Impacts of rising temperature, carbon dioxide concentrations and sea-level on wheat production on the North Nile Delta

ABSTRACT

Climate change poses a serious threat to arid and low-elevation coastal zones. Kafrelsheikh Governorate, as a large agricultural and coastal region on the Egyptian North Nile Delta, is one of the most vulnerable areas to higher temperature and global sea-level rise. Two DSSAT wheat models (CERES and N-Wheat) were calibrated using a local cultivar (Misr3) grown under irrigated conditions in Egypt. Experimental data of two successive growing seasons during 2014/2015 and 2015/2016 were used for calibration using different treatments of irrigation, planting dates and fertilization. Both models simulated the phenology and wheat yield well, with root mean square deviation of <10%, and d-index >0.80. Climate change sensitivity analysis showed that rising temperature by 1 °C to 4 °C decreased wheat yield by 17.6%. However, elevated atmospheric CO₂ concentrations increased yield and could compensate for some of the negative temperature responses. Sea-level rise by 2.0 m will reduce the extent of agricultural land on the North Nile Delta of Egypt by ~60% and would create additional challenges to wheat production in this region.

Keywords: DSSAT, CERES, N-Wheat, food security, climate change

*Correspondence should be addressed to Ahmed Mohammed Saad Kheir; Soils, Water and Environment Research Institute, Agricultural Research Center, 9 Cairo University Street, Giza, Egypt Tel:00201011276536; Fax: 0020473224458; (drahmedkheir2015@gmail.com).

1. Introduction

Egypt's climate is predominantly arid, with low precipitation of <130 mm per year. The River Nile is the main source of irrigation water. The rapidly growing population (900M people in 2015), and a stagnation in wheat yields over the last decade (FAO, 2012), will lead to increased wheat shortages in Egypt. The situation is further compounded by climate change, through both increased temperatures and sea-level rise affecting crops. Food security is generally negatively impacted by increasing wheat demand and input prices, soil degradation, greenhouse emissions and competition between land and water (Challinor et al., 2014, Pretty et al., 2010, Hertel, 2011). In the study area, the soil is mainly clay with low hydraulic conductivity, with soil available water-holding capacity of ~21% (Seleiman and Kheir, 2018, Sugita et al., 2017).

Excessive temperature increase due to climate change has negative impacts on wheat productivity and thus on food production (Asseng et al., 2015). The main impact of increasing temperature on wheat crop productivity is mainly due to a reduced time from crop emergence to maturity.

Like temperature, sea-level rise (SLR) is one of the main direct impacts of climate change on agriculture. Many scenarios predict SLR in the 21st Century, some scenarios predict an increase of 0.8 m by 2095 (IPCC, 2001). Another IPCC prediction scenario in 2007 predicted a SLR of 0.6 m by 2100. SLR in the 5th IPCC Assessment Report was predicted to be 52–98 cm by 2100 (IPCC, 2014). Therefore, there are many SLR scenarios, as each team has different approaches and analyses, but they all agree on some SLR due to climate change. One of the most hazardous impacts of SLR on agriculture is the inundation of low-elevation coastal areas (M^CGranahan et al., 2007). The Nile Delta of Egypt is highly vulnerable to inundation through SLR. Marine transgression will decrease the extent of agricultural land and thus decrease crop production and

1 food security (Rotzoll and Fletcher, 2013). Impacts of SLR as a function of climate change have
2 received considerable attention. However, most studies have focused on economic impacts and
3 damage to coastal ecosystems (Darwin and Tol, 2001, Rositasari et al., 2011), with less attention
4 on agriculture and crop production, particularly in Egypt.

5 Crop models are considered useful tools to study and quantify the likely impacts of climate
6 change, as they can link climate variables and crop development processes that are particularly
7 vulnerable to climate change. Consequently, models have been widely applied and tested in
8 different studies, including impacts of temperature on crop production (Rosenzweig et al., 2014).
9 The ‘Decision Support System for Agro-technology Transfer’ (DSSAT) models (Jones et al.,
10 2003) are considered the leading models and are widely used in different environments.

11 N-Wheat is a wheat model in APSIM (Holzworth et al., 2014, Asseng et al., 1998). It is a
12 derivative crop synthesis model from CERES which includes different justifications (Ritchie *et*
13 *al.*, 1998). Replacing the crop water uptake system in CERES with another approach, based on
14 the soil available water critical fraction, is a modification option in N-Wheat. It is also possible
15 to replace the function of Leaf Area Index (LAI) and potential evapotranspiration in CERES with
16 water demand and biomass transpiration efficiency. These model differences could result in
17 simulation differences between CERES-Wheat and N-Wheat models. Climate change and
18 variability usually have negative impacts on agricultural production (Challinor et al., 2007,
19 Müller et al., 2011). These impacts might be increased by global warming (Thornton et al., 2010,
20 Wheeler and Von-Braun, 2013); a conclusion supported by regional studies in Africa (Cairns et
21 al., 2013, Cooper and Coe, 2011). Egypt is among the most vulnerable countries in Africa due to
22 its arid environment and dependence on the River Nile as its primary water source (Rosenzweig
23 and Hillel, 1994, Rosenzweig et al., 1995).

Wheat is one of the most strategic crops for food and feed. Nevertheless, no previous studies have quantified wheat yields subjected to rising temperature and SLR on Egyptian coastal areas. In addition, the cultivar (Misr3) is a new variety and needs further studies to explore its potential resistance to higher temperatures and carbon dioxide concentrations. Therefore, the main objectives of this study were: (1) to calibrate and evaluate both the CERES-Wheat and N-Wheat models with the new high-yielding cultivar (Misr3) under current conditions, (2) to investigate the impacts of increased temperature and CO₂ concentrations and sea-level rise on the wheat yield of Misr3 in a major agricultural coastal area of Egypt, and (3) to quantify the total reduction in wheat production under different scenarios of SLR in the study region.

2. Materials and methods

The current investigation includes two DSSAT models calibrated using field experiments conducted through two successive growing seasons in coastal Egypt. Then, the calibrated models were used to predict wheat yields under different scenarios of temperature increase (+1, 2, 3 and 4 °C) and elevated CO₂ (concentrations +400, 500, 600 and 700 ppm) and compared with baseline yields in the period 1981-2010. As the study area is prominently a low-elevation coastline, it is expected to be vulnerable to projected SLR. We therefore quantified the inundation area and thus the reduction in wheat yield due to marine transgression, based on a digital elevation map (DEM) and three potential SLR scenarios (0.5, 1.5 and 2.0 m). These stages could be used as suitable tools to quantify wheat production in a coastline governorate in Egypt subjected to rising temperature and SLR.

2.1. The study location

The study was conducted on the North Nile Delta of Egypt in Kafr El-Sheikh Governorate (KFS), Sakha, which is a coastal area of northern Egypt. The study area is bounded by longitude

31.0-31.3E and latitudes 31.3-30.0N and elevation is ≤ 6.0 m above sea-level. Annual rainfall ranges from 100-150 mm and annual mean temperature is $\sim 21.5^{\circ}\text{C}$. Soil groups in Egypt include Aridisols, Entisols and Vertisols (Said, 1993). The dominant soil temperature regime is thermic, and the dominant soil moisture regime is torric. We investigated Aridisols, as they form the dominant soil group in this area. Analysed soil parameters are reported in Tables 1 and 2.

Table 1

Table 2

2.2. Field experiment and agricultural practises

A field experiment was conducted at Sakha Agricultural Research Station, Sakha, Egypt, during two successive wheat growing seasons in 2014/2015 and 2015/2016. The experiment included a split-plot design with three replicates. The main plots were assigned to planting dates 20 November (the recommended date) and 30 November (late date). Sub-plots were irrigation treatments as a proportion of actual evapotranspiration (ET_c) as 1.5, 1.0 and 0.5 ET_c . The sub-sub plot treatments were fertilization as a combination between mineral nitrogen (N) and compost as an organic fertilizer, as follows:

1. Control (without mineral N fertilization and with 15 t ha^{-1} of compost), N0.
2. 100% of recommended N (120 kg N/ha) with 9.2 t ha^{-1} of compost, N1.
3. 70% of recommended N with 11.5 t ha^{-1} of compost, N2.
4. 50% of recommended N with 13.8 t ha^{-1} of compost, N3.

A new and common high-yield wheat cultivar (Misr 3) was chosen. It is a modern variety and was recently added to the Egyptian cultivar inventory by ‘The International Maize and Wheat Improvement Center’ (CIMMYT). Yield and phenology parameters, including grain

yield, total final biomass, anthesis date (DAS) and maturity date (DAS), were investigated. These parameters were used to prepare file A in DSSAT to calibrate the DSSAT models under current conditions.

2.3. Weather conditions

Daily maximum and minimum temperature and solar radiation data were obtained from the 'Central Laboratory of Agricultural Climate' (CLAC) of Egypt (<http://www.clac.edu.eg/>) (Fig.1). Kafrelsheikh Region is identified as the first ecological zone in Egypt and is characterized by a thermic soil temperature regime and torric soil moisture regime (USDA, 2010). The maximum temperature during the wheat growing season ranged from 15-35 °C and minimum temperatures ranged between 9-20 °C (Fig. 1). Solar radiation ranged between 3-22 MJ m⁻² day⁻¹ (Fig. 1).

Fig. 1

2.4. Crop simulation models

In this study we used the two wheat models CERES-Wheat and N-Wheat (previously APSIM-Wheat) embedded in Decision Support Systems for Agrotechnology Transfer (DSSAT, v 4.6), (Hoogenboom et al., 2015; Jones et al., 2003). These models were chosen based on their global acceptance in climate change studies (Tubiello and Ewert, 2002). DSSAT models are designed to simulate crop growth as a function of crop features, soil characteristics, weather and management. In this study, both models were calibrated and tested with Misr 3 wheat cultivar. Calibration was performed manually through checking the optimum set of parameters in models in the specific location.

2.5. Model applications

Daily baseline climatic data (1981-2010) from the NASA AgCFSR climate dataset (<http://data.giss.nasa.gov/impacts/agmipcf/>) were used to quantify the projected future wheat yields subjected to different scenarios of temperature (T) and CO₂ concentrations using CERES-Wheat and N-Wheat models under irrigated conditions. The most common approach to investigate the likely impacts of climate change on wheat yield is changing temperatures (T), CO₂ and moisture, through applying such changes to baseline data (Rosenzweig and Parry, 1994). We therefore used different scenarios of T, CO₂ and their interactions to explore the potential impacts of climate change on wheat yield (Table 3). The performance of calibrated models was evaluated using the coefficient of determination (R^2), root mean square deviation (RMSD) and Model Index of Agreement (d) (Willmott, 1984; Jacovides and Kontoyiannis, 1995; Moriasi et al., 2007).

Table 3

2.6. SLR impacts on wheat production

The area potentially inundated by SLR was predicted using a digital elevation model (DEM), which was interpolated by its altitude. Identifying the coastal areas that are vulnerable to marine transgression was determined by the correlation between projected SLR and local topography. Three SLR scenarios were used (IPCC., 2007; Rahmstorf, 2007; Pfeffer et al., 2008), which assume sea-level rises of 0.5, 1.5 and 2.0 m, respectively (IPCC., 2007; Rahmstorf, 2007; Pfeffer et al., 2008). Therefore, we generated a new inundation map using ARC-GIS based on local topography and the severe uncertainty scenario (SLR of 2.0 m). Where the pixel value of SLR was greater or equal to local elevation, that area was identified as vulnerable to inundation.

3. Results

3.1. Calibration and evaluation of CERES-Wheat and N-Wheat models

Ceres-Wheat and N-Wheat crop models were calibrated using the dataset of 2014/2015 growing season and validated using the dataset of the 2015/2016 growing season for the Misr3 cultivar. The calibration process was performed manually through modifying only the genetic parameters of the cultivar to accord with the observed dataset under all treatments. The calibrated cultivar parameters for Misr 3 for the two models are reported in Table 4. For the calibration process, the genetic parameters have obtained in a step-wise process: (1) phenology, (2) grain yield and (3) biomass. The genetic coefficient of determination was calculated manually using the trial and error method of Godwin and Singh (1998). The values were modified based on the minimum root mean square deviation (RMSD) between predicted and observed data. The calibration of CERES-Wheat and N-Wheat was successful (Figure 2). The prediction of grain yield, total biomass, anthesis date and maturity date was accurate, with minimum deviation from observed values.

The DSSAT models reproduced grain yields well with R^2 values of 0.93 and 0.90 for N-Wheat and CERES-Wheat, respectively. There were an overall root means square deviation (RMSD) of 413 and 346 kg ha⁻¹ and a high Index of Agreement (d) of 0.97 and 0.90 for N-Wheat and CERES, respectively (Table 5). Therefore, the models showed the highest yield simulations under current conditions. Total biomass was also successfully simulated under both models (Fig. 2). R^2 for biomass simulations were 0.80 and 0.60, RMSD values scored 1783 and 1648 kg ha⁻¹, while d values ranged from 0.70-0.80 for N-Wheat and CERES-Wheat, respectively (Table 5).

The phenological parameters of simulated anthesis and maturity dates (DAS) were generally in agreement (Fig. 2), along with a good agreement of low RMSD and higher d (Table 5). Nevertheless, simulations of maturity of both models were slightly better than those of anthesis,

which showed some over-estimation, particularly under full irrigation treatment (Fig. 2). Applied water, fertilization treatments and planting dates had large impacts on observed grain yield, final biomass and phenological parameters and the DSSAT models successfully reproduced these parameters (Fig. 2). For instance, deficit irrigation, fertilization stress and late planting date decreased grain yield from 8.2 to 3.7 t ha⁻¹ and observed total biomass from 16.5 to 7.9 t ha⁻¹. However, the models showed a slight over-estimation for final biomass under conditions of insufficient irrigation and fertilization (Fig. 2). This may be attributed to over-estimates of soil water content by both models. Insufficient irrigation and fertilization treatments accelerated observed anthesis and maturity dates from 115 to 105 DAS for anthesis and from 144 to 128 DAS for maturity.

Table 4

Table 5

Fig. 2

3.2. Ceres-Wheat and N-Wheat applications: climate variability impacts

Four temperature and CO₂ scenarios were used to study the impacts of climate change on wheat yield, based on baseline climate. Both models predicted crop yields under baseline climatic conditions (Fig. 3). Wheat yield decreased with increasing temperature and the lowest yield was predicted in the warmest year (2010).

Rising temperature markedly decreased wheat yields, as predicted by both models (Figure 4A) and the lowest yield was projected under the highest temperature increase (4 °C). Compared with yields under baseline climatic conditions, the relative changes of grain yield as a mean prediction by both models were -5.08, -9.35, -13.11 and -17.65 % for increased temperatures of +1, +2, +3 and +4 °C, respectively (Figure 4B). The performance of both models was similar in predicting wheat yield.

Simulations of wheat grain yields using both models under elevated CO₂ concentrations (assuming the yield at 360 ppm as the baseline) projected increased yields (Figure 5A). The projected wheat grain yield increased by 3.6, 11.9, 19.0 and 25.0 % for CO₂ concentrations rising to 400, 500, 600 and 700 ppm, respectively, relative to baseline yield (Figure 5B). The combined impacts of rising temperature and CO₂ on wheat grain yield found that in the scenarios of 400 and 500 ppm CO₂, there are usually negative impacts on wheat grain yield under all temperature scenarios. The exceptions were increased temperature by 1 and 2 °C in the 500 ppm CO₂ scenario, under which projected wheat grain yields increased (Fig. 6A). Elevating CO₂ concentrations to 600 and 700 ppm increased wheat grain yields under all temperature scenarios. However, the increase was at a lower rate under elevated temperatures, but the mean change was positive in the 600 and 700 ppm CO₂ concentration scenarios (Figure 6B).

Fig. 3

Fig. 4

Fig. 5

Fig. 6

3.3. Impacts of sea-level rise on land inundation and loss of agricultural area and wheat production

To explore the impacts of SLR on land inundation, accurate elevation maps of the study area were derived from Google Earth and manipulated using ARC-GIS software (v10.22). Supplementary Fig. 1 shows the topography of the study area, where areas coloured yellow and grey represent elevations ≤ 2.0 m, while higher elevations (2.0-8.0 m) are coloured red (2.0-4.0 m), purple (4.0-6.0 m) and blue (6-8 m). Ground-water depth data (as reported by RIGW., 2014), and water quality (expressed as salinity as determined by FAO., 2009) are also presented in Supplementary Fig. 1. Areas close to the Mediterranean Sea have low elevations and shallow and

saline ground-water. Based on the elevation data and the SLR scenarios, the total inundated areas in KFS were calculated to be 195.65, 158695.7 and 182608.7 ha under A1F1, Rahmstorf, and Pfeffer scenarios, respectively (Supplementary Fig. 2). Therefore, the agricultural land expected to be inundated due to SLR is 0.07, 52.9, and 60.8 % for these three scenarios, respectively. Thus, wheat production would be markedly decreased due to the loss of agricultural land through marine transgression.

Supp. Fig. 1

Supp. Fig. 2

4. Discussion

CERES-Wheat and N-Wheat crop models can be used to select suitable cultivars and predict probable wheat yields under various scenarios of climate change. The phenology of wheat has marked impacts on crop growth, development and yield (Ceglar et al., 2011). The models realistically simulated wheat phenology using the specific model indices (Fig. 2 and Table 4). In N-Wheat, anthesis time was controlled by VSEN and PPSEN, while maturity dates were determined by P5 (Table 4). Therefore, phenology calibration of wheat in the N-Wheat Model needs these three parameters (Asseng et al., 1998, 2013, 2015). P1V, P1D, P5 and Phint are necessary as controls and to justify phenology in CERES-Wheat (Andarzian et al., 2015). However, changing P1, P2, P3 and P4 in the ecotype file is necessary to enhance model accuracy and decrease uncertainty (Johnen *et al.*, 2012). Thus, wheat phenology could be determined by temperature and photoperiod variables (Aslam et al., 2017). High quality calibration can be achieved by ensuring accurate phenology data (Archontoulis et al., 2014; Ahmed et al., 2016). By achieving high phenology accuracy, genotypic variations could be captured by models which affect yield, biomass and leaf area development (Robertson et al.,

2002). The interception of solar radiation and radiative use efficiency are the main factors controlling biomass production. Our findings resulted in accurate estimates of biomass production (Arora et al., 2007), due to the positive relationship between biomass and grain yield (Dettori et al., 2011). Biomass in this study was controlled by STMMX and G3 for the N-wheat and CERES-Wheat models, respectively (Table 4).

Grain yield is related to the interception of solar radiation by the crop canopy, radiation use efficiency and Harvest Index. Both models achieved a convincing simulation of grain yield. In N-Wheat the calibration of grain yield was controlled using the GRNO and MXFIL parameters, while the required parameters in CERES-Wheat are G1, G2 and G3 (Hunt and Boote, 1998). This calibration step should follow the phenology calibration (Ma et al., 2011). Simulation modelling is a complex process, involving interactions of multiple factors, including soil, climate and crop variables. However, the simulations contain uncertainties (Kassie et al., 2016). Quantifying uncertainties in a single crop model is problematic, particularly considering likely climate change impacts on crop yield (Rotter et al., 2011, Asseng et al., 2013). Ensemble multi-models for simulations have been suggested to quantify model uncertainty (Martre et al., 2015). For instance, by expanding existing model platforms (Feng et al., 2014), an additional wheat model (N-Wheat) has been added to the current wheat models on the DSSAT platform (Kassie et al., 2016).

Ensemble multiple models are very important for decision-makers (Rosenzweig, 2013). Like other crop models, DSSAT models have limitations, particularly regarding the effects of diseases and pests on crop development. These limitations require further analysis and discussion of model simulations.

1 The soils developed on the Nile Delta are known globally and the coastal area covers >5000
2 km², thus creating potential vulnerability to SLR. Furthermore, climate change, particularly
3 rising temperatures, might add additional challenges to wheat production on the Delta. KFS is
4 considered representative of coastal Egypt and so the analysis has broader implications for agro-
5 environmental policy on the Nile Delta.

6 There was a decline in wheat grain yield during the baseline (1981-2010), which both models
7 predicted was due to increased temperatures. The lowest wheat yield was predicted in the
8 warmest year (2010) (Fig. 3). Our analysis suggests that climate change in KFS, especially
9 increased temperatures will decrease future wheat yields (Fig. 4). This is mainly due to
10 accelerating crop development and decreasing biomass (Asseng et al., 2015). Furthermore,
11 increased temperatures could shorten the crop life-cycle (Sayre et al., 1997) and thus decrease
12 the interception of solar radiation (Heng et al., 2007; Alexandrov and Hoogenboom, 2000). It
13 appears realistic that a 1.0 °C, temperature increase would decrease wheat grain yield by ~6.0 %,
14 which accords with the findings of Asseng et al. (2015). On the other hand, increasing CO₂
15 concentrations would probably increase wheat grain yield (Fig. 5). This is mainly due to
16 increasing the rate of photosynthesis by increasing cellular CO₂ concentrations, which is mainly
17 responsible for minimizing stomatal conductance and decreasing transpiration rates (Asseng et
18 al., 2004). Furthermore, the combined impacts of increased CO₂ and temperature increased
19 predicted wheat grain yield, but after 3 °C increase, there is a predicted decline in wheat yield
20 until CO₂ concentrations exceed 400 ppm. In the scenario of elevated CO₂ concentrations >600
21 ppm, there is a predicted increase in wheat grain yield under all investigated scenarios of
22 increased temperature (Fig. 6). These findings suggest that the impacts of higher temperatures
23 could be alleviated by elevated CO₂, particularly with the most resistant cultivars, such as Misr 3.

Increasing wheat grain yield in response to elevated CO₂ had been achieved by increasing grain numbers per ear (Dias de Oliveira et al., 2015). The suggested mechanisms are increased net leaf photosynthetic rate and increased carbon assimilation in the floret due to elevated CO₂. Consequently, floret death rates decreased and grain number increased by 42%. Therefore, they suggested the possibility of breeding new resistant cultivars that have more florets, thus responding to increased CO₂ fertilization under high temperature and drought conditions. Our findings concluded that the Misr3 cultivar has many florets and responded to elevated CO₂ concentrations, which compensated for higher temperatures. Data presented in Supplementary Fig. 3 showed a marked increase in wheat grain numbers, particularly under elevated CO₂ concentrations ≥ 600 ppm, even at high temperatures. This could be due to decreasing floret death rates with increasing CO₂, so higher temperatures were mitigated by elevated CO₂ concentrations. This indicates the potential of the Misr3 cultivar for resistance to high temperatures due to its response to CO₂ fertilization. However, the CO₂ growth stimulus could be less than suggested in the simulation (and in short-term field experiments), as indicated in long-term experiments in which the growth stimulus from elevated CO₂ concentration in C3 grasses declined over time (Reich et al., 2018).

Supp. Fig. 3

Alongside the temperature and CO₂ impacts on wheat yield in KFS, there are also the negative impacts of SLR due to climate change. The direct physical impact of SLR on wheat production in KFS appears through the loss of agricultural land due to marine transgression. Currently, the total irrigated area in KFS is ~300,000 ha and the extent of wheat cultivation is ~90,000 ha (FAO., 2015). Thus, the wheat area represents ~34% of the total irrigated area. To quantify total wheat production in KFS requires the mean crop yields in all other districts and the experimental

site. Therefore, wheat yield for all other districts in KFS was obtained from farmers and prepared by the Ministry of Agriculture and Land Reclamation (MALR, 2016) (Fig. 7). The estimated mean wheat grain yield for all districts was 7.15 t ha⁻¹. Based on the total wheat agricultural area and the mean wheat yield, the total wheat production in KFS is estimated to be ~643500 t. This quantity is expected to be decreased by SLR through land inundation. Our findings quantified the loss of agricultural land due to inundation under different SLR scenarios (Supplementary Fig. 2, Fig. 8A). The expected loss of total agricultural land due to SLR and inundation is 0.07, 52.9 and 60.8% if sea-level rose by 0.5, 1.5 and 2.0 m, respectively. Consequently, based on the calculated inundated wheat area, wheat production in KFS will decrease by 0.09, 76.7, and 88.3% under A1F1, Rahmstorf, and Pfefeer scenarios, respectively (Figs. 8B and 8C). In addition to lost wheat yield in response to SLR, there would also be major losses due to rising temperature, which would be especially high under medium CO₂ concentrations. Therefore, major decreases in wheat production in KFS are feasible due to the combined effects of SLR and increased temperatures. These effects require the government, scientists and decision-makers to develop viable mitigation and adaptation plans.

Fig. 7

Fig. 8

5. Conclusions

Egypt has relatively few studies of climate change, hence projections of the probable impacts of climate change on wheat production and food security are uncertain. Moreover, Kafrelsheikh Province is a major agricultural and coastal area in Egypt and is especially vulnerable to marine inundation. Quantifying the impacts of increasing temperature and SLR on wheat production in KFS can help decision-makers seeking options to minimize agro-environmental damage. The ensemble of two DSSAT wheat models (CERES-Wheat and N-Wheat) was used for calibration

and evaluation using a recent wheat cultivar (Misr3) and field experimental data. Selected agronomic treatments (including planting dates, irrigation and fertilization) were conducted during two-successive wheat growing seasons. Both models were successfully calibrated under irrigated conditions and proved successful in terms of model evaluation indices of grain yield and phenology. Following calibration, different climate change scenarios of rising temperature, CO₂ concentrations and the combination of increasing temperature and CO₂ under irrigated conditions in Egypt were analysed using the models. The results predicted decreased wheat grain yield with rising temperature, while increased CO₂ concentrations increased yields. The combined effect of increased temperature and CO₂ concentrations projected an increase in wheat yield under higher CO₂ concentrations. However, in the scenarios of relatively small increases in CO₂ concentrations, increased temperatures decreased projected wheat yields. Results suggest that the Misr3 cultivar (Misr3) could be particularly resistant, as it has many florets and is responsive to higher CO₂ concentrations under warming conditions. Another threat of climate change on wheat production in the study area is sea-level rise. Three scenarios of SLR and their impacts on land inundation and hence on the loss of agricultural land were studied. The results showed that much agricultural land would be lost due to marine transgression in response to SLR. The projected lost agricultural area would be ~60% of the total agricultural land under the worst-case scenario (SLR of 2.0 m). Consequently, total wheat production in KFS would be markedly decreased by climate change due to rising temperature or SLR or a combination of the two. Thus, it is imperative that scientists and decision-makers seek for potential solutions.

Acknowledgements

We thank the Agricultural Research Center; Soils, Water and Environment Research Institute (SWERI) for financial support. Grateful thanks are extended to Professor Dr Senthold Asseng

(University of Florida, USA) for his review of the draft version of this paper. The authors declare that there are no conflicts of interest.

References

- AHMED, M., AKRAM, M.N., ASIM, M., ASLAM, M., HASSAN, F., HIGGINS, S., STÖCKLE, C.O., HOOGENBOOM, G. 2016. Calibration and validation of APSIM-Wheat and CERES-Wheat for spring wheat under rainfed conditions: Models evaluation and application. *Computers and Electronics in Agriculture* 123, 384-401.
- ALEXANDROV, V.A., HOOGENBOOM, G. 2000. The impact of climate variability and change on crop yield in Bulgaria. *Agric. For. Meteorol.* 104, 315-327.
- ANDARZIAN, B., HOOGENBOOM, G., BANNAYAN, M., SHIRALI, M., ANDARZIAN, B. 2015. Determining optimum sowing date of wheat using CSM-CERES-Wheat model. *J. Saudi. Soc. Agri. Sci.* 14, 189-199.
- ARCHONTOULIS, S.V., MIGUEZ, F.E., MOORE, K.J. 2014. A methodology and an optimization tool to calibrate phenology of short-day species included in the APSIM PLANT model: application to soybean. *Environ. Modell. Soft.* 62, 465-477.
- ARORA, V.K., SINGH, H., SINGH, B. 2007. Analyzing wheat productivity responses to climatic, irrigation and fertilizer-nitrogen regimes in a semi-arid sub-tropical environment using the CERES-Wheat model. *Agric. Water Manage* 94, 22-30.
- ASLAM, M.A., AHMED, M., STÖCKLE, C.O., HIGGINS, S.S., HASSAN, F., HAYAT, R. 2017. Can Growing Degree Days and photoperiod predict spring wheat phenology? *Frontiers in Environmental Science* 5, Article 57.
- ASSENG, S., EWERT, F., MARTRE, P., ROTTER, R.P., LOBELL, D.B., CAMMARANO, D., KIMBALL, B.A., OTTMAN, M.J., WALL, G.W., WHITE, J.W., REYNOLDS, M.P., ALDERMAN, P.D., PRASAD, P.V.V., AGGARWAL, P.K., ANOTHAI, J., BASSO, B., BIERNATH, C., CHALLINOR, A.G., DE SANCTIS, G., DOLTRA, J., FERERES, E., GARCIA-VILA, M., GAYLER, S., HOOGENBOOM, G., HUNT, L.A., IZAURRALDE, R.C., JABLOUN, M., JONES, C.D., KERSEBAUM, K.C., KOEHLER, A.K., MULLER, C., NARESH KUMAR, S., NENDEL, C., LEARY, G.O., OLESEN, J.E., PALOSUO, T., PRIESACK, E., EYSHI REZAEI, E., RUANE, A.C., SEMENOV, M.A., SHCHERBAK, I., STOCKLE, C., STRATONOVITCH, P., STRECK, T., SUPIT, I., TAO, F., THORBURN, P.J., WAHA, K., WANG, E., WALLACH, D., WOLF, J., ZHAO, Z., ZHU, Y. 2015. Rising temperatures reduce global wheat production. *Nat Clim Change* 5, 143-147.
- ASSENG, S., EWERT, F., ROSENZWEIG, C., JONES, J. W., HATFIELD, J. L., RUANE, A. C., BOOTE, K. J., THORBURN, P. J., ROOTER, R. P., CAMMARANO, D., BRISSON, N., BASSO, B., MARTRE, P., AGGARWAL, P. K., ANGULO, C., BERTUZZI, P., BIERNATH, C., CHALLINOR, A. G., DOLTRA, J., GAYLER, S., GOLDBERG, R., GRANT, R., HENG, L., HOOKER, J., HUNT, L. A., INGWERSEN, J., IZAURRALDE, R. C., KERSEBAUM, K. C., MULLER, C., NARESH KUMAR, S., NENDEL, C., O'LEARY, G., OLESEN, J. E., OSBURNE, T. M., PALOSUO, T., PRIESACK, E., RIPOCHE, D., SEMENOV, M. A., SHCHERBAK, I., STEDUTO, P., STOCKLE, C., STRATONOVITCH, P., STRECK, T., SUPIT, I., TAO, F., TRAVASSO, M., WAHA, K., WALLACH, D., WHITE, J. W., WILLIAMS, J. R. & WOLF, J. 2013. Uncertainty in simulating wheat yields under climate change. *Nat Clim Change*, 3, 827-832.
- ASSENG, S., JAMIESON, P.D., KIMBALL, B., PINTER, P., SAYRE, K., BOWDEN, J.W., HOWDEN, S.M. 2004. Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO₂. *Field Crop Res.* 85, 85-102.

- ASSENG, S., KEATING, B.A., FILLERY, I.R.P., GREGORY, P.J., BOWDEN, J.W., TURNER, N.C., PALTA, J.A., ABRECHT, D.G. 1998. Performance of the APSIM-wheat model in western Australia? *Field Crops Res.* 57, 163-179.
- CAIRNS, J.E., HELLIN, J., SONDER, K., ARAUS, J.L., MACROBER, J.F., THIERFELDER, C., PRASANNA, B.M. 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Security* 5, 345–360.
- CEGLAR, A.C., REPINŠEK, Z., KAJFEŽ-BOGATAJ, L., POGAČAR, T. 2011. The simulation of phenological development in dynamic crop model: the Bayesian comparison of different methods. *Agric. For. Meteorol.* 151, 101-115.
- CHALLINOR, A.G., WATSON, J., LOBELL, D.B., HOWDEN, S.M., SMITH, D.R., CHHETRI, N. 2014. A meta-analysis of crop yield under climate change and adaptation. *Nat. Clim. Change* 4, 287–291.
- CHALLINOR, A.G., WHEELER, T., GARFORTH, C., CRAUFORD, B., KASSAM, A. 2007. Assessing the vulnerability of food crop systems in Africa to climate change. *Clim. Change* 83, 381–399.
- COOPER, P.J.M., COE, R. 2011. Assessing and addressing climate-induced risk in sub-Saharan rainfed agriculture. *Exp. Agric.* 47, 179.
- DARWIN, R.F., TOL, R.S.J. 2001. Estimates of the economic effects of sea level rise. *Environment Resource Economics* 19, 113-129, <http://dx.doi.org/10.1023/A:1011136417375>
- DETTORI, M., CESARACCIO, C., MOTRONI, A., SPANO, D., DUCE, P. 2011. Using CERES-Wheat to simulate durum wheat production and phenology in Southern Sardinia. *Field Crop Res.* 120, 179-188.
- DIAS DE OLIVEIRA, E., PALTA, J.A., BRAMLEY, H., STEFANOVA, K., SIDDIQUE, K.H.M. 2015. Elevated CO₂ reduced floret death in wheat under warmer average temperatures and terminal drought. *Front. Plant Sci.* 6.
- FAO 2012. *FAO Statistical Yearbook. World Food and Agriculture*. Rome.
- FAO. 2009. Rapid assessment study: towards integrated planning of irrigation and drainage in Egypt. In: *Support of the Integrated Irrigation Improvement and Management*. <http://www.fao.org/3/a-a0021e/a0021e09.htm>
- FAO. 2015. *Egypt Wheat Sector Review*. Rome.
- FENG, Z., YAO, Y., HUILONG, C., FENG, Y. 2014. Reusable component model development approach for parallel and distributed simulation. *Sci. World J. Volume 2014, Article ID 696904*. <http://dx.doi.org/10.1155/2014/696904>
- GODWIN, D.C., SINGH, U. 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In: Tsuji, G., Hoogenboom, G., Thornton, P. (Eds), *Understanding Options for Agricultural Production*. Springer, The Netherlands, 55-77.
- HENG, L.K., ASSENG, S., MEJAHED, K., RUSAN, M. 2007. Optimizing wheat productivity in two rain-fed environments of the West Asia-North Africa region using a simulation model. *Eur. J. Agron.* 26, 121-129.
- HERTEL, T.W. 2011. The global supply and demand for agricultural land in 2050: A perfect storm in the making? *Amer. J. Agr. Econ.* 93, 259–275.
- HOLZWORTH, D.P., HUTH, N.I., DEVOIL, P.G., ZURCHER, E.J., HERRMANN, N.I., M^CLEAN, G., CHENU, K., VAN OOSTEROM, E.J., SNOW, V., MURPHY, C., MOORE, A.D., BROWN, H., WHISH, J.P.M., VERRALL, S., FAINGES, J., BELL, L.W., PEAKE, A.S., POULTON, P.L., HOCHMAN, Z., THORBURN, P.J., GAYDON, D.S., DALGLIESH, N.P., RODRIGUEZ, D., COX, H., CHAPMAN, S., DOHERTY, A., TEIXEIRA, E., SHARP, J., CICHOTA, R., VOGELER, I., LI, F.Y., WANG, E.L., HAMMER, G.L., ROBERTSON, M.J., DIMES, J.P., WHITBREAD, A.M., HUNT, J., VAN REES, H., M^CCLELLAND, T., CARBERRY, P.S., HARGREAVES, J.N.G., MACLEOD, N., M^CDONALD, C., HARSDFORD, J., WEDGWOOD, S., KEATING, B.A. 2014. APSIM –evolution towards a new generation of agricultural systems simulation. *Environ. Modell. Software* 62, 327-350.

- HOOGENBOOM, G., JONES, J.W., WILKENS, P.W., PORTER, C.H., BOOTE, K.J., HUNT, L. A., SINGH, U., LIZASO, J.I., WHITE, J.W., URYASEV, O., OGOSHI, R., KOO, J., SHELIA, V., TSUJI, G.Y. 2015. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.6 (www.DSSAT.net). DSSAT Foundation, Prosser, Washington.
- HUNT, L.A., BOOTE, K.J. 1998. Data for model operation, calibration, and evaluation. In: Tsuji, G., Hoogenboom, G., Thornton, P. (Eds). *Understanding Options for Agricultural Production*. Springer, The Netherlands, 9-39.
- IPCC 2014. *Climate Change 2014, Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds)]. Geneva, Switzerland, 151.
- IPCC. 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press.
- IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [Solomon, S., D. Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996.
- JACOVIDES, C.P., KONTOYIANNIS, H. 1995. Statistical procedures for the evaluation of evapotranspiration computing models. *Agricultural Water Management* 27, 365-371.
- JOHNEN, T., BOETTCHER, U., KAGE, H. 2012. A variable thermal time of the double ridge to flag leaf emergence phase improves the predictive quality of a CERES-Wheat type phenology model. *Comput. Electr. Agric.* 89, 62-69.
- JONES, J.W., HOOGENBOOM, G., PORTER, C.H., BOOTE, K.J., BATCHELOR, W.D., HUNT, L.A., WILKENS, P.W., SINGH, U., GIJSMAN, A.J., RITCHIE, J.T. 2003. The DSSAT cropping system model? *Eur. J. Agron.* 18, 235-265.
- KASSIE, B.T., ASSENG, S., PORTER, C.H., ROYCE, F.S. 2016. Performance of DSSAT N-Wheat across a wide range of current and future growing conditions *Europ. J. Agronomy* 81, 27-36.
- MA, L., AHUJA, L.R., SASEENDRAN, S.A., MALONE, R.W., GREEN, T.R., NOLAN, B.T., BARTLING, P.N.S., FLERCHINGER, G.N., BOOTE, K.J., HOOGENBOOM, G. 2011. A protocol for parameterization and calibration of RZWQM2 in field research. In: Ahuja, L.R., Ma, L. (Eds). *Methods of Introducing System Models into Agricultural Research*. Am. Society Agron., Crop Science Society of America, Soil Science Society of America, 1-64.
- MALR 2016. *Bulletins of Agricultural Statistics*. Arab Republic of Egypt, Ministry of Agriculture and Land Reclamation, the Egyptian Economic Affairs Sector. Department of Agricultural Economics & Statistics, 12-15.
- MARTRE, P., WALLACH, D., ASSENG, S., EWERT, F., JONES, J., ROTTER, R., BOOTE, K., RUANE, A.C., THORBURN, P., CAMMARANO, D., HATFIELD, J., ROSENZWEIG, C., AGGARWAL, P., ANGULO, C., BASSO, B., BERTUZZI, P., BIERNATH, C., BRISSON, N., CHALLINOR, A., DOLTRA, J., GAYLER, S., GOLDBERG, R., GRANT, R., HENG, L., HOOKER, J., HUNT, L., INGWERSEN, J., IZAURRALDE, R., KERSEBAUM, K., MULLER, C., KUMAR, S., NENDEL, C., O'LEARY, G., OLESEN, J., OSBORNE, T., PALOSUO, T., PRIESACK, E., RIPOCHE, D., SEMENOV, M., SHCHERBAK, I., STEDUTO, P., STOCKLE, C., STRATONOVITCH, P., STRECK, T., SUPIT, I., TAO, F., TRAVASSO, M., WAHA, K., WHITE, J., WOLF, J. 2015. Multimodel ensembles of wheat growth: many models are better than one? *Global Change Biol.* 21, 911-925.
- M^CGRANAHAN, G., BALK, D., ANDERSON, B. 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization* 19, 17-37.

- MORIASI, D.N., ARNOLD, J.G., LIEW, M.W.V., BINGNER, R.L., HARMEL, R.D., VEITH, T.L. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* 50, 885-900.
- MÜLLER, C., CRAMER, W., HARE, W.L., LOTZE-CAMPEN, H. 2011. Climate change risks for African agriculture. *Proc. Natl. Acad. Sci.* 108, 4313–4315.
- PFEFFER, W.T., HARPER, J.T., O'NEEL, S. 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science* 321, 1340–1343.
- PRETTY, J., SUTHERLAND, W.J., ASHBY, J., AUBURN, J., BAULCOMBE, D., BELL, M., BENTLEY, J., BIKERSTETH, S., BROWN, K., BURKE, J., CAMPBELL, H., CHEN, K., CROWLEY, E., CRUTE, I., DOBELAERE, D., EDWARDS-JONES, G., FUNES-MONZOTE, F., GODFRAY, H.C.J., GRIFFON, M., GYPMANTISIRI, P., HADDAD, L., HALAVATAU, S., HERREN, H., HOLDERNESS, M., IZAC, A., JONES, M., KOOHAFKAN, P., LAL, R., LANG, T., M^CNEELY, J., MUELLER, A., NISBETT, N., NOBLE, A., PINGALI, P., PINTO, Y., RABBINGE, R., RAVINDRANATH, N.H., ROLA, A., ROLING, N., SAGE, C., SETTLE, W., SHA, J.M., SHIMING, L., SIMONS, T., SMITH, P., STRZEPEK, K., SWAINE, H., TERRY, E., TOMICH, T.P., TOULMIN, C., TRIGO, E., TWOMLOW, S., VIS, J.K., WILSON, J., PILGRIM, S. 2010. The top 100 questions of importance to the future of global agriculture. *Int. J. Agr. Sustain.* 8, 219–236.
- RAHMSTORF, S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science* 315, 368-370. DOI: 10.1126/science.1135456.
- REICH, P.B., HOBIE, S.E., LEE, T. D., PASTORE, M.A. 2018. Unexpected reversal of C3 versus C4 grass response to elevated CO₂ during a 20-year field experiment. *Science* 360, 317-320.
- RIGW. 2014. Safe use studies for groundwater reservoirs in the Nile Delta and Upper Egypt. Research Institute for Groundwater, Ministry of Water Resources and Irrigation MWRI, Cairo, Egypt.
- RITCHIE, J.T., SINGH, U., GODWIN, D., BOWEN, W.T. 1998. Cereal growth, development, and yield. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds), *Understanding Options for Agricultural Production*. Dordrecht, The Netherlands: Kluwer Academic, 79-98.
- ROBERTSON, M.J., CARBERRY, P.S., HUTH, N.I., TURPIN, J.E., PROBERT, M.E., POULTON, P.L., BELL, M., WRIGHT, G.C., YEATES, S.J., BRINSMEAD, R.B. 2002. Simulation of growth and development of diverse legume species in APSIM. *Aust. J. Agric. Res.* 53, 429-446.
- ROSENZWEIG, C., ELLIOTT, J., DERYNG, D., RUANE, A.C., MULLER, C., AMETH, A., BOOTE, K. J., FOLBERTH, C., GLOTTER, M., KHABAROV, N., NUEMANN, K., PIONTEK, F., PUGH, T.A.M., SCHMID, E., STEFHEST, E., YANG, H., JONES, J.W. 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc. Natl. Acad. Sci.* 111, 3268–3273.
- ROSENZWEIG, C., HILLEL, D. 1994. *Egyptian agriculture in the 21st century*. International Institute for Applied Systems Analysis, Laxenburg, Austria.
- ROSENZWEIG, C., PARRY, M.L. 1994. Potential impact of climate change on world food supply. *Nature* 367, 133-138.
- ROSENZWEIG, C., PARRY, M.L., FISCHER, G. 1995. World food supply. In Strzepek K.M., Smith J.B. (Eds), *As Climate Changes: International Impacts and Implications*. Cambridge: Cambridge University Press.
- ROSENZWEIG, C.E.A. 2013. The agricultural model intercomparison and improvement project (AgMIP): protocols and pilot studies. *Agric. For. Meteorol.* 170, 166-182.
- ROSITASARI, R., SETIAWAN, W.B., SUPRIADI, I.H., HASANUDDIN, PRAYUDA, B. 2011. Coastal vulnerability prediction to climate change: Study Case in Cirebon Coastal Land. *Jurnal Ilmu dan Teknologi Kelautan Tropis*, 3, 52-64.
- ROTTER, R.P., CARTER, T.R., OLESEN, J.E., PORTER, J.R. 2011. Crop-climate models need an overhaul? *Nat. Clim. Change* 1, 175-177.

- 1 ROTZOLL, K., FLETCHER, C.H. 2013. Assessment of groundwater inundation as a consequence of sea-
2 level rise. *Nature Climate Change* 3, 477-481. <http://dx.doi.org/10.1038/nclimate1725>.
- 3 SAID, R. 1993. *The River Nile Geology and Hydrology and Utilization*. Pergamon, Oxford.
- 4 SAYRE, K.D., RAJARAM, S., FISCHER, R.A. 1997. Yield potential progress in short bread wheats in
5 Northwest Mexico. *Crop Sci.* 37, 36-42.
- 6 SELEIMAN, M.F., KHEIR, A.M.S. 2018. Saline soil properties, quality and productivity of wheat grown with
7 bagasse ash and thiourea in different climatic zones. *Chemosphere* 193, 538-546.
- 8 SUGITA, M., MATSUNO, A., EL-KILANI, R.M.M., ABDEL-FATTAH, A., MAHMOUD, M.A. 2017. Crop
9 evapotranspiration in the Nile Delta under different irrigation methods. *Hydrological Sciences*
10 *Journal* 62, 1618-1635
- 11 THORNTON, P.K., JONES, P.G., ALAGARSWAMY, G., ANDRESEN, J., HERRERO, M. 2010. Adapting to
12 climate change: agricultural system and household impacts in East Africa. *Agric. Syst.* 103, 73–
13 82.
- 14 TUBIELLO, F.N., EWERT, F. 2002. Simulating the effects of elevated CO₂ on crops: approaches and
15 applications for climate change. *Eur. J. Agron.* 18, 57-74.
- 16 USDA 2010. *Keys to Soil Taxonomy*. United States Department of Agriculture: Natural Resources
17 Conservation Service (NRCS) Third Edition.
- 18 WHEELER, T., VON-BRAUN, J. 2013. Climate change impacts on global food security. *Science* 341, 508–
19 513.
- 20 WILLMOTT, C.J. 1984. On the evaluation of model performance in physical geography. In *Spatial*
21 *Statistics and Models*, Gaile G.L., Willmott C.J. (Eds). D. Reidel: Boston, 443-460.

1 **Figure Captions**

2 Figure 1. Daily maximum temperature (red), minimum temperature (green) and solar radiation
3 (blue) for Kafrelsheikh during two growing seasons 2014/2015 and 2015/2016.

4 Figure 2. Calibrations of N-Wheat (black closed circles) and CERES-Wheat (open circles)
5 models under different treatments (planting dates, irrigation and fertilization) at Sakha.

6 Figure 3. Wheat grain yield prediction, annual maximum temperature and total annual
7 precipitation during the baseline (1981-2010) based on two wheat models. Baseline climatic data
8 generated by NASA website for Kafrelsheikh Governorate (the study area).

9 Figure 4. Impacts of temperature increase on wheat yield (A) and relative change to baseline (B)
10 in Kafrelsheikh based on the prediction of two wheat-models.

11 Figure 5. Impacts of increasing CO₂ concentrations on wheat yield (A) and yield change (B)
12 relative to baseline yield (1981-2010) using two wheat models.

13 Figure 6. Combined impact of temperature and CO₂ increases on wheat yield (A) and percentage
14 change of wheat relative to baseline (B). In (A) black colour refers to baseline, while blue, green,
15 yellow and red refer to temperature increases of 1, 2, 3 and 4 °C, respectively.

16 Figure 7. Wheat farmers yield in Kafr El-Sheikh Province (MALR, 2016). Wheat yields (at 10%
17 grain moisture).

18 Figure 8. Inundated area due to SLR (A), total wheat production (B) and change in wheat
19 production (C) under different scenarios of SLR in Kafrelsheikh Governorate (the study area).