useful procedure to collect information about yield reduction. Furthermore, it could save a lot of time and efforts.

Water stress during maize growing season resulted in plant height reduction, leaf area index reduction [1] and total leaf area reduction [2]. In addition, number of ovules that fertilized and developed into grains decreased rapidly when drought occurred during flowering [3]. Moreover, both final maize yield and kernel number were reduced as a result of water stress during grain filling period [4].

Soil salinity also constructs another problem to crop productivity. Salinity inhibits plants growth as a result of stomatal closure, which reduces the CO_2 to O_2 ratio in the leaves and inhibits CO_2 fixation [5], as a result of reduction of the rate of leaf elongation, enlargement and cells division [6]. Furthermore, salts in the soil water solution can reduce evapotranspiration by making soil water less available for plant root extraction [7]. Maize is characterized as being moderately sensitive to salinity stress [6]. For maize grown under salinity, reduction in growth characters and yield were observed [8] and [9].

The combined effect of both of water and salinity stresses could significantly reduced yield. Under deficit irrigation with saline water, a water conserving practice, the crop experiences simultaneous metric and osmotic stresses [10] and that resulted in growth and yield reduction [11].

Furthermore, heat stress could accelerate the rate of plant growth and consequently reduce the length growing season. Yield reduction was observed under heat stress conditions. Estimates ranged up to 17% for each degree Celsius increase in average growing temperature [12]. High temperature can reduce kernel sink capacity and limit subsequent kernel development and grain yield [13].

The objectives of this research were to use Yield-Stress model to predict maize yield: (i) under deducting 20% of the total irrigation. (ii) Under saline water irrigation with EC=2 dS/m. (iii) under deducting 20% of the total irrigation with EC=2 dS/m. (iv) under heat stress.

MATERIALS AND METHODS

Two field experiments were conducted in 2005 and 2006 growing seasons at the farm of Central Administration for Agricultural Experiments at Kalubia Governorate (latitude = 30º, longitude = 31º, and elevation = 14 m), Egypt to collect data on maize yield of three cultivars (SC10, SC152 and TWC321) to be used to validate Yield-Stress model [14]. A randomize complete blocks design with four replications was used. Sowing was done on the 26th of May in the two growing seasons. Plot size was 14 m². Nitrogen fertilizer was applied in the form of Urea (288 kg/ha, 46% N) and was divided into 2 doses (before the 2nd irrigation and before the 3rd irrigation). Phosphorus fertilizer was applied in the form of single super phosphate (480 kg/ha, 15% P_2O_5) and was incorporated into the soil during land preparation. Potassium sulphte was applied before planting (120 kg/ha, 48% KO2). Surface irrigation was used. All the three hybrids received seven irrigations, which were applied to ensure enough soil moisture is available for the growing plants. The second irrigation was applied 3 weeks after the 1st irrigation, and then irrigation was applied every 2 weeks (a common irrigation practice for maize in Egypt). Weeds control was done manually twice, before the 2nd irrigation and before the 3rd irrigation. Harvest was done on the 2nd week of September in both growing seasons. Soil analysis according to Piper (1950) [15] was done for the experimental field in the depth of 0-60 cm (Table 1).

Table 1. Soil analysis at of the experimental site

Soil fraction	Content (%)
Sand	8.20
Silt	57.4
Clay	34.4
Organic matter	1.60
$CaCO_3$	2.40
Texture class	Clay loam

Actual evapotranspiration was estimated by soil sampling method and calculated according to Israelsen and Hansen (1962) [16] using the following formula:

$$CU = \frac{(\Theta_2 - \Theta_1) * Bd * ERZ * 10000}{100 * 100}$$

Where:

CU = the amount of consumptive use in m^3/ha.

Θ_2 = soil moisture percentage after irrigation.

Θ_1 = soil moisture percentage before the following irrigation.

Bd = bulk density in g/cm^3

ERZ = effective root zone (0.6 m)

Soil moisture constants (% per weight) and bulk density (g/cm^3) in the depth of 0-60 cm are shown in Table (2).

Table 2. Soil moisture constants of the experimental field

Depth	Field capacity %	Wilting point %	Available water %	Bulk density (g/cm^3)
0 – 15	41.85	18.61	23.24	1.15
15 – 30	33.68	17.5	16.18	1.24
30 – 45	28.36	16.92	11.46	1.20
45 – 60	28.05	16.54	11.51	1.28

At harvest, the yield (ton/ha) of each of the three varieties was measured and used with measured water consumptive use to validate Yield-Stress model. Predicted yield and water consumptive use was compared to the measured values. Furthermore, percent difference between measured and predicted yield, root mean square error (RMSE) and Willmott index of agreement [17] were calculated. These three previously mentioned parameters were used to test the accuracy of the model. To ensure accurate prediction, percent difference between and predicted and RMSE should be close to zero, and Willmott index of agreement should be close to one.

Yield-Stress Model Description

Yield-Stress model is capable of accurately predicting crop yield and water consumptive use under the application of actual irrigation amount. Furthermore, under water stress, the model calculates a water stress coefficient and predict yield in relation to that water stress coefficient. The model does not required calibration for each site. However, FAO's crop coefficient (Kc) should be adjusted to the local weather conditions.

"Yield-Stress" requires two types of input data. Input data by the user and input data file. The model asks the user to input planting and harvesting date, the length of the growing season, and crop yield. The model also asks the user to input soil characteristics i.e. clay, silt, sand, organic matter, and $CaCO_3$ percentages. The other input data source is a file represent the whole growing season, starts with sowing month and date, and ends with harvesting month and date. The file contain maximum, minimum and mean temperature, relative humidity, solar radiation, wind speed, crop coefficient and the date and the amount of each irrigation. Weather parameters for the two growing seasons were collected and means are included in Table (3).

Table 3. Seasonal weather parameters for maize planted in 2005 and 2006 growing seasons

Growing season	Mean temperature (ºC)	Relative humidity (%)	Solar radiation (Mj/m^2/day)	Wind speed (m/sec)
2005	26.8	57	1.8	24.6
2006	28.0	56	1.7	24.5
Mean	27.4	56	1.8	24.6

The model was also used to predict maize yield under the following hypothetical stress conditions:

1. Predicting potential maize yield under water stress, if 20% of total irrigation amounts was deducted.
2. Predicting potential maize yield under salinity stress, if the EC of irrigation water was increased to 2 dS/m.
3. Predicting potential maize yield under both water and salinity stresses, if 20% of total irrigation amounts was deducted with EC=2 dS/m.
4. Predicting potential maize yield under heat stress, if 1.5 ºC was added to the current temperature throughout the whole growing season.

Yield-Stress model was modified to account for heat stress via heat stress coefficient [18], which was used to reduced yield. New input data files were prepared and used to run the model to predict maize yield under the previously mentioned conditions. Table (4) showed the actual applied irrigation amount and the proposed amounts under the above mentioned scenarios.

RESULTS

Yield-Stress model validation

Maize yield and water consumptive use was predicted under optimum conditions (Table 5). Results in that table showed that the model prediction gave a good agreement with measured yield of the three varieties over the two growing seasons. Similarly, the model prediction gave a good

Table 4. Actual irrigation water (m^3/ha) and proposed amounts under different stress conditions.

	2005 growing season				
	Total irrigation	Total irrigation less 20%	Salinity stress	Water and salinity stresses	Heat Stress
SC 10	5934	4793	5934	4793	5934
SC 152	5859	4687	5859	4687	5859
TWC 321	5894	4716	5894	4716	5894
Average	5896	4732	5896	4732	5896
	2006 growing season				
	Total irrigation	Total irrigation less 20%	Salinity stress	Water and salinity stress	Heat Stress
SC 10	5842	4674	5842	4674	5842
SC 152	5766	4613	5766	4613	5766
TWC 321	5856	4685	5856	4685	5856
Average	5821	4657	5821	4657	5821

agreement with measured water consumptive use. RMSE and Willmott index of agreement for yield were 0.0107 and 0.9999, respectively. Whereas, RMSE and Willmott index of agreement were 0.0288 and 0.9998 for water consumptive use, respectively. This is an indication of the accuracy of the model, which facilitate using it for further yield predictions with different stress conditions. Similar results were obtained by [10] when the model was used to predict wheat yield and water consumptive use, and for sunflower yield and water consumptive use [18]. Furthermore, similar results were obtained when the model was used to predict barley yield [19] and for sesame yield [20].

Figure (1) represented the depletion of readily available water from root zone under the application of total irrigation for maize hybrid SC10 in 2005 growing season. Seven hills are shown in that graph, each top of these hills represent irrigation day and the amount of readily available water at root zone. The graph also showed that all readily available water at root zone was completely depleted after the application of the 4th irrigation; where water stress was exist for 3 days.

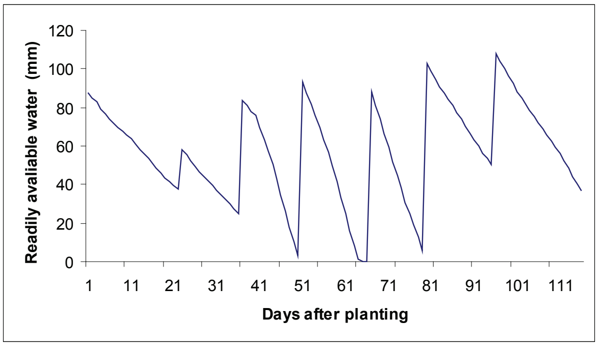

Figure 1. Readily available water depletion from root zone after the application of each individual irrigation under the application of total irrigation amount for maize hybrid SC10 grown in 2005 season.

Predicting maize yield and water consumptive use under water stress

The model was used to predict maize yield and water consumptive use under deducting 20% of total irrigation (Table 6). Results in that table indicated that maize yield was reduced by 4.29 and 4.87% in 2005 and 2006 growing seasons, respectively. Whereas, water consumptive use was reduced by 4.60 and 7.87% in 2005 and 2006 growing seasons, respectively. The high reduction in water consumptive use in 2006 growing

Table 5. Measured versus predicted maize yield and water consumptive use

	Seed yield (ton/ha)			Water consumptive use (cm)		
	Measured	Predicted	% difference	Measured	Predicted	% difference
2005 growing season						
SC 10	8.93	8.91	0.22	49.45	50.45	2.02
SC 152	8.20	8.15	0.61	48.83	48.50	0.67
TWC 321	8.73	8.66	0.80	49.12	49.04	0.16
2006 growing season						
SC 10	8.73	8.69	0.46	53.10	52.72	0.72
SC 152	8.51	8.45	0.71	52.42	51.77	1.24
TWC 321	8.67	8.55	1.38	53.24	51.58	3.11
RMSE	0.0107			0.0228		
Willomtt	0.9999			0.9998		

Table 6. Predicted maize yield and water consumptive use under deducting 20% of the total irrigation

	Seed yield (ton/ha)			Water consumptive use (cm)		
	Measured	Predicted	% Reduction	Measured	Predicted	% Reduction
2005 growing season						
SC 10	8.93	8.69	2.69	49.45	48.36	2.20
SC 152	8.20	7.77	5.24	48.83	46.15	5.48
TWC 321	8.73	8.30	4.93	49.12	46.11	6.12
Average	8.62	8.25	4.29	49.13	46.87	4.60
2006 growing season						
SC 10	8.73	8.42	3.55	53.10	50.17	5.53
SC 152	8.51	8.03	5.64	52.42	48.16	8.12
TWC 321	8.67	8.20	5.42	53.24	47.93	9.97
Average	8.64	8.22	4.87	52.92	48.75	7.87

season compared with 2005 growing season could be attributed to high seasonal mean temperature in 2006 compared to 2005 growing season. High temperature could increase atmospheric demand and consequently increase water consumptive use [21]. These results are in agreement with what was found by [22], where irrigation amount was reduced from 6290 to 5032 m^3/ha with yield reduction less than 2%.

Figure (2) illustrated the depletion of readily available water from root zone under the application of total irrigation and under deducting 20% of the total irrigation for maize hybrid SC10 in 2005 growing season. The figure showed that readily available water was completely depleted under the application of the 3rd, the 4th and the 5th irrigation, where water stress was prevailed for 11 days, which reduced yield by 2.69% (Table 6).

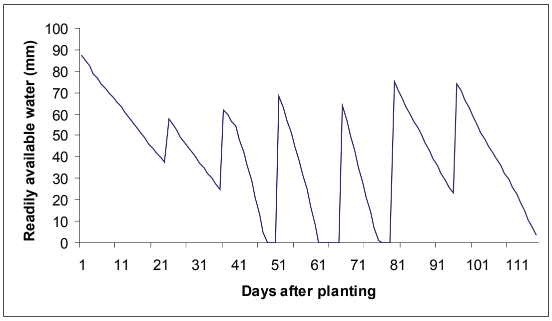

Figure 2. Readily available water depletion from root zone after the application of each individual irrigation under the application of total irrigation amount less 20% for maize hybrid SC10 grown in 2005 season.

Predicting maize yield and water consumptive use under saline water irrigation (EC=2 dS/m)

Results in Table (7) implied that the potential maize yield could be reduced by 3.29 and 4.21% in 2005 and 2006 growing seasons, respectively under irrigation with saline water (EC=2 dS/m). Furthermore, 1.49 and 4.56% reduction in water consumptive use could be expected under irrigation with saline water. The high reduction in water consumptive use in 2006 growing season compared with 2005 growing season could be also attributed to the effect of high seasonal mean temperature in 2006 compared to 2005 growing season.

Predicting maize yield and water consumptive use under saline water irrigation (EC=2 dS/m) less 20%

Modeling the combined effect of both salinity and water stresses on maize yield and water consumptive use is included in Table (8). Results in that table indicated that high yield reduction could be obtained under these conditions. Maize yield could be reduced by 6.80 and 7.84% for the 1st and the 2nd season, respectively. Furthermore, under these circumstances, water consumptive use was reduced by 7.55 and 10.74% for the 1st and the 2nd season, respectively.

Predicting maize yield and water consumptive use under current temperature rise by 1.5 ºC

A raise in current temperature by 1.5 ºC could have a bad effect on maize yield than deficit saline irrigation water. Results in Table (9) showed that under that condition, maize yield could be reduced by up to 9.5%. Eid et al. (1997) [23] stated that maize production will be reducing about 19% in comparison with current climate conditions under current temperature

Table 7. Predicted maize yield and water consumptive use under EC=2 dS/m

	Seed yield (ton/ha)			Water consumptive use (cm)		
	Measured	Predicted	% Reduction	Measured	Predicted	% Reduction
2005 growing season						
SC 10	8.93	8.66	3.02	49.45	48.99	0.93
SC 152	8.20	7.93	3.29	48.83	48.06	1.57
TWC 321	8.73	8.42	3.55	49.12	48.15	1.97
Average	8.62	8.34	3.29	49.13	48.40	1.49
2006 growing season						
SC 10	8.73	8.44	3.32	53.10	51.19	3.61
SC 152	8.51	8.14	4.35	52.42	50.26	4.12
TWC 321	8.67	8.24	4.96	53.24	50.06	5.97
Average	8.64	8.27	4.21	52.92	50.50	4.56

Table 8. Predicted maize yield and water consumptive use under saline water irrigation (EC=2 dS/m) less 20%

	Seed yield (ton/ha)			Water consumptive use (cm)		
	Measured	Predicted	% Reduction	Measured	Predicted	% Reduction
2005 growing season						
SC 10	8.93	8.46	5.26	49.45	46.90	5.16
SC 152	8.20	7.57	7.68	48.83	44.71	8.43
TWC 321	8.73	8.08	7.45	49.12	44.66	9.07
Average	8.62	8.04	6.80	49.13	45.42	7.55
2006 growing season						
SC 10	8.73	8.2	6.07	53.10	48.64	8.41
SC 152	8.51	7.76	8.81	52.42	46.65	11.00
TWC 321	8.67	7.92	8.65	53.24	46.41	12.82
Average	8.64	7.96	7.84	52.92	47.23	10.74

rise by 3.6 ºC. Results in that table also implied that water consumptive use could be increased by up to 10.62 % under a raise in current temperature by 1.5 ºC.

Figure (3) illustrated the depletion of readily available water from root zone under current temperature rise by 1.5 ºC for maize hybrid SC10 in 2005 growing season. The figure showed that readily available water was completely depleted under the application of the 3rd, the 4th and the 5th irrigation, where water stress was prevailed for 7 days.

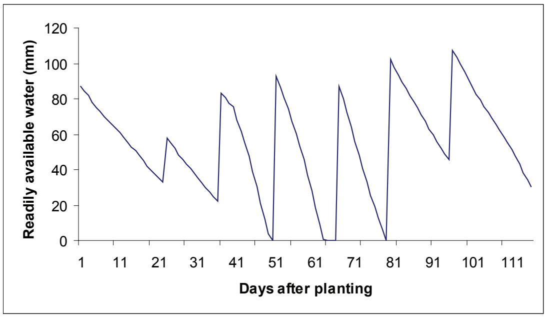

Figure 3. Readily available water depletion from root zone after the application of each individual irrigation under current temperature rise by 1.5 ºC for maize hybrid SC10 grown in 2005 season.

DISCUSSION

Expressive information on the effect of different stress conditions on maize productivity could be very useful in determining yield losses for economical purposes. Therefore, modeling the effect of these stresses could be the ultimate solution. Yield-Stress model employed soil water depletion equations to instantly predict potential yield under varying degree of stress, which could partially replacing expensive field experiments. Furthermore, as long as evapotranspiration is met by the readily available soil moisture, yield accumulation continues on a daily basis. When readily available soil moisture fails to meet evapotranspiration demand, yield reduction occurred through multiplying the value of Ks by daily yield increment [10]. The good agreement between measured and predicted yield implied that the model is capable of investigating radical alternatives representing environmental stresses.

Minimizing yield loses under water, salinity and heat stresses conditions could be attained. Reducing the total amount of applied irrigation water and avoiding sensitive water stress growth stages could lower the harm effect of water stress on maize yield [2]. Improving management practices, such as the use of soil amendments, deep ploughing, fertilization, applying minimum leaching requirements and organic manure application could overcome the harm effect of salts accumulation in the soil as a result of deficit irrigation, saline water irrigation or deficit saline water irrigation [7]. To increase plants tolerance to heat stress, several adaptation options could be done to over come yield reduction, such as delay sowing, increasing irrigation amounts and increasing fertilizer amounts [24]. Furthermore, mitigation of water stress [25] and salinity stress [26] through spraying chemical substances is another management practices to be done to relief the stress and increase yield. Lastly, breeding for water, salinity and heat stresses tolerance in maize could be an important procedure to combat stress.

Table 9. Predicted maize yield and water consumptive use under heat stress

	Seed yield (ton/ha)			Water consumptive use (cm)		
	Measured	Predicted	% Reduction	Measured	Predicted	% Reduction
2005 growing season						
SC 10	8.93	8.14	8.85	49.45	54.38	9.97
SC 152	8.20	7.41	9.63	48.83	53.13	8.82
TWC 321	8.73	7.88	9.74	49.12	53.17	8.25
Average	8.62	7.81	9.41	49.13	53.56	9.01
2006 growing season						
SC 10	8.73	7.94	9.05	53.10	57.65	8.56
SC 152	8.51	7.69	9.64	52.42	59.5	13.51
TWC 321	8.67	7.82	9.80	53.24	58.45	9.79
Average	8.64	7.82	9.50	52.92	58.53	10.62

CONCLUSION

Over the last two decades, modeling has become a major research tool in agriculture for resource management. Yield-Stress model was successful in providing this type of information. The results of the model validation implied that the model can be used with confidence in predicting maize yield under different hypothetical stress situations. Under deducting of 20% of the actual irrigation, the potential maize yield could be reduced by an average of 4.54%. If salinity conditions was imposed (EC=2dS/m), the potential maize yield could be reduced by an average of 3.75%. Using deficit saline irrigation could reduce yield by an average of 7.23%. Finally, if current temperature would increase by 1.5 ºC, the potential maize yield could be reduced by an average of 9.50%. Therefore, defeating these stresses conditions could improve maize growth environment and improve final yield.

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