VULNERABILITY AND ADAPTATION ASSESSMENT OF AGRICULTURE TO CLIMATE CHANGE IN EGYPT USING MATHEMATICAL MODELS

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ABSTRACT

Agriculture is considered as an essential economic driver in Egypt. It is an issue as a local food source, for international trade, the food industry and fiber manufacturing as well as water and land use. The climate change vulnerability of agriculture can be mainly attributed to parameters of the economy, society and the environment. Climate change will affect agricultural crop yields which consequently impact different food security domains, namely access to food, food supplies stability, food utilization and food production and trade. The aim of this research paper is to undertake an assessment of the impacts of climate change on agricultural crop yields and national sufficiency based on real observations and results obtained by previous research in Egypt. Both Regional Circulation Models (RCM) and Decision Support System for Agro-technology Transfer (DSSAT) have been used to generate climate projections up to 2050. Results indicate that climate model performance varies for different regions or processes under consideration; the Model ECHAM5 gives the best matching results to observations compared with other models. Climate change can exacerbate the food security crises that Egypt already faces, and without an urgent and comprehensive set of adaptation measures, Egypt may experience adverse impacts on more than one strategic crop.

Keywords: Climate Change, Global Circulation Models, Regional Circulation Models, mathematical computer models, temperature, Egypt.

INTRODUCTION

Egypt is very sensitive to climate change because it relies for about 95 percent of its fresh water budget on the Nile River (Rosenzweig *et al.,* 2002; World Bank Report, 2007). The Initial and Second National Communication reports (EEAA, 1999, 2010) reported that although Egypt's emissions from Greenhouse Gases is less than 1% of total global emissions, it is highly vulnerable to the adverse effects of climate change. A variety of research has highlighted the high sensitivity of the Nile River to temperature and precipitation change (Riebsame, 2005). Agriculture in Egypt is expected to suffer adverse impacts due to heat waves, which will affect the crop productivity of more than one strategic crop. These effects are intensifying because agriculture and agro-ecological systems are classified as the main economic drivers of Egypt (Riebsame, 2005). Additional research was conducted to simulate and assess climate change on crop yields and crop water requirements under different agro-climatological zones in Egypt (Abou Hadid, 2006; El-Marsafawy *et al.,* 2007). The studies projected a decrease in food production in Egypt by about 11-19% by 2050.

Adaptation to climate change can modify the projected harshness of food production (Easterling, 2007). Some economic changes (e.g. shifts in planting dates and converting to alternative and available crop mixtures) may balance the negative impacts; but the biggest benefits will likely arise from expensive actions comprising improvement of new crop collections and irrigation (Abou Hadid, 2006).

Seven Global Circulation Models (GCMs) were examined and compared with observed meteorological data from 1980 to 2010 at eight different locations representing different climate profiles in Egypt. Observed data from previous field experiments were used as inputs to the models. The efficiency of different Regional Climate Models (RCMs) in the downscaling process has been tested to select the best with a suitable GCM in Egypt. This study was carried out by running two RCMs on reanalyzed data at a higher resolution and comparing the results from both with observed data. The study concluded that the RegCM.4 model gives better results than PRECIS when compared with observations. An agricultural model was used to assess crop sensitivity to climate change. The aim of the study is to use models to assess the climate change impacts on some strategic crops (maize, milled rice and wheat) over the long run. Verifications of the model outcomes still need to be calibrated through implementation of more field experiments.

MATERIALS AND METHODS

A) Selection of Models:

(i) **Climate Models:**

- Seven climate models were selected for performance assessment, the list of models comprises (CCSM3, CCSR, ECHAM5, CCCMA, GFDL, CNRM and BCC); a short description of the GCMs is illustrated in Table (1).
- Analysis of time series and three statistical metrics were identified and used, i.e. the correlation coefficient, standard deviation and Root Mean

Square Error (RMSE). These statistical analytic approaches have been used for two climate variables (precipitation and temperature).

- The model's results were checked and compared separately with field measurements based on its power to emulate detected seasonal patterns of temperature and precipitation over Egypt region over the period 2005-2015; meteorological data were obtained from the Central Laboratory for Agricultural Climate (CLAC) – Agriculture Research Center (ARC).
- Eight weather stations were selected with high to low agricultural density covering most of the climatic profiles in Egypt.
- The efficiency of a GCM may change depending upon meteorological elements and regions. Typically, GCMs are verified for their power to emulate dimensional patterns of specific meteorological elements and their periodicity (McKendry *et al.,* 1995; Huth, 1997, Nemesova and Kalvova, 1997; Nemesova *et al.,* 1999)

(ii) Agricultural Model:

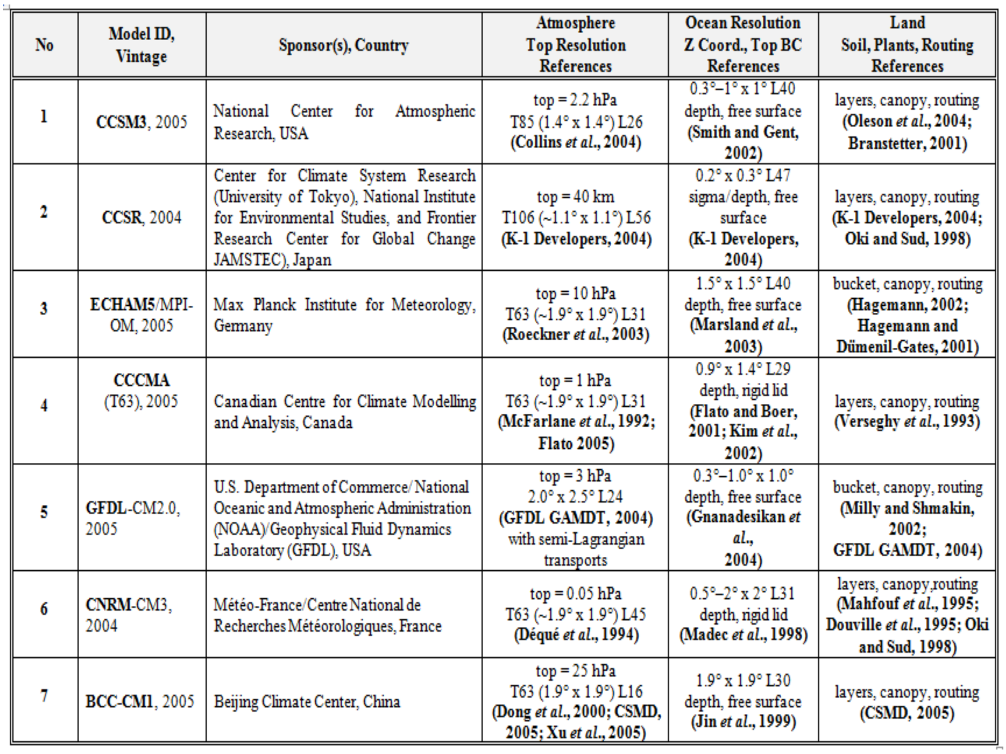
The Decision Support System for Agrotechnology Transfer (DSSAT) was selected; this is a software application with crop simulation models for more than 42 crops. The Model was used to assess crop sensitivity; specific major crops were selected based on the obtained results from most previous studies.

B) Identification of time duration and crops

Time durations of the study were selected using several different criteria. Among those criteria is the crop importance (strategic level of the crop) for a specific region considering the human population [Hunger Importance

Indicator (HII)]. Maize, milled rice and wheat were selected among the list of strategic crops of Egypt (**FAO, 2012**).

Table 1: List of selected Global Circulation Models for use in the study



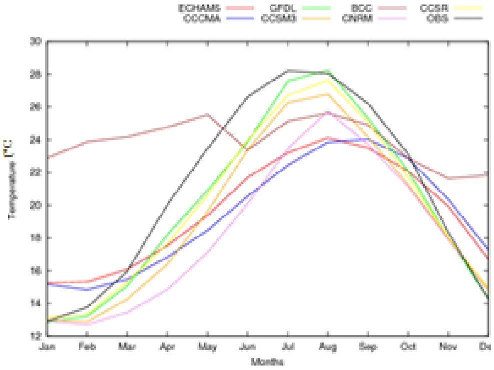
No	Model ID, Vintage	Sponsor(s), Country	Atmosphere Top Resolution References	Ocean Resolution Z Coord., Top BC References	Land Soil, Plants, Routing References
1	**CCSM3**, 2005	National Center for Atmospheric Research, USA	top = 2.2 hPa T85 (1.4° x 1.4°) L26 **(Collins *et al.*, 2004)**	0.3°–1° x 1° L40 depth, free surface **(Smith and Gent, 2002)**	layers, canopy, routing **(Oleson *et al.*, 2004; Branstetter, 2001)**
2	**CCSR**, 2004	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change JAMSTEC), Japan	top = 40 km T106 (~1.1° x 1.1°) L56 **(K-1 Developers, 2004)**	0.2° x 0.3° L47 sigma/depth, free surface **(K-1 Developers, 2004)**	layers, canopy, routing **(K-1 Developers, 2004; Oki and Sud, 1998)**
3	**ECHAM5**/MPI-OM, 2005	Max Planck Institute for Meteorology, Germany	top = 10 hPa T63 (~1.9° x 1.9°) L31 **(Roeckner *et al.*, 2003)**	1.5° x 1.5° L40 depth, free surface **(Marsland *et al.*, 2003)**	bucket, canopy, routing **(Hagemann, 2002; Hagemann and Dümenil-Gates, 2001)**
4	**CCCMA** (T63), 2005	Canadian Centre for Climate Modelling and Analysis, Canada	top = 1 hPa T63 (~1.9° x 1.9°) L31 **(McFarlane *et al.*, 1992; Flato 2005)**	0.9° x 1.4° L29 depth, rigid lid **(Flato and Boer, 2001; Kim *et al.*, 2002)**	layers, canopy, routing **(Verseghy *et al.*, 1993)**
5	**GFDL**-CM2.0, 2005	U.S. Department of Commerce/ National Oceanic and Atmospheric Administration (NOAA)/Geophysical Fluid Dynamics Laboratory (GFDL), USA	top = 3 hPa 2.0° x 2.5° L24 **(GFDL GAMDT, 2004)** with semi-Lagrangian transports	0.3°–1.0° x 1.0° depth, free surface **(Gnanadesikan *et al.*, 2004)**	bucket, canopy, routing **(Milly and Shmakin, 2002; GFDL GAMDT, 2004)**
6	**CNRM**-CM3, 2004	Météo-France/Centre National de Recherches Météorologiques, France	top = 0.05 hPa T63 (~1.9° x 1.9°) L45 **(Déqué *et al.*, 1994)**	0.5°–2° x 2° L31 depth, rigid lid **(Madec *et al.*, 1998)**	layers, canopy,routing **(Mahfouf *et al.*, 1995; Douville *et al.*, 1995; Oki and Sud, 1998)**
7	**BCC-CM1**, 2005	Beijing Climate Center, China	top = 25 hPa T63 (1.9° x 1.9°) L16 **(Dong *et al.*, 2000; CSMD, 2005; Xu *et al.*, 2005)**	1.9° x 1.9° L30 depth, free surface **(Jin *et al.*, 1999)**	layers, canopy, routing **(CSMD, 2005)**

RESULTS AND DISCUSSION

A) Climate Models Results

A time series analysis validation yields a a good comparison between the models' results and observations; the ECHAM5 GCM data give the best results in relation to observations compared with other models, the comparison between climate change scenarios A1B and A2 for ECHAM5 GCM by RegCM.4 were undertaken in order to choose the best of them for Egypt. It was found that applying the scenario A1B gives good results compared with A2. The mean annual cycles of models' simulated temperatures and precipitations were analyzed for the eight stations and compared to observations. The Alexandria station was selected in this study as an example, but the rest of the stations were treated using the same processes.

Figure (1.a) and Figure (1.b) show the annual cycle of the model's mean temperature and precipitation compared with the observation, for temperature, almost all GCMs reproduce quite well the annual cycle except the Chinese model (BCC) which failed to capture the temperature of the winter months, while for precipitation, all models capture the rainy (winter) season with an underestimation for some models and overestimation for others. However, all the models give a false precipitation via the dry (summer) season except the ECHAM5 and GFDL models which capture the characteristic feature of the wet (winter) and dry (summer) seasons.



Figure(1.a): The annual cycle of temperature for Alexandria as estimated using 7 models

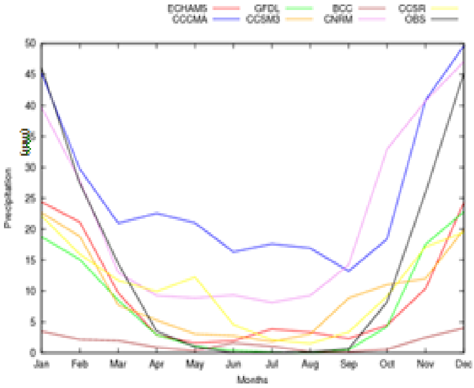


Figure (1.b): The annual cycle of precipitation for Alexandria as estimated using 7 models

A comparison between the models and observations with statistical methods such as the root mean square error (RMSE), correlation coefficient, and the mean absolute error (MAE) were processed.

Figure (2.a) shows the correlation for the temperature. It was found that all models have a good correlation in temperature. The correlation has values from 0.85 up to 0.97 except for the BCC model which is anomalous because it gives a very high overestimation especially in the winter months. Figure (2.b) shows the correlation for the precipitation; it was found that Alexandria as a rainy station has a good correlation relative to the other stations.

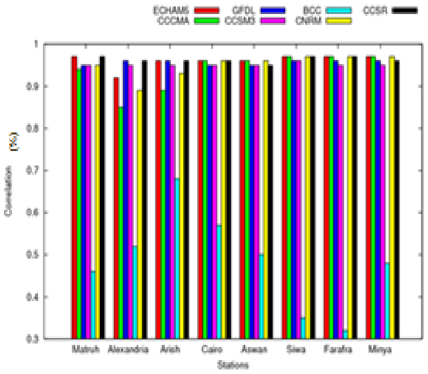


Figure (2.a): The temperature correlation as estimated using 7 models

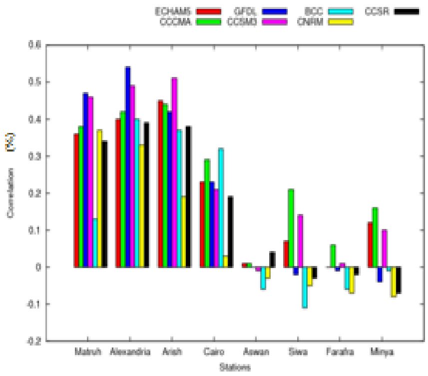


Figure (2.b): The precipitation correlation as estimated using 7 models

The Mean Absolute Error (MAE) test was applied to evaluate the models, for temperature, Figure (3.a) shows that the models vary within a small range except for the BCC model which has the largest MAE, while for precipitation it was found that the error was big.

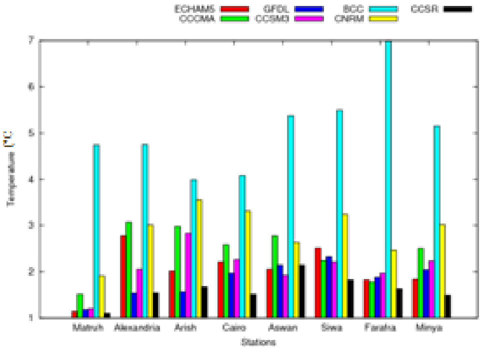


Figure (3.a): The temperature Mean Absolute Error (MAE) as estimated using 7 models

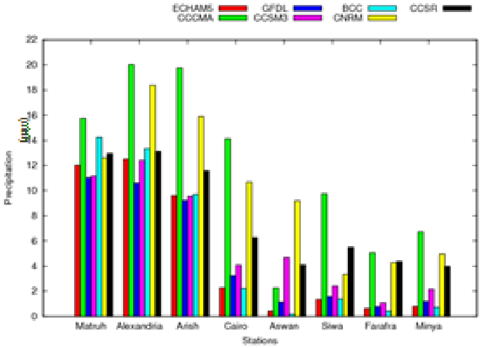


Figure (3.b): The precipitation Mean Absolute Error (MAE) as estimated using 7 models

The Root Mean Square Error (RMSE) test was applied also; it was found that similarly to the results of the MAE, the BCC is the anomalous one with a very high error as shown in Figures (4.a) and (4.b).

The analysis indicates that the ECHAM5 presented the best results; and it was concluded that ECHAM5 is the most suitable model for Egypt

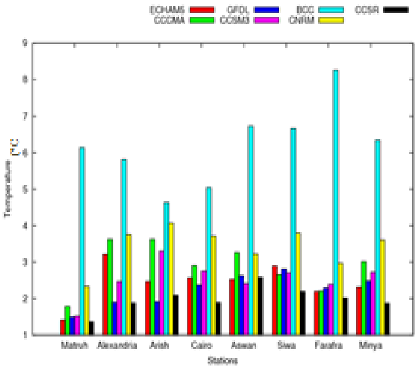


Figure (4.a): The temperature Root Mean Square Error (RMSE) as estimated using 7 models

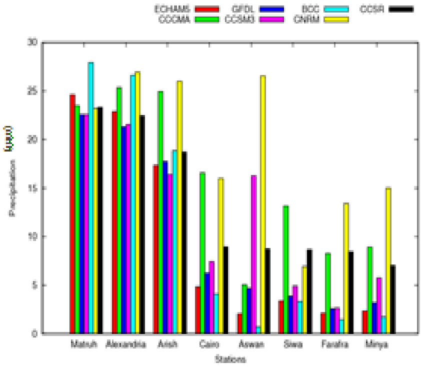


Figure (4.b): The precipitation Root Mean Square Error (RMSE) as estimated using 7 models

B) Crop Models Results

The meteorological data (temperature and precipitation) resulting from GCM was used as input for crop models; the crop model outputs concluded that strategic crops are characterized by self-sufficiency under future climate change conditions until 2050 (with no climate change impacts, which is known as the Business-As-Usual scenario), as illustrated in Table (2) and Figure (5), if the cultivated land and crop yield are the same as the current, self-sufficiency with maize, milled rice and wheat which may record 25.6%,83.2% and 29.7% compared to 53.6%,160.9% and 57.4%. Considering increase in population growth rate, water supply shortage and sea level rise and its effect on soil salinization of the North Nile Delta which could decrease the total agriculture area, all these factors will increase the crop sensitivity to climate change in the future. Input data were based on Central Agency for Public Mobilization and Statistics (**CAPMS 2013**).

Table 2: Estimated rates of self-reliance and self-sufficiency in the main crop yields, with no climate change impacts (Business As Usual Scenario-BAU)

Main food commodities	**Crop yield of 2011**			**Crop yield estimates in 2050 (no climate change impacts)**		
	Prod. (1,000 tons)	**Requirements (1,000 tons)**	**Self suf.(%)**	**Prod. (1,000 tons)**	**Requirements (1,000 tons)**	**Self suf.(%)**
Wheat	8407	14650	57.4	8407	28251	29.7
Milled rice	5675	3528	160.9	5675	6821	83.2
Maize	6876	12827	53.6	6876	26840	25.6
Population	83 millions			158 millions		

Resulting outcomes from the current study agree with Fahim *et.al* (2013) who found that yield declines for strategic crops would be about 25% by 2030 because of climate change effects; the results anticipate that the continuous increase in greenhouse gas emissions into the atmosphere because of what mankind’s actions induce will dramatically impact crop yields and consequently crop prices. Meanwhile, if Egypt engages in adaptation measures in relation to climate change, as shown in Table (3), and with the increase of cultivated land and production by 10% (as stated in the Sustainable Agriculture Development Strategy Towards 2030, SADS), then maize, milled rice and wheat self-sufficiency could reach 23%, 136.1% and 40% by 2050 respectively.

Table 3: Estimated rates of self-reliance and self-sufficiency in the yield of main crops under climate change with and without adaptation actions (Models Simulated)

Main food commodities	**2050 estimates with climate change + no adaptation action**			**2050 estimates with climate change + adaptation action**		
	Prod. (1,000 tons)	**Requirements (1,000 tons)**	**Self suf.(%)**	**Prod. (1,000 tons)**	**Requirements (1,000 tons)**	**Self suf.(%)**
Wheat	7535.8	28251	26.7	11303.6	28251	40
Milled rice	6078.3	6821	89.1	8576.3	6821	136.1
Maize	5766.4	26840	21.5	6174.6	26840	23
Population	158 millions			158 millions		

The resulting outcomes from the current study correspond to a considerable degree with results of some previous studies (Hassanien *et.al*, 2007; Abolmaaty *et al.,* 2010; Yones *et al.,*2011; Fahim *et al.,* 2013), while being different in terms of the level of self-sufficiency of some strategic crops in Egypt under a "no adaptation action" as the continuous increase in national population adds additional burden to climate change’s adverse effects and it can be expected to decrease the level of self-sufficiency of strategic crops under study to lower than 3 to 5%.

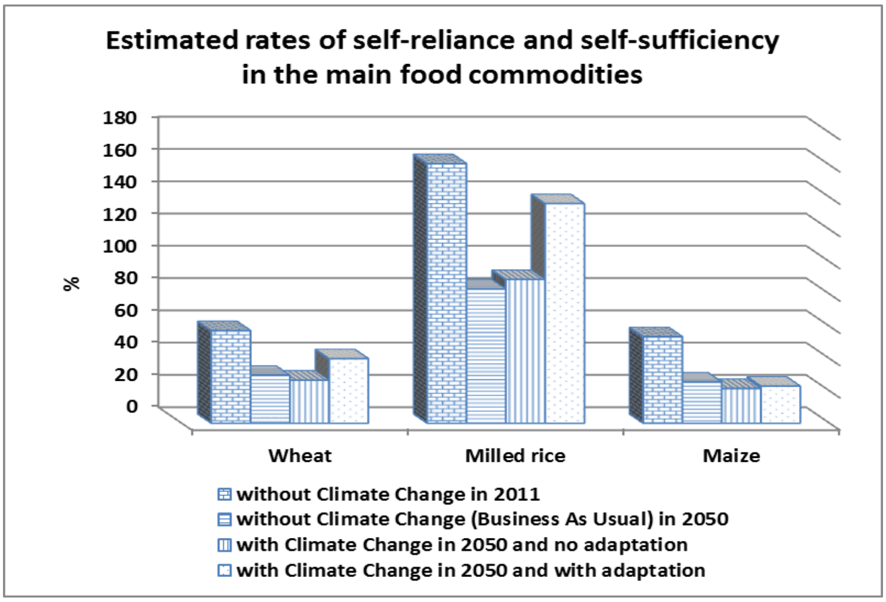


Figure (5): Changing in the main crop yield self-sufficient in Egypt up to 2050 under different scenarios.

C) Climate change effects on selected strategic crops in Egypt

The crop model DSSAT and other RCM models were processed to project climate change effects on selected crop yields; also some previous field studies have predicted production decreases in the major crops in Egypt as shown in Table (4) and Table (5).

Table 4: Change in major crop yield production in Egypt by the year 2050 due to climate change.

		Crops		
	Item	**Maize**	**Rice**	**Wheat**
Current	Yield (t/ fed)	3.6	4.3	2.9
	Area (Mfed)	2.0	1.9	3.1
	Total Yield (Mt)	6.6	7.6	8.4
Projected	Change (%)	-23.4	-15.8	-19.8
	Yield Deficit (Mt)	-1.8	-1.2	-1.6

Resulted outcomes from the current study agree with Fahim *et.al*. (2013) who found that changes in crop productivity are mainly related to the projected increase in temperature, which negatively affect cereal filling time and have significant effects on the essential flowering stage, and consequently impact the quality and yield of the crop. In addition, the current study shows that crop-water stress under projected threats due to the projected yearly deficiency of the Nile water budget because of dam construction in the upper areas of the Nile Basin will be other factors causing productivity reduction under climate change. Among the results of the DSSAT crop model, it was noted that climate change effects on the crop yield of wheat because of increasing temperature will reduce the length of the crop growing period and negatively affect the yield.

Hassanein *et al*. (2012) showed that for the scenario of temperature increasing by +1.5° C, the model predicted that a decrease in cereal crop yield would be in the rage of 12% at Sakha, 9% at Sids and 11% at Shandaweel. While for the scenario of +3.5°C the cereal crop yield would be reduced by about 27 % at both the Sakha and Sids locations, and by about 31% at the

Shandaweel location. The results of the current study agree with Hassanein *et al.* (2012) and added that a high probability in the future with an accelerating growing cycle, the wheat crop yield could be decreased at the three locations, particularly under the +3.5°C scenario, which implies earlier cultivation and specific agricultural practices.

Table 5: Projected changes in crop production of some major crops in Egypt under climate change conditions

Crop	**Change %**		**Reference**
	2050s	**2100s**	
Cotton	**+17%**	**+31%**	**Eid** *et al.*, **1997a**
Maize	**-19%**		**Eid** *et al.*, **1997b**
Maize	**-14%**	**-20%**	**Hassanien and Medany 2007**
Potato	**-0.9 to -2.3%**	**+0.2 to +2.3 %**	**Medany and Hassanein 2006**
Rice	**-11%**		**Eid and El-Marsafawy 2002**
Soybeans	**-28%**		**Eid and El-Marsafawy 2002**

CONCLUSION AND RECOMMENDATIONS

The potential decreases in food production until 2050 are not significantly small. Strengthening agricultural research and experiments under different climatic circumstances to reach resilient agricultural ecosystems, and expanding the cultivated area are priorities. Until 2050, the most serious and widespread agricultural and food security problems related to climate change are likely to arise from the impact of climate variation, and not from progressive climate change, although the latter will be important where it compounds existing agro-climate constraints.

Policies for agricultural development will need to emphasize the importance of improving not just the production capacity of agricultural ecosystems but also their diversity and resilience.

It's recommended that future studies take into consideration the assessment of the on-farm irrigation management, cultivation dates, cropping patterns and risk assessment tools to identify agricultural vulnerability and adaptation in Egypt.

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تقييم المخاطر والتكيف مع التغيرات المناخية على قطاع الزراعة باستخدام النماذج الرياضية

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المستخلص

تمثل الزراعة قضية اقتصادية كبرى بالنسبة لمصر، فهي مصدر أساسي للغذاء، والتجارة الدولية، واستخدامات الأراضي والمياه، وكمُنْتج أساسي لتصنيع المواد الغذائية والألياف. ويُعزي تعرض الزراعة للتغيرات المناخية أساسا إلى المعاملات الاجتماعية- الاقتصادية، والطبيعية- الحيوية. وسيؤدي تغير المناخ للتأثير على إنتاجية المحاصيل الزراعية التي بالتالي ستؤثر على الأمن الغذائي في كافة مراحله بدءا من الحصول على الغذاء، واستقرار الإمدادات الغذائية، وإنتاج وتجارة الغذاء. والهدف من هذه الدراسة هو تقييم تأثيرات التغيرات المناخية ونسبة الاكتفاء الذاتي من المحاصيل باستخدام النماذج المناخية والزراعية اعتمادا على مدخلات لتجارب زراعية بالحقل بالإضافة إلى نتائج عدد من الدراسات التي أجُريت بمصر. تم استخدام النماذج المناخية للدوران، وكذا نماذج دعم واتخاذ القرار ونقل التكنولوجيا الزراعية لتطوير توقع مناخي حتى عام ٢٠٥٠. أوضحت النتائج أن كفاءة مخرجات نماذج المناخ تختلف باختلاف المناطق وإجراءات النمذجة، وأن النموذج المناخي ECHAM5 يعطي أفضل النتائج الأقرب للواقع مقارنة بالنماذج الأخرى. وأن التغيرات المناخية يمكن أن تساهم في الإسراع من أزمة الأمن الغذائي التي تعاني منها مصر بالفعل.