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Using CropSyst Model to Predict Barley Yield under Climate Change Conditions in Egypt: I. Model Calibration and Validation under Current Climate

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ABSTRACT

The CropSyst model was calibrated and validated using field data of barley grain and biological yield and consumptive use (CU) obtained from a two-year field experiment conducted in 2007/08 and 2008/09 at El-Kalubia governorate, South Delta, Egypt. Six barley cultivars were planted ('Giza 123', 'Giza 125', 'Giza 126', 'Giza 2000', 'Giza 129' and 'Giza 130'). The aim of this work was to identify parameters that could be used as indicators of yield stability in barley cultivars, which could be useful under stressful conditions of climate change. The CropSyst model was used to simulate the effect of irrigation rescheduling on barley yield and water use efficiency (WUE). Three parameters were used to test the yield stability of barley cultivars i.e. harvest index (HI), WUE and percentage of irrigation water saved under simulation of irrigation rescheduling (IR). The results of the accurate prediction of the CropSyst model for barley yield and CU suggested that the model can be used with confidence to predict the effect of irrigation rescheduling on yield. Using HI to test the stability of yield revealed that 'Giza 126', 'Giza 129' and 'Giza 130' were characterized by similar HI values in both growing seasons. Regarding the percentage of irrigation water saved under simulation of IR, yield of these three cultivars, in addition to 'Giza 123', was not reduced under IR and the amount of saved irrigation water was similar under both growing seasons. The value of WUE under actual irrigation and under simulation of IR was similar in both growing seasons for 'Giza 126'. Thus, based on the comparative results between the six barley cultivars, it could be concluded that 'Giza 126' possesses yield stability traits.

Keywords: consumptive use, harvest index, irrigation rescheduling, water use efficiency

INTRODUCTION

Barley (*Hordeum vulgare* L.) is grown in almost all parts of the world for human consumption, industry and animal feed. In Egypt, the barley growing season ranges between 120 and 140 days and requires 314-372 mm of irrigation water depending on the location (Ainer *et al.* 1999). Recently, great interest was paid to barley because of its nutritive value as it is mixed with wheat in the bread-making industry (CAMPAS 2003). Barley is a very hardy crop, which can grow in adverse agroclimatic conditions such as drought because of its ability to tolerate moderate levels of water stress (Mishra and Shivakumar 2000). Comparative studies on wheat and barley (López-Castañeda and Richards 1994; Manschadi *et al.* 2006a) suggest that the higher yielding ability of barley in drier environments is largely due to earlier commencement of flowering and maturity and a faster rate of leaf canopy development and root growth early in the season when vapor pressure deficit is low. These characteristics result in reduced evaporative loss of water from the soil surface, and increase water use efficiency (WUE) for above-ground biomass production (Manschadi *et al.* 2006b), which make barley a good candidate to replace wheat under severe climate change conditions.

The increasing needs for more efficient management of crop production systems along with more consideration in environmental issues resulting from management decisions, has necessitated the use of crop simulation models as additional management tools for researchers and agricultural extension personnel. Crop growth/irrigation scheduling simulation models are becoming an integral part of crop management schemes, designed to maximize input use. Several simulation models have been developed and used to predict barley yield in the past 20 years. A model was developed in Australia by Goyne *et al.* (1996) called QBAR and used to evaluate production management strategies for barley. CropSyst model was used to simulate cropping systems, including barley, maize and soybean in Italy (Donatelli *et al.* 1997). Etizinger *et al.* (2004) compared the ability of three simulation models i.e., CRESE, SWAP and WOFOST to simulate barley yield and concluded that the three models gave similar results. The APSIM-wheat module was adapted to simulate growth and development of barley by altering the key variables describing the distinguishing physiological traits between two species (Manschadi *et al.* 2006b). A Yield-Stress model was used to predict barley yield under optimum irrigation and water stress (Khalil *et al.* 2007).

CropSyst is one of the most important process-oriented simulation models at present. It is a multi-year, multi-crop, daily time step crop growth simulation model, developed with emphasis on a friendly user interface, and with a link to GIS software and a weather generator (Stockle *et al.* 1994). The model was largely used for many crops all over the world, such as maize (Diaz-Ambrona *et al.* 2004; Rivington *et al.* 2007; Tingem *et al.* 2007) and wheat (Punnkuk *et al.* 1998; Wang *et al.* 2006; Moriondo *et al.* 2007; Singh *et al.* 2008). Similarly, in Egypt, the model was used to simulate the yield of maize (El-Marsafawy *et al.* 2000; Ouda *et al.* 2009) and wheat (Khalil *et al.* 2009). The performance of CropSyst was compared with the performance of several simulation models. It was compared with CERES-maize and EPIC, where CropSyst was superior in predicting water uptake in maize (Jara and Stockle 1999).

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Moreover, CropSyst predicted maize yield more accurately, compared with CRESE-Maize and SWACROP models (Clemente *et al.* 2005). CropSyst prediction of wheat yield and biomass was closer to the measured values than CERES-Wheat (Singh *et al.* 2008).

The objectives of this research were: (i) to validate the CropSyst model with data for barley yield grown under required irrigation; (ii) To use the model to simulate the effect of rescheduling irrigation on barley yield and irrigation water saving.

MATERIALS AND METHODS

Two field experiments were conducted in 2007/08 and 2008/09 growing seasons at Shalakan, El-Kalubia governorate, South Delta, Egypt to collect data on barley yield and consumptive use. The aim of these experiments was to identify parameters to be used as indicators of yield stability of barley cultivars under sufficient irrigation and simulation of irrigation water saving, which could be useful under the stressful condition of climate change. Four barley hulled cultivars were used i.e. 'Giza 123', 'Giza 125', 'Giza 126', and 'Giza 2000', in addition to two hull-less barley cultivars i.e. 'Giza 129' and 'Giza 130'. A complete randomize block design with four replicates was used. The preceding crop was maize in both seasons and the soil type was clay loam with the following characteristics: 7.5% sand, 59.1% silt, 33.4% clay, pH = 7.55, Ec = 0.26 dsm^{-1}, Ca^{++} = 1.1, Mg^{++} = 0.5, Na^{+} = 1.3, K^{+} = 0.8, HCO_3 = 0.4, Cl^{-} = 2.6, SO_4^{--} = 0.58 (meq/lit). Barley seeds were sown on the 3rd and 5th of December 2007 and 2008, respectively. Potassium fertilizer was added at a rate of 58 kg/ha (K_2SO_4). Nitrogen fertilizer as 108 kg/ha was divided into two equal doses, the first was added 25-30 days after planting and the second was added 30-35 days after the first dose. First irrigation was applied at sowing day, the second irrigation was applied one month after the first irrigation then plants were irrigated every 21 days. The total number of irrigations was five. Soil moisture was sampled before irrigation to calculate the needed amount of applied irrigation water to reach field capacity. Consumptive use was calculated using the following equation (Israelsen and Hansen 1962):

$$CU = (\Theta_2 - \Theta_1) * Bd * ERZ \quad [1]$$

where CU = the amount of consumptive use (mm), Θ_2 = soil moisture percentage after irrigation, Θ_1 = soil moisture percentage before the following irrigation, Bd = bulk density (g/cm^3) and ERZ = effective root zone. Weather data in both growing seasons are included in **Table 1**.

Days to emergence, anthesis, beginning of grain filling and physiological maturity were estimated. Maximum leaf area index was measured at anthesis. At harvest, grain and biological yield were measured and harvest index (HI) was calculated. HI is the proportion of biological yield represented by economic yield (Gardner *et al.* 1985).

CropSyst model calibration and validation

The CropSyst (Cropping Systems Simulation Model) (Stockle *et al.* 1994) objective is to serve as an analytical tool to study the effect of cropping systems management on crop productivity and the environment. For this purpose, CropSyst simulates the soil water budget, soil-plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and pesticide fate. These are affected by weather, soil and crop characteristics, and cropping system management options including crop rotation, variety selection, irrigation, nitrogen fertilization, pesticide applications, soil and irrigation water salinity, tillage operations, and residue management.

After each growing season, input files required by the CropSyst model for El-Kalubia location and barley crop were prepared and used to run the model. These input files are soil file and weather file for El-Kalubia location and crop management for barley crop in the same location. A few variety-specific parameters were calibrated within a reasonable range of fluctuation set in the CropSyst manual (http://www.bsyse.wsu.edu//CS_Suite). After calibration, the model was validated using the measured data of the yield and consumptive use of the six barley cultivars. To test the goodness of fit between the measured and predicted data, the percent difference between measured and predicted values for each variety in each growing season were calculated, in addition to root mean squared error (RMSE; Jamieson *et al.* 1998) and Willmott index of agreement (WIA; Willmott 1981).

Simulation of the effect of irrigation rescheduling on barley yield and consumptive use

Under the Egyptian conditions, defining a suitable irrigation interval for a certain crop is very important for extension workers, where it will be easy to be conveyed to farmers than a certain irrigation amount. After the calibration and validation processes, a new irrigation schedule was tested, with the intention of saving irrigation water and lowering yield losses. The new schedule was used to reduce the number of irrigations to 4 instead of 5 by increasing the irrigation interval to 30 days instead of 21 days. On the date of each single irrigation, the model was asked to apply enough water to fill the root zone to reduce the chance of water stress occurrence. The amount of applied irrigation water under this schedule was calculated by the model for each cultivar and compared with the measured value in the field.

Water use efficiency

WUE (kg/mm) values for the six barley cultivars were calculated in each growing season under full irrigation and after simulation of the effect of irrigation rescheduling by the following equation (Vites 1965):

WUE = Grain yield (kg/ha)/Consumptive use (mm)

RESULTS AND DISCUSSION

Barley field experiments

The results in **Table 2** imply that some cultivars possessed yield stability traits under both growing seasons. We used the HI value to theoretically test yield stability of each cultivar. Our rationale for doing that is that HI describes the partitioning of the accumulated dry matter by the plant. When the value of HI was similar in both growing seasons it could imply relative yield stability, which could be useful under varying levels of water stress (Guttieri *et al.* 2001). According to that test, 'Giza 126', 'Giza 129' and 'Giza 130' possessed yield stability traits because the HI values in both growing seasons were close to each other. In both

Table 1 Seasonal weather parameters for both growing season at El-Kalubia governorate.

Month	2007/08 growing season			2008/09 growing season		
	TempM (ºC)	RH (%)	SR^a (cal/cm^2/day)	TempM (ºC)	RH (%)	SR^a (cal/cm^2/day)
December	18.7	67	268	17.1	66	268
January	18.0	69	280	17.0	62	280
February	16.2	70	453	17.8	53	453
March	16.2	62	441	18.2	47	441
April	20.8	59	519	21.4	44	519
Average	18.0	56	392	18.3	54	392

TempM = mean temperature; RH = relative humidity; SR = solar radiation.

[a] Estimated from normal (average of 50 years).

Table 2 Barley yields, harvest index and irrigation amount for the six cultivars in both growing seasons.

Variety	**2007/08 growing season**				**2008/09 growing season**			
	GY (ton/ha)	**BY (ton/ha)**	**HI**	**I (mm)**	**GY (ton/ha)**	**BY (ton/ha)**	**HI**	**I (mm)**
Giza 123	3.99	10.67	0.37	328	3.77	9.08	0.41	333
Giza 125	3.76	8.24	0.46	320	2.90	9.32	0.31	326
Giza 126	3.24	7.95	0.41	325	3.13	7.47	0.42	330
Giza 2000	3.63	7.27	0.50	327	3.34	7.16	0.47	333
Giza 129	2.69	9.83	0.27	317	2.48	8.85	0.28	325
Giza 130	2.99	9.23	0.32	318	2.75	8.99	0.31	326

GY = barley grain yield; BY = barley biological yield; HI = harvest index (dimensionless); I = irrigation amount.

Table 3 Measured versus predicted barley grain yield planted in two growing seasons.

Variety	**2007/08 growing season**			**2008/09 growing season**		
	Measured	**Predicted**	**PD %**	**Measured**	**Predicted**	**PD %**
Giza 123	3.99	3.96	0.75	3.77	3.73	0.97
Giza 125	3.76	3.76	0	2.90	2.88	0.62
Giza 126	3.24	3.23	0.23	3.13	3.12	0.32
Giza 2000	3.63	3.61	0.55	3.34	3.33	0.16
Giza 129	2.69	2.65	1.43	2.48	2.48	0
Giza 130	2.99	2.98	0.28	2.75	2.74	0.52
RMSE	0.0451					
WIA	0.9988					

PD% = percent difference between measured and predicted values; RMSE = root mean square error; WIA = Willmot index of agreement.

Table 4 Measured versus predicted barley biological yield planted in two growing seasons.

Variety	**2007/08 growing season**			**2008/09 growing season**		
	Measured	**Predicted**	**%**	**Measured**	**Predicted**	**%**
Giza 123	10.67	10.69	+0.19	9.08	9.05	-0.33
Giza 125	8.24	8.19	-0.61	9.32	9.28	-0.43
Giza 126	7.95	7.88	-0.88	7.47	7.43	-0.54
Giza 2000	7.27	7.23	-0.55	7.16	7.12	-0.56
Giza 129	9.83	9.81	-0.20	8.85	8.86	+0.11
Giza 130	9.23	9.34	+1.19	8.99	8.86	-1.45
RMSE	0.0894					
WIA	0.9789					

PD% = percent difference between measured and predicted values; RMSE = root mean square error; WIA = Willmot index of agreement.

growing seasons, the highest HI was obtained for ‘Giza 2000’ and the lowest for ‘Giza 129’.

Furthermore, the results in **Table 2** indicate that the water requirement for each cultivar was higher in the 2nd growing season compared with the 1st growing season. This could be attributed to a higher temperature which prevailed in the 2nd growing season. The highest grain yield values resulted from the highest amount of applied irrigation water, which was obtained for ‘Giza 123’ in both growing seasons. Similarly, the lowest yield value was obtained for ‘Giza 129’, which was accompanied with the lowest amounts of applied irrigation.

Simulation of barley grain yield

The CropSyst model prediction of barley grain yield was highly accurate (**Table 3**). Overall, for all barley cultivars, the model under-predicted barley grain yield by a small percentage. The percent difference between measured and predicted grain yield for all cultivars was less than 1%, except for ‘Giza 129’ in the 2007/08 growing season, where it was 1.43%. RMSE was also low i.e., 0.0451 kg/ha and the WIA was 0.9988. These results proved that the incorporation of the weather file of El-Kalubia location, in addition to the soil characteristics of the field experiment and barley management practices file in the CropSyst model was appropriate, which reflected on the simulation processes of barley yield and resulted in closeness between measured and predicted values. Other simulation models were used to simulate barley yield at other locations around the world. The APSIM-Barley model simulated barley grain yield with RMSE = 0.0697 and 0.5600 ton/ha at two locations in Australia (Manschadi *et al.* 2006b). Both CERES and SWAP models simulated grain yield of barley well in Austria (Eitzinger *et al.* 2003). Furthermore, the Yield-Stress model predicted barley yield with an RMSE and WIA of 0.0022 and 0.9999, respectively in Egypt (Khalil *et al.* 2007).

Simulation of barley biological yield

The simulation of barley biological yield by the CropSyst model was relatively less accurate than the simulation of grain yield because of the occurrence of over-prediction, although with a low percentage (**Table 4**). The model over-predicted the biological yield for ‘Giza 123’ and ‘Giza 130’ in the 2007/08 growing season and ‘Giza 129’ in the 2008/09 growing season. The HI value was used to calibrate the model for dry matter partitioning between grain and biological yield. However, it was our desire to achieve more accurate prediction of grain yield on behalf of biological yield. As a result, RMSE was higher for biological yield than for grain yield. RMSE was 0.0894 ton/ha and the WIA was 0.9789. APSIM-Barley predicted barley biomass at maturity with RMSE = 0.1082 ton/ha (Manschadi *et al.* 2006b).

Simulation of consumptive use of barley

The CropSyst model provides a choice between two evapotranspiration models i.e. Priestley-Taylor and Penman-Monteith. We chose to use the Priestley-Taylor model to calculate consumptive use of barley because it could be calibrated using the Priestley-Taylor constant, which resulted in more accurate simulation of evapotranspiration under Egyptian conditions, compared with the Penman-Monteith model. The results in **Table 5** showed that the model under-predicted barley consumptive use by less than 1%, excepted for ‘Giza 2000’ in the 2nd growing season and ‘Giza 130’ in the 1st growing season, which was less than 1.5%. Over-prediction also occurred for ‘Giza 129’ in the 1st growing season and for ‘Giza 125’ in the 2nd growing season with a value of < 1%. RMSE was 0.0931 mm and the WIA was 0.9843. Eitzinger *et al.* (2004) stated that CERES,

Table 5 Measured versus predicted barley consumptive use planted in two growing seasons.

Variety	2007/08 growing season			2008/09 growing season		
	Measured	Predicted	%	Measured	Predicted	%
Giza 123	30.96	30.84	-0.39	31.95	31.68	-0.85
Giza 125	29.61	29.77	+0.54	30.60	30.47	-0.42
Giza 126	30.39	30.13	-0.86	31.38	31.13	-0.80
Giza 2000	30.68	30.39	-0.95	31.67	31.32	-1.11
Giza 129	29.34	29.33	-0.03	30.33	30.36	+0.10
Giza 130	29.69	29.33	-1.21	30.68	30.57	-0.36
RMSE	0.0931					
WIA	0.9843					

PD% = percent difference between measured and predicted values; RMSE = root mean square error; WIA = Willmot index of agreement

Table 6 Percent change in grain and biological yield and consumptive use of barley as a result of a new irrigation schedule.

Variety	2007/08 growing season				2008/09 growing season			
	GY %	BY %	CU %	I %	GY %	BY %	CU %	I %
Giza 123	0	+0.19	-0.35	-4	-0.54	+0.33	-0.84	-4
Giza 125	-1.06	-1.82	-0.79	-4	0	-0.54	-0.50	-3
Giza 126	0	-0.88	-0.32	-4	0	-0.54	-1.36	-4
Giza 2000	0	-0.69	-2.55	-5	+0.60	-0.56	-1.61	-4
Giza 129	0	-0.20	-0.03	-3	0	+0.11	-0.55	-3
Giza 130	0	+0.98	-0.07	-3	+0.36	-1.45	-0.55	-3

GY = grain yield; BY = biological yield; CU = consumptive use; I = irrigation amount.

WOFOST and SWAP models simulated soil water content in the soil profile with similar results. Their calculation of RMSE range of soil water content was 0.71–4.67% for barley depending on the model and soil type. Moreover, th Yield-Stress model predicted consumptive use of barley with RMSE and WIA of 0.0488 and 0.9995, respectively (Khalil *et al.* 2007).

Simulation of the effect of irrigation rescheduling on barley yield and consumptive use

The response of the of the six barley cultivars to irrigation rescheduling in both growing seasons was different in terms of an increase or decrease in grain and biological yield (**Table 6**). The proposed irrigation reschedule saved an average of 4% of irrigation water in the 1st growing season. That saved amount did not reduce grain yield of all barley cultivars, except for 'Giza 125', where the reduction was 1.06%. Biological yield responded differently, where it was deceased by < 1% for 'Giza 126', 'Giza 2000' and 'Giza 129'. Reduction in biological yield of these cultivars compared with no reduction of grain yield could be explained by the complete depletion of soil moisture in the root zone that might occur during vegetative growth and not during the grain-filling stage, which reflected on barley above-ground biomass. A different response of biological yield was observed for 'Giza 123' and 'Giza 130', where it increased by < 1%, although grain yield was not affected. However, the reduction in biomass was relatively low, which did not affect grain yield. Regarding 'Giza 125', reduction in grain yield by 1.06% accompanied with a reduction in biological yield by 1.82%, which implied that when the reduction in biological yield exceeded 1%, it could negatively affect the final yield. For all barley cultivars, consumptive use was decreased by low percentage in the 1st growing season, except for 'Giza 2000' where the reduction was 2.55% and the saving in the applied irrigation water was 5%.

Regarding the 2nd growing season, the results in **Table 6** indicate that all 6 cultivars responded differently to an average of 3% saving in the applied irrigation water, compared with the 1st growing season, particularly for grain and biological yield. With respect to consumptive use, a similar trend was observed with a higher percentage of reduction. These inconsistencies in the response of these cultivars in their capacity to reduce the amount of applied irrigation water suggest a complicated genotype × environment interaction. These results imply that although barley cultivars are sufficiently irrigated, they can tolerate low levels of water stress. Thus, rescheduling irrigation was found to be a way to save irrigation water in barley. This result is supported by the finding of Khalil *et al.* (2007) when rescheduling irrigation was used to save irrigation water and reduce barley yield losses by skipping the last irrigation.

Furthermore, the effect of saving a fixed irrigation percentage in both growing seasons on grain yield of the 6 cultivars was considered as an indication of yield stability. Following this assumption, 'Giza 123', 'Giza 126', 'Giza 129' and 'Giza 130' were candidates, where the percentage of saved irrigation water was the same in both growing seasons and the yield was not reduced as a result of that saving (**Table 6**).

Water use efficiency

Under sufficient irrigation application (actual schedule) WUE was higher in the 1st growing season than in the 2nd growing season (**Table 7**) as a result of better weather conditions during the 1st growing season (**Table 1**). A higher mean temperature and low relative humidity in the 2nd growing season caused stressful conditions for the growing plants and resulted in relatively lower grain and biological yield and applied irrigation amounts (**Table 2**) and higher consumptive use (**Table 5**). The results in **Table 7** also show differences between barley cultivars in WUE under the actual irrigation schedule. These differences in WUE were mostly related to the differences in transpiration efficiency i.e. biomass produced per unit transpiration, in addition to slow canopy development, which could increase soil evaporation (Thoma and Fukai 1995).

The proposed irrigation schedule increased WUE of the 6 barley cultivars in both growing seasons, which resulted in less amounts of irrigation being applied to obtain similar yield to what was obtained under measured irrigation amount in the field (**Table 6**). Under both irrigation schedules, the highest WUE was found for 'Giza 123' and the lowest for 'Giza 129' in both growing seasons.

Moreover, we used WUE to test the yield stability of the three cultivars that we concluded they possess yield stability i.e. 'Giza 126', 'Giza 129' and 'Giza 130' (**Table 2**). The results in **Table 7** support this assumption for 'Giza 126' and refuted it for the other two cultivars. The WUE value for 'Giza 126' was similar in both growing seasons and under both irrigation schedules. On the contrary, the WUE values for 'Giza 123', 'Giza 129' and 'Giza 130' in both growing seasons and under both irrigation schedules were different. Such dissimilarity demonstrates that other traits, other than HI, should be identity to theoretically test

Table 7 Water use efficiency (kg/mm) of barley cultivars under actual irrigation schedule and the proposed irrigation schedule.

Variety	2007/08 growing season		2008/09 growing season	
	Actual schedule	Proposed schedule	Actual schedule	Proposed schedule
Giza 123	11.98	12.33	11.50	11.77
Giza 125	11.55	11.89	9.06	9.32
Giza 126	9.80	10.17	9.64	10.00
Giza 2000	10.92	11.44	10.20	10.67
Giza 129	8.28	8.45	7.82	8.09
Giza 130	9.17	9.48	8.68	8.97

the stability of cultivar yield. Thus, WUE could also be another indicator for yield stability.

CONCLUSION

Expressive information on the effect of irrigation rescheduling on barley productivity could be very useful in determining yield losses for economical purposes. Thus, using simulation models to attain that could be the ultimate solution. A good agreement between measured and predicted barley yield and consumptive use values implied that the CropSyst model is capable of investigating radical alternatives of irrigation water to increase WUE and reduce yield losses to a minimal.

Stability of grain yield performance is an important characteristic under adverse growth conditions, such as water stress or heat stress. Two parameters were used to test that stability i.e. HI and WUE. Using HI 'Giza 126', 'Giza 129' and 'Giza 130' were characterized by similar values in both growing seasons. Furthermore, the yield of these 3 cultivars, in addition to 'Giza 123' was not reduced under irrigation rescheduling and the amount of saved irrigation water was similar under both growing seasons. However, the value of WUE under actual irrigation and under simulation of irrigation rescheduling was similar in both growing seasons for only 'Giza 126'. Thus, based on the comparative results between the 6 barley cultivars, it could be concluded that 'Giza 126' possesses yield stability traits. Further testing for that cultivar is needed under field conditions.

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