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Calibration of the DSSAT-CERES Wheat Crop Model under Scenarios of Climate Change Adaptation and Biotic Stress

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

A field experiment was conducted during the 2018/2019 wheat growing season in Kafr El-Sheikh Governorate. This is to assess the potential impact of climate change on wheat production under different irrigation treatments using the DSSAT-CERES wheat simulation model and climate change scenarios; to determine the best sowing date to be used as an adaptation strategy under climate change scenarios.

The model effectively simulates wheat yield, with a high goodness of fit and d-Stat value, and low root mean square per observation, resulting in an overall goodness of fit of average 13.8 kg/fed. The model's performance was satisfactory, with high R^2 and d-Stat values and low RMSE/obs, with

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overall values of 0.830, 0.951, and 2.3 mm, respectively for water consumption. The CERES-Wheat model accurately simulates wheat yield and water consumption, allowing us to assess climate change's impact on wheat yield in 2030 and 2040. The study shows a decrease in solar radiation (SR) by 1.9 and 2.1 MJ/m^2/day in 2030 and 2040, while maximum temperature increases by 1.5 and 1.9°C due to climate change, and minimum temperature decreases by 1.8 and 2.3°C in 2030 and 2040. This results in an increase in potential evapotranspiration (PET) by 0.2 and 0.3 mm. The study predicts that season length will shorten in 2030 and 2040 due to temperature increases. In 2030, it will be reduced by 2, 4, and 4 days under different treatments. In 2040, it will be lower, with reductions of 3, 5, and 5 days. The study found that wheat yield losses would be lowest under the first sowing date and irrigation treatment, while the highest reductions were found under the third treatment. Climate change will reduce wheat water consumption due to shorter growing seasons and heat stress, with the lowest reductions occurring in 2030 and 2040 at 8 and 18%, respectively. The highest reductions in wheat yield were observed under the third sowing date and irrigation treatment. We suggest planting wheat in November, using full irrigation to prevent high-yield losses, and implementing adaptation strategies to reduce wheat plant vulnerability to climate change risks.

Keywords: DSSAT-CERES wheat model; water consumption; planting dates; climate change scenarios; adaptation; biotic stress.

1. INTRODUCTION

A software program called the Decision Support System for Agrotechnology Transfer (DSSAT) mimics the growth and development of crops. One of the crop models in DSSAT is the CERES-Wheat model. In a variety of conditions, the CERES-Wheat model has been used to simulate wheat growth and development [1]. A significant source of energy for the human diet, wheat is a key cereal crop grown all over the world [2]. Arid and semi-arid regions irrigate wheat to a 90% degree. Climate change has the greatest impact on wheat in rainfed regions. Every year, 2.85 billion dollars' worth of wheat are lost due to decreased production due to climate change in Australia and Mexico [3]. Due to climate change and an increase in carbon dioxide levels, it is predicted that by 2050, food consumption will have doubled, with production yields declining [4]. The effects of global warming on plants, diseases, insects, and pests are extremely detrimental [4]. Climate change is likely to increase the spread potential of wheat stem rust, a significant crop disease, due to warmer temperatures and reduced humidity [5]. Understanding the potential impacts of climate change is very important in developing both adaptation strategies and actions to reduce climate change risks [6]. A range of valuable national studies have been carried out and published. However, assessing the impact of climate change is a challenge for scientists and it needs collaboration of multidiscipline [7]. Unfortunately, the limitation in the information regarding to past and future climate change and its impacts on crops reduce the ability of policy makers in Egypt to adjust their future plans to cope with the future [8]. Crop production is affected biophysically by changing meteorological variables, including rising temperatures, changing precipitation regimes and increasing levels of atmospheric carbon dioxide [9]. Changes in yield behavior in relation to shifts in climate can become critical for the economy of farmers. An increasing probability of low returns as a consequence of more frequent occurrence of adverse conditions could prove dramatic for farmers operating at the limit of economic stress [10]. To estimate future climate change, scientists have developed greenhouse gas and aerosol emission scenarios for the 21st century. These are not predictions of what will actually happen. They allow analysis of “what if?” questions based on various assumptions about human behavior, economic growth and technological change [11]. Computer models of the climate system are the best tools available for simulating climate variability and change. These models are called General Circulation Models (GCMs). These types of GCM are a mathematical representation of the general circulation of a planetary atmosphere (AGCM) or the ocean (OGCM) and it was used to develop climate change scenarios. As stated by [12], the output of GCM was not generally of a sufficient resolution or reliability to estimate regional climate even in the present. To solve this problem and to develop climate change scenarios, baseline observational data was used to represent the present-day climate, and then adjusted to represent the 2XCO_2 climates [13].

These obtained values are then, added to the current weather file to develop a climate change scenario. These types of models are generally susceptible to simple analysis and their results are generally easy to understand, which endure less accuracy [14]. Atmospheric and Oceanic GCMs (AGCM and OGCM) are key components of Global Climate Models along with sea-ice and land-surface components. These models include representations of the atmosphere, oceans, biosphere and Polar Regions [15]. Confidence in the reliability of these models for climate projections has also improved [16], based on tests of the ability to simulate the present average climate, including the annual cycle of seasonal changes, year-to-year variability, extreme events, such as storms and heat waves, climates from thousands of years ago, and observed climate trends in the recent past. Atmospheric and Oceanic General Circulation Models (AOGCMs) represent the pinnacle of complexity in climate models and internalize as many processes as possible. They are the only tools that could provide detailed regional predictions of future climate change. The way a climate model responds to changes in external forcing, such as an increase in anthropogenic greenhouse gases, is characterized by two standard measures: (1) ‘equilibrium climate sensitivity’ (the equilibrium change in global surface temperature following a doubling of the atmospheric equivalent CO_2 concentration), and (2) ‘transient climate response’ (the change in global surface temperature in a global coupled climate model in a 1% per year CO_2 increase experiment at the time of atmospheric CO_2 doubling. The first measure provides an indication of feedback mainly residing in the atmospheric model but also in the land surface and sea-ice components, and the latter quantifies the response of the fully coupled climate system including aspects of transient ocean heat uptake [17]. These two measures have become standard for quantifying how an AOGCM will react to more complicated forcing in scenario simulations [18].

1.1 Simulation of the Effect of Climate Change on Wheat Productivity

In Egypt, many studies predicted the implications of climate change on the yield of several crops and raised sensible anxiety about the threat of climate change to sustainable development. [19] revaluated the potential impact of climate change on wheat production in Egypt by simulating crop production under different climatic scenarios in the three main agricultural regions (Delta, Middle and Upper Egypt). Crop seasonal ET changes were estimated. Under GCM climate change scenarios, yield of wheat decreased in comparison to current climate conditions, even when crop was benefited from the direct CO_2 effects. [20], studied the potential impact of climate change on field crop water needs. CERES-WHEAT (DSSAT3 model) was used to predict yields and ET for wheat using GISS, GFDL and UKMO climate change scenarios. The results indicated that climate change will negatively affect wheat crop yield and ET. Future adaptation strategies to climate change may involve the development of new and more heat-tolerant cultivars. Modification of cropping pattern, by reducing the current area under cultivation with some high-water consumer crops (i.e. sugar cane and rice crops) and/or, keeping on the current area of sugar cane and altering the needed expansion with new similar crop (i.e. sugar beet). [21] investigated the impact of climate change on wheat production using Sirius model. The effects of different concentrations of CO_2, i.e. 380, 420, 460, 500, 540, 580 and 620 ppm and the increasing rate of average annual air temperature by 1.5, 3.0, 4.5 and 6 °C were studied. The obtained results showed that the increasing of CO_2 lead to increase the yield of wheat, while the increasing the temperature had a negative effect on the wheat production. The increase of wheat production as a result of increasing CO_2 was less than the reduction rate in wheat yield, as a result of increasing temperature. [22] Studied the effect of climate change on the yield of three wheat varieties (Sids1, Sakha 93 and Giza 168) grown under surface irrigation in clay soil was studied using A2 and B2 climate change scenarios. The effect of two early sowing dates on wheat yield was simulated and used as adaptation options, i.e. 1st of November and 21st of October to reduce the harm effect of climate change and a new irrigation schedule was used. The results revealed that for both climate change scenarios, Sakha 93 variety was found to be more tolerant to heat stress, where yield losses were 45 and 38% under A2 and B2 scenarios, respectively. The results also showed that wheat yield improvement and irrigation water saving could be attained using the proposed adaptation strategies. Under cultivation in November, 1st, a slight improvement in yield losses could be achieved with a slight increase in the amount of applied irrigation water. Whereas, under sowing in October, 21st, a decrease in yield losses could be achieved with a decrease in the amount of applied irrigation water.

[23] Indicated that wheat cultivar. Sakha 93 was used to compare between the effect of farmer's application of field chemicals (broadcasting fertilizers, insecticide and herbicide on the soil) and chemigation (application all field chemical via irrigation water) on yield losses under climate change. Moreover, the effect of the interaction between each treatment and two early sowing dates was simulated to develop effective adaptation strategy to reduce climate change risk on wheat yield grown in sandy soil. The results showed that under the two climate change scenarios, wheat grain was reduced by average of 30% under farmer irrigation and by an average of 25% when chemigation. The results also revealed that sowing wheat one week earlier under chemigation treatment improved wheat yield by an average of 6 and 5% under A2 and B2 scenarios, respectively.

[24] Studied the effect of using improved agricultural management practices, i.e. fertigation on wheat cultivar Sakha 93 grown in sandy soil. The aim of these experiments was to determine whether these practices will reduce the vulnerability of wheat to the aboitic stress of climate change. Eight fertigation treatments (interaction between irrigation with 0.6, 0.8, 1.0 and 1.2 of ETc and fertigation application in 60 and 80% of irrigation time), in addition to farmer irrigation were tested. The results showed that the highest yield reduction, i.e. 39 and 37% was obtained under A2 and B2 climate change scenarios, respectively for farmer irrigation. The lowest yield reduction was obtained under irrigation with 1.0 of ETc and fertigation application in 80% of irrigation time, i.e. 27 and 24% under A2 and B2 climate change scenarios, respectively. [25] Simulated the effect of climate change on four wheat cultivars, i.e. Sakha 94, Sakha 93, Giza 168 and Gemmiza 9 grown under three sowing dates: 9th of November, 24th of November and 8th of December. Wheat was grown under sprinkler irrigation in four irrigation treatments, i.e. irrigation with 0.6, 0.8, 1.0 and 1.2 of ETc. The results showed that the highest reduction in wheat yield was obtained under A2 climate change scenario for all cultivars and under the three sowing dates. The results also revealed that irrigation with 0.6 of ETc gave the highest yield reduction and irrigation with 1.2 of ETc gave the lowest yield reduction for all the cultivars and under both climate change scenarios. Furthermore, yield losses of the four cultivars were lower when wheat was planted in the 24th of November, compared with the other two sowing dates. Sakha 93 was found to be more tolerant to the aboitic stress of climate change, compared with the three other cultivars under the two climate change scenarios. The reduction in its yield, when it planted on the 24th of November, was 21 and 18% under A2 and B2 climate change scenarios, respectively. [20] conducted field experiments at three different agroclimatic locations (Sakha, Sids and Shandaweel) at winter season of 2009/2010 to study the effects of two sowing dates and three irrigation levels (60, 80 and 100% of the full water requirements) on grain yield and its attributes of four bread wheat cultivars (Gemmeiza 9, Giza 168, Sakha 93 and Misr 1). Experimental conditions and results obtained from those locations were used as a database for calibration of CERES-Wheat model under DSSAT4.5 package to study the sensitivity of climate change on wheat growth and yield. Two climate change scenarios have been employed with changes in temperature. The first scenario supposed that increasing in temperature of 1.5°C would happen, and the second scenario supposed that increasing of 3.5°C would happen. The results showed that the future impacts of climate change on wheat showed that increasing in temperature will reduce length of growing cycle and the time needed to full tillering in addition to the final yield. This subsequently will reduce the amount of grain yield; accelerate time for maturity and harvesting. For +1.5°C scenario, reduction in grain yield, as predicted by the model, will be in average among cultivars of 12% at Sakha location, 9% at Sids location and 11% at Shandaweel location. Scenario of +3.5°C will reduce grain yield within an average of 27% at both Sakha, Sids locations, and 31% at Shandaweel location. [26] Conducted experiments to simulate the effect of using improved agricultural management practices to reduce wheat yield losses under climate change using CropSyst model. Three irrigation treatments were used, i.e. farmer irrigation (characterized by large applied irrigation amount), required irrigation amount for wheat and irrigation amount applied for raised bed cultivation. The cultivated cultivar was Sakha 93. The results indicated that farmer irrigation increase wheat vulnerability to climate change, where the average value of yield losses was between 44-50% under A2 climate change, and between 41-46% under B2 climate change scenario average over the two seasons, with the lowest water productivity. Lower yield losses,

compared with farmer irrigation, were obtained when wheat was irrigated by required amount in both growing seasons. Furthermore, raised bed irrigation amount resulted in even lower yield losses, with the highest water productivity as a result of better growing environment for wheat plants. [27] Used CropSyst model to simulate wheat grain yield by using field experimental data under A2 and B2 climate change scenarios. Two wheat cultivars, i.e. Giza 168 and Sakha 93 were grown in clay soil under surface irrigation. Under each climate change scenario, the effect of four sowing dates, four irrigations schedules and the interaction between them was simulated. Sakha 93 was found to be more tolerant to climate change than Giza 168, where its yield losses were 35 and 41% under A2 and B2, respectively. The best adaptation strategy under A2 and B2 climate change scenario was sowing wheat in the 1st week of November and applying second irrigation four weeks after sowing and then every 30 days.

[28] Studied the impact, vulnerability and adaptation of climate change on wheat production and water requirements in North delta of Egypt. CERES-wheat model embedded in the Decision Support System for Agrotechnology Transfer (DSSAT4.5) model was used for the crop simulation with current and possible future management practices. Impacts on crop productivity were assessed according to future conditions derived from GCMs/MAGICC/SCENGEN scenarios. The results revealed that, the two considered climate change scenarios resulted in decrease in wheat yield. At the same time, water consumptive use increased as a result of increasing temperature compared to the current water consumptive use. On the other hand, results of adaptation options indicated that planting Giza-168 cultivar and sowing between 10th-20th of December in North delta (Sakha) is recommended to reduce unfavorable effects of climate change on wheat production under climate future. Also, adding 400 mm/season as irrigation water quantity could be recommended as a way to conserve irrigation water without clear reduction in wheat yield. [29] Evaluated the performance of four bread wheat cultivars (Misr-1, Sakha-93, Giza-168 and Gemmeiza-9) sown in three sowing dates (15th October, 15th November,15th December) under the metrological conditions of North Sinai. Results obtained from experimental field studies were used as indicators to test the performance of DSSAT-CSM (Cropping System Model) Ver. 4.5.1.023. Calibration and validation of applying CERES-Wheat model was done through using d-Stat index of agreement between simulated and observed values. The output data from the CERES-Wheat model showed that Gemmeiza-9 cultivar recorded the highest observed grain yield in the 1st and 2nd seasons (5352 and 5928 kg/ha, respectively) and highest predicted grain yield (3957 and 4619 kg/ha, respectively) in mediate sowing date (mid-November) as compared to other wheat cultivars Misr-1, Sakha-93 and Giza-168.

2. MATERIALS AND METHODS

2.1 The DSSAT Model

The Decision Support System for Agrotechnology Transfer (DSSAT) is a software application program that comprises crop simulation models for over 18 crops, as of Version 4.5 (DSSAT.net, 2012) [30]. The choice of such model was because of its ability to simulate growth, development, and yield of several crops. CERES-Wheat model [31] is a simulation model for wheat in the DSSAT package that describes daily phenological development and growth in response to environmental factors (soils, weather and management). Experimental conditions and results obtained from it were used as a database for calibration and validation of CERES-Wheat model through DSSAT 4.5 software to simulate and predict wheat yield. The comparison between measured and predicted data were done through CERES-Wheat model under DSSAT interface in three steps, retrieval data (converting data to CERES-Wheat model), and validation data (comparing between predicted and observed data) and run the DSSAT model provides validation of the crop models that allows users to compare simulated outcomes with observed results. More details about DSSAT model are included in [32].

2.2 Goodness of Fit Test between Measured and Predicted Values

Calibration and validation of applying CERES-Wheat model was done through using goodness of fit test between measured and simulated values as follows:

2.2.1 Willmott index of agreement (d-stat)

It is the standardized measure of the degree of model prediction error which varies between 0 and 1. A value of 1 indicates a perfect match, and value of 0 indicates no agreement at all [33].

$$\mathrm{d-stat} = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}[(|(S_i - \bar{O})|+|(O_i - \bar{O})|)^2]} \qquad (1)$$

Where Oi, $\bar{O}$ and Si represent the observed, observed average and simulated values.

2.2.2 Coefficient of determination (R^2)

R^2 tells us how much better we can do in predicting observation by using the model and computing the simulation by just using the mean observation as a predictor [34].

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad (2)$$

R^2 ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable [35].

2.2.3 Root mean square error per observation (RMSE/obs)

It gives the general standard deviation of the model prediction error per observation [34].

$$RMSE/obs = \sqrt{\left(\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}\right)} \qquad (3)$$

Where n represents the number of observed and simulated values used in comparison.

2.3 Climate Change Model

ECHAM5 model [36] is a global climate change model with 1.9 X 1.9° resolution. The model has been developed from the ECMWF operational forecast model cycle 36 (1989) (therefore the first part of its name: EC) and a comprehensive parameterization package developed at Hamburg (therefore the abbreviation HAM). The part describing the dynamics of ECHAM is based on the ECMWF documentation, which has been modified to describe the newly implemented features and the changes necessary for climate experiments. Since the release of the previous version, ECHAM4, the whole source code has been extensively redesigned in the major infrastructure and transferred to FORTRAN 95. ECHAM is now fully portable and runs on all major high-performance platforms. The restart mechanism is implemented on top of net CDF and because of that it absolutely independent on the underlying architecture [36]. This model is included in the following website: http://www.ccafs.cgiar.org/marksimgcm#.Ujh1gj-GfMY.

2.3.1 Climate change scenarios

ECHAM5 model was used to develop A1B climate change scenario for the selected site. [18] Describes the A1 storyline and scenario family as a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. One of its family is A1B, where its technological balance across all sources (balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies). The downloaded scenario was for the years 2030 and 2040 and composed of maximum and minimum temperature, rain and solar radiation.

3. RESULTS AND DISCUSSION

3.1 Calibration of DSSAT Model

3.1.1 Wheat yield calibration

The model was calibrated for seed yield and water consumptive use under the three sowing dates and three irrigation treatments. Table 1 revealed that the performance of the model was highly acceptable in simulating wheat yield. The goodness of fit test showed that R^2 was over 0.75 for each of sowing date with overall value equal to 0.646. Regarding to d-Stat value, it was also acceptable, with overall value equal to 0.833. Root mean square per observation (RMSE/obs) was low, i.e. 26.8, 31.5 and 34.4 kg/fed for D1, D2 and D3 respectively. The overall value was 13.8 kg/fed.

3.1.2 Water consumption use calibration

Similarly, the model performance was acceptable, where R^2 and d-Stat was high and RMSE/obs was low. The overall value for R^2, d-Stat and RMSE/obs was 0.830, 0.951 and 2.3 mm, respectively (Table 2).

Table 1. Measured versus predicted wheat yield (kg/fed) and goodness of fit test

Sowing date	Irrigation treatment	Measured yield	Predicted yield	R^2	d-Stat	RMSE/ obs	Observation
D1	I1	2861	2862	0.819	0.836	26.8	3
	I2	2523	2632				
	I3	2320	1886				
D2	I1	2434	2609	0.753	0.632	31.5	3
	I2	2345	2792				
	I3	2150	1949				
D3	I1	2258	2441	0.933	0.768	34.4	3
	I2	2072	2136				
	I3	1941	1589				
Overall values				0.646	0.833	13.8	9

Table 2. Measured versus predicted yield water consumptive use (mm) and goodness of fit test

Sowing date	Irrigation treatments	Measured WCU	Predicted WCU	R^2	d-Stat	RMSE/ obs	Observation
D1	I1	435	435	0.865	0.949	2.0	3
	I2	386	410				
	I3	349	329				
D2	I1	428	420	0.846	0.941	2.3	3
	I2	374	406				
	I3	325	332				
D3	I1	419	405	0.850	0.952	2.3	3
	I2	352	368				
	I3	325	303				
Overall values				0.830	0.951	2.3	9

The above results implied that CERES-Wheat model imbibed in DSSAT model was capable of simulating wheat yield and water consumptive use with high degree of accuracy as it was shown by the goodness of fit test. Therefore, we proceeded with assessment of the effect of climate change on wheat yield in 2030 and 2040.

3.2 Assessment of the Effect of Climate Change

3.2.1 Variability of climate annual values in 2030 and 2040

The comparison of the annual values of weather elements in 2018, 2030, and 2040, as shown in Table 3, revealed that solar radiation (SR) is expected to decrease by 1.9 and 2.1 MJ/m^2/day in 2030 and 2040, respectively. This decrease can be attributed to the increased emission of greenhouse gases, which will scatter the solar radiation and also increase aerosol and cloud amounts [37]. On the other hand, a different trend was observed for the maximum temperature (MaxT), which is projected to increase by 1.5 and 1.9°C in 2030 and 2040, respectively. This increase can be attributed to the greenhouse effect that will dominate under climate change. In contrast, the value of the minimum temperature is expected to decrease by 1.8 and 2.3°C in 2030 and 2040, respectively, compared to the value in 2018. Consequently, the potential evapotranspiration (PET) is expected to increase by 0.2 and 0.3 mm in 2030 and 2040, respectively.

3.2.2 Comparison between monthly averages data in 2014, 2030 and 2040

Fig. 1 showed that in, 2030 and 2040, the monthly values of solar radiation will be lower than its counterpart in 2018. It is also noticed from the Figure that the highest reduction in the solar radiation in both 2030 and 2040 will be from April to July.

Fig. 2 indicated that maximum temperature will be higher in all months of 2030 and 2040, compared to 2018. Furthermore, the increase will be higher in summer months, compared to winter months.

Fig. 3 showed that minimum temperature will be lower in 2030 and 2040, compared to 2018.

Table 3. Change in the values of weather elements and potential evapotranspiration in 2030 and 2040

	SR	MaxT	MinT	PET
2030	-1.9	+1.6	-1.8	+0.2
2040	-2.1	+2.2	-2.3	+0.3

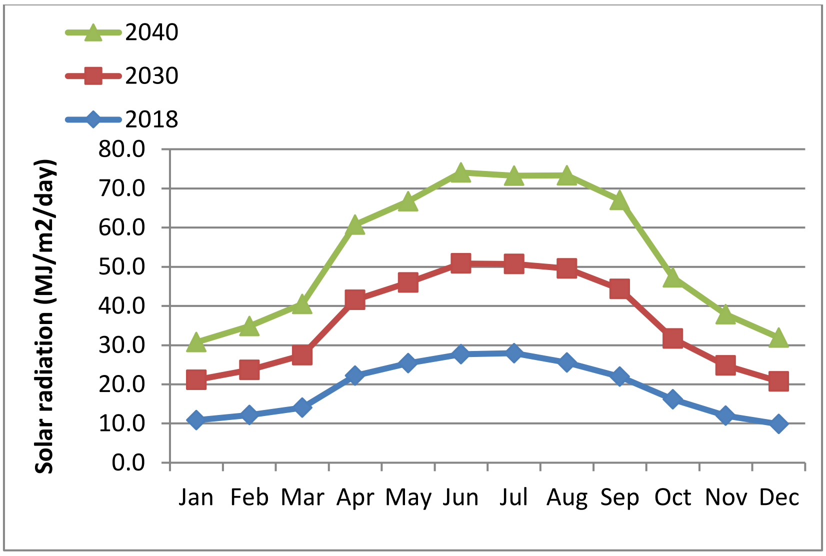

Fig. 1. Comparison between solar radiation in 2018, 2030 and 2040

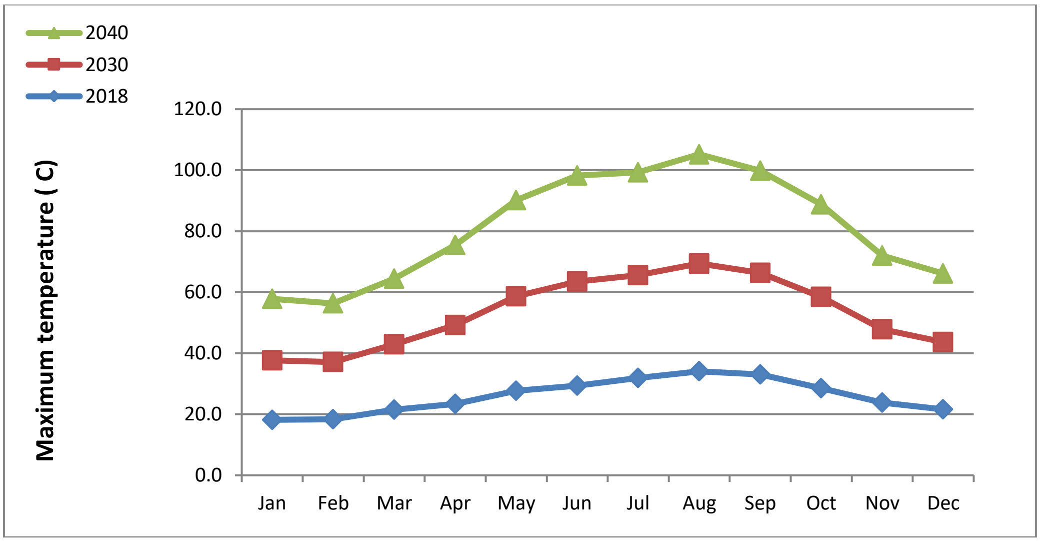

Fig. 2. Comparison between maximum and minimum temperatures in 2018, 2030 and 2040

In 2030 and 2040, monthly potential evapotranspiration will be higher than its counterpart in 2018 (Fig. 4).

3.2.3 Effect of climate change on wheat season length

In both 2030 and 2040, season length is expected to be shortened as a result of the increase in temperature. In 2030, season length will be reduced by 2, 4, 4 days under D1, D2 and D3, respectively. Furthermore, in 2040, season length will be lower, compared to season length in the field experiment. The reduction will be 3, 5 and 5 days under D1, D2 and D3, respectively (Table 4). [38] stated that wheat growing season under climate change scenario was reduced, compared to the current situation. They also stated that possible reasons were the increase in temperature rate and the accelerated growth stages of wheat.

3.2.4 Effect of climate change on wheat yield

The findings in Table 5 indicate that when the first sowing date and the first irrigation treatment are employed, the decrease in wheat yield will be the least in both 2030 and 2040, which amounts to 5% and 10% respectively. On the other hand, the greatest reduction in wheat yield was observed when the third sowing date and the third irrigation treatment were applied, resulting in a decrease of 36% and 37% in 2030 and 2040 respectively. The decline in yield due to climate change can be attributed to a shorter growing season and the negative impact of heat stress. Climate change will disrupt the optimal growing conditions for wheat, leading to abiotic stressors such as heat and water scarcity. Subjecting wheat plants to excessive moisture stress reduces their seasonal water consumption and grain yield [39]. During the vegetative growth phase, wheat experiences a decrease in the time interval between leaf appearances under water stress [40], resulting in smaller leaves that can potentially reduce the leaf area index [41] and the number of reproductive tillers, consequently limiting their contribution to grain yield [42]. Moreover, wheat is highly susceptible to high temperatures [43]. The impact of heat stress on wheat varies depending on the phenological stage, with the reproductive phase being more

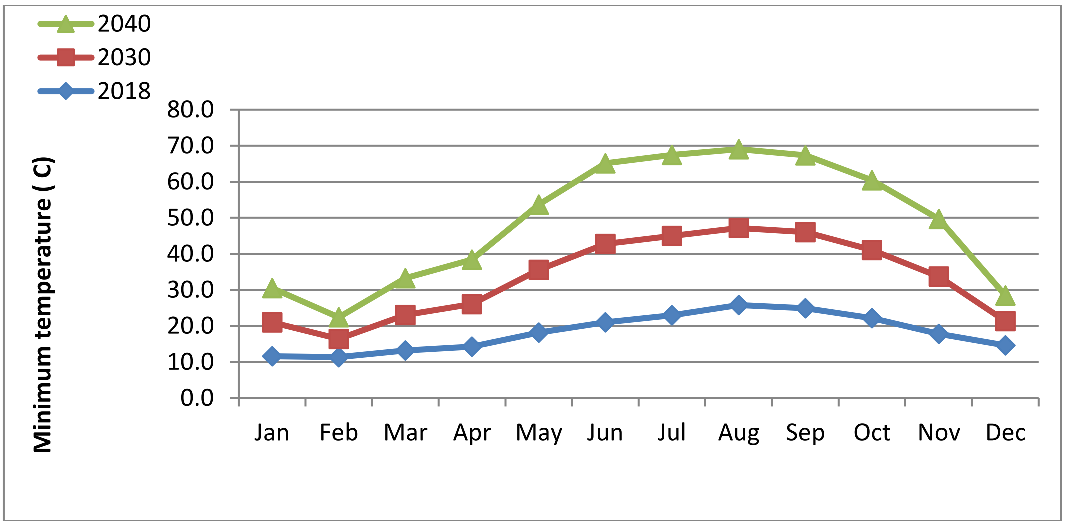

Fig. 3. Comparison between minimum temperature in 2018, 2030 and 2040

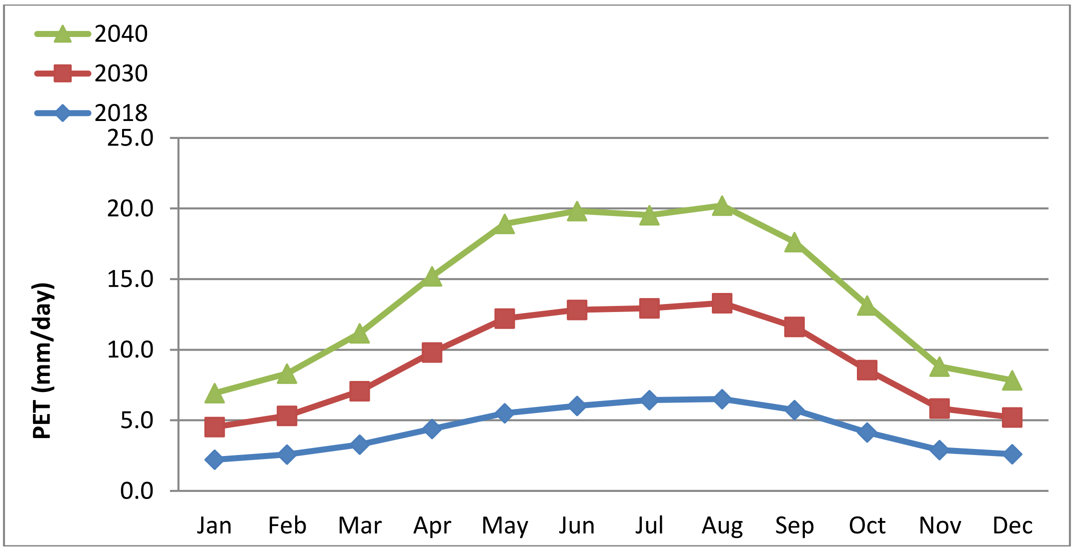

Fig. 4. Comparison between potential evapotranspiration in 2018, 2030 and 2040

Table 4. Effect of climate change on wheat season length (day) under different sowing dates and irrigation treatments

Sowing date	Irrigation treatments	2030			2040		
		Measured	Predicted	Reduction	Measured	Predicted	Reduction
D1	I1	161	160	2	161	159	3
	I2	161	160	2	161	159	3
	I3	161	160	2	161	159	3
D2	I1	156	152	4	156	151	5
	I2	156	152	4	156	151	5
	I3	156	152	4	156	151	5
D3	I1	149	145	4	149	144	5
	I2	149	145	4	149	144	5
	I3	149	145	4	149	144	5

Table 5. Percentage of reduction in wheat yield in 2030 and 2040 under different sowing dates and irrigation treatments

Sowing date	Irrigation treatments	2030			2040		
		Measured	Predicted	Reduction	Measured	Predicted	Reduction
D1	I1	2861	2717	5	2861	2569	10
	I2	2523	2155	15	2523	1764	30
	I3	2320	1760	24	2320	1485	36
D2	I1	2434	1985	18	2434	1836	25
	I2	2345	1800	23	2345	1706	27
	I3	2150	1397	35	2150	1374	36
D3	I1	2258	1743	23	2258	1831	19
	I2	2072	1571	24	2072	1626	22
	I3	1941	1245	36	1941	1231	37

detrimental due to its direct effect on grain number and dry weight [44]. A study by [45] revealed that wheat yield losses in Kafr El-Shiekh due to climate change ranged from 12% to 27%.

3.2.5 Effect of climate change on water consumptive use

As a consequence, the use of water for wheat cultivation will decrease due to the changing climate, resulting in a shorter growing season and a smaller amount of above ground biomass due to heat stress. Therefore, the least amount of reduction in water consumption will occur in 2030 and 2040, specifically 8% and 18% respectively. The greatest decrease in wheat yield was observed when the third sowing date and the third irrigation treatment were applied, with reductions of 23% and 26% in 2030 and 2040 respectively according to Table 6.

Table 6. Percentage of reduction in water consumptive use in 2030 and 2040 under different sowing dates and irrigation treatments

Sowing date	Irrigation treatments	2030			2040		
		Measured	Predicted	Reduction	Measured	Predicted	Reduction
D1	I1	435	399	8	435	355	18
	I2	386	329	15	386	303	22
	I3	349	289	17	349	259	26
D2	I1	428	337	21	428	323	25
	I2	374	311	17	374	289	23
	I3	325	255	22	325	241	26
D3	I1	419	349	17	419	331	21
	I2	352	312	11	352	294	16
	I3	325	250	23	325	239	26

4. CONCLUSION

The utilization of simulation models can facilitate the examination of events that have not been tested in real-world scenarios. Consequently, simulation models are the sole instrument capable of evaluating the impact of climate change on crop production. The outcomes presented in this section have demonstrated that the CERES-Wheat model effectively represents the field experiment that was conducted, as evidenced by the high level of agreement between the measured and predicted values of wheat yield and water consumptive use, as determined by the goodness of fit test.

Additionally, the findings have revealed that, under the conditions of climate change in 2030 and 2040, there will be a decrease in the length of the wheat growing season, consequently leading to a reduction in dry matter accumulation. Moreover, the results have indicated that wheat yield will be diminished due to the combination of a shorter growing season and the detrimental effects of heat stress during this period. Furthermore, a decline in water consumptive use will occur as a consequence of the decrease in above-ground biomass and plant size, which is attributable to the presence of heat stress.

Hence, we strongly recommend cultivating wheat during the second week of November and implementing full irrigation practices in order to mitigate the substantial losses in yield. Furthermore, it is imperative to undertake adaptation strategies that aim to decrease the vulnerability of wheat plants to the various risks posed by climate change [46].

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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