Evaluation of Climate Change Impacts on Cotton Yield using Cropsyst and Regression Models

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Abstract

The regional as well as the international crop production is expected to be influenced by climate change. This study describes an assessment of simulated potential cotton yield using CropSyst, a cropping systems simulation model, in Northern Greece. CropSyst was used under the General Circulation Model CGCM3.1/T63 of the climate change scenario SRES B1 for time periods of climate change 2020-2050 and 2070-2100 for two planting dates. Additionally, an appraisal of the relationship between climate variables, potential evapotranspiration and cotton yield was done based on regression models. Multiple linear regression models based on climate variables and potential evapotranspiration could be used as a simple tool for the prediction of crop yield changes in response to climate change in the future. The CropSyst simulation under SRES B1, resulted in an increase by 6% for the period 2020-2050 and a decrease by about 15% in cotton yield for 2070-2100. For the earlier planting date a higher increase and a slighter reduction was observed in cotton yield for 2020-2050 and 2070-2100, respectively. The results indicate that alteration of crop management practices, such as changing the planting date could be used as potential adaptation measures to address the impacts of climate change on cotton production.

Indexing terms/Keywords: Climate Change; Cotton Yield; Cropsyst Model; Regression Models; Adaptation Measures

Subject Classification: Agriculture and Climate change

Type (Method/Approach): Crop growth simulation model; Regression models

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Introduction

Climate change is the largest threat the world ever faced as it widely affects the earth's natural resources from tropical to arctic and from sea to land and atmosphere. As reported by IPCC [1], the climate system warming is unequivocal**,** and since the 1950s, the majority of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean temperatures have increased, the sea level has risen and the amounts of snow and ice have diminished. The warming of the climate is primarily caused by increasing concentrations of greenhouse gases (CO_2, CH_4, O_3, CFCs and Nitrous oxide) produced by human activities such as the burning of fossil fuels and deforestation [2]. According to the fourth IPCC report for climate change [2], the Mediterranean Basin will be among the areas to be most adversely affected in terms of a rise in temperature, a decrease in overall water balance and a higher frequency of extreme climatic events.

An issue of global concern is the possible change in crop production in response to different scenarios of climate change. Agricultural crop production is significantly affected by climate variables because photosynthetically active radiation, air temperature and water are the driving forces for crop growth [3, 4, 5]. Most plants grown under increased atmospheric CO_2 conditions show an increased rate of photosynthesis and this manifests itself in higher biomass accumulation [6]. But in the case of C4-plants, there is uncertainty as to whether or not there is an increase in the photosynthetic rate. Climate change will significantly alter the conditions for crop production, with important implications for worldwide food security [4, 5].

Cotton is a crop of high importance for Greek agricultural production. Greece is the biggest cotton producer in the European Union accounting for almost 80% of its total production [7]. Several studies have been conducted to assess the potential impacts of climate change on cotton yields at different locations around the world. Yoon et al. [8] reported that an elevated CO_2 concentration could increase both the above ground biomass and boll weight of cotton. According to Bange et al. [9], the restriction of water resources induced by climate change in Australia will adversely affect cotton production in respect to other crops and make imperative a continuous effort for improvement in whole farm and crop water use efficiency. In a recent interdisciplinary study funded by the Bank of Greece [10], it was predicted that cotton yields were going to increase in the climatic zones of Northern and Western Greece, but decline in Central-Eastern Greece under the A1B and A2 emission scenarios. A study by Voloudakis et al. [11] revealed positive impacts of climate change on seed cotton yields in the areas of Western Greece and negative impacts or great fluctuations in Northern and Central Greece. Increased temperatures associated with global warming will have an impact on plant development in species where the growth rate is directly dependant on thermal time. Such plants, including cotton, are more likely to demonstrate an advancement in their phenological stages [12].

Despite the progress in providing data and the understanding of crop yield predictions, it is not currently possible to create future ecosystems or the atmospheric and climatic conditions that will occur in the future. This, therefore, justifies the use of models for predicting and simulating crop responses to future conditions. Crop simulation models use long-term weather data to account for weather variability in assessing risks involved with adopting alternative crop management strategies at a site of interest [13]. CropSyst (Cropping Systems Simulation Model) is a multi-year multi-crop simulation model developed to study the effect of cropping systems management on productivity and environment [14, 15]. This model has been used to simulate the growth and development of several crops such as maize, wheat, barley, soybean and sorghum with generally good results [16] in many parts of the world, i.e. Mali [17], United Kingdom [18], Italy [19], western USA, southern France, northern Syria, northern Spain and western Australia. CropSyst has also been used to investigate potential impacts of climate change on crop production (e.g., [20, 21, 22]).

Another common approach for the prediction of crop yield responses to climate change is the use of statistical models and some simplified measurements of weather variables, such as temperature and precipitation. The main advantages of these models are their limited reliance on field calibration data and their transparent assessment of model uncertainties [23]. For example, if a model does a poor job of representing crop yield responses to climate, this will be reflected in a low coefficient of determination (R^2) between modeled and

observed quantities, as well as a large confidence interval around model coefficients and predictions [23]. Research has shown that predictions of the yield changes in response to changes in climate variables, from regression models based on historical climate data for specific crops are relatively accurate [24, 25, 26].

In view of the impacts of climate change on agriculture, there is the need to develop adaptation measures aiming at high standards of production and limiting the unfavorable impacts on crop production. Increasing the amount of applied irrigation and nitrogen fertilizers and changing the planting date could be used as adaptation measures to make crops more resilient to climate change. In former studies [20, 27], early sowing for summer crops had a positive effect on crop yield. Furthermore, altering of the irrigation schedule could provide a cheap and easy to implement adaptation option, as long as the increased amount is low. Results by Ouda et al. [28] showed that either irrigation schedule could reduce yield losses and increase water use efficiency, without low additional amount of irrigation water.

The objective of this study was to investigate the effect of climate change on cotton yield in Agios Mamas area in Northern Greece for the middle (2020-2050) and the end (2070-2100) of the running century. The predictions were based on the implementation of CropSyst under the General Circulation Model (GCM) CGCM3.1/T63 of the climate change scenario SRES B1 for the time periods of climate change 2020-2050 and 2070-2100. Additionally, another approach for the prediction of cotton yield was used with multiple regression models based on climate variables. This study could help policy makers to integrate and implement relevant adaptation strategies for reducing the negative effects of climate change, such as shifting to an earlier planting date which is a feasible and easy to implement adaptation strategy. Therefore, this research seeks to investigate the potential of cotton production in Nothern Greece under predicted future climate and to identify possible ways of addressing the impact of climate change.

Materials and Methods

Study area and data sets

The impact of climate change on cotton yield was studied in Agios Mamas area in the prefecture of Chalkidiki in Northern Greece (Figure 1). The study area was selected because of its meteorological station (40°15′ N lat; 23°20′ E long) whose meteorological data were used in order to generate the climate change scenarios and to estimate the cotton yield in the study area. The study area is agricultural with irrigated regions. The area of Agios Mamas was also selected because its meteorological station allocates the following advantages: i) the most meteorological data in daily time step, and ii) it is located in low altitude and therefore, describes better the conditions of irrigated regions as they are found in similar altitude and in close proximity to the station.

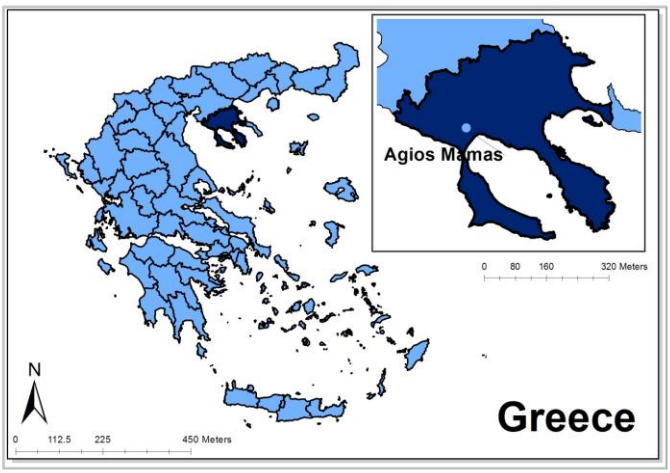


Figure 1. The location of Agios Mamas in Greece.

Crop growth simulation was performed for cotton (*Gossypium hirsutum* L.) and planting and harvest dates were set on 21 April and on 29 September, respectively. The application of irrigation was in eight doses and the total amount of water applied was 473 mm. The total fertilizer application was obtained from data from studies on cotton. Cropping system management practices including land preparation, crop rotation, variety selection, pesticide applications, tillage operations, residue management and other agronomic practices of the crop were applied as per the recommendation of CropSyst. Two simulation scenarios were designed to investigate the impact of climate change on cotton yield. For the first scenario, the CropSyst model was run to predict cotton yield for the baseline climate (1977-1997) to simulate historic yields and for the projected climate (2020-2050 and 2070-2100) maintaining traditional planting date assuming that the management practices will be preserved in the future. The second simulation scenario was designed to investigate the utility of an earlier planting date as an adaptive strategy to climate change by running CropSyst for the projected climate using an earlier planting date (21 March) maintaining steady all the management practices.

Climate change scenarios

In order to provide information on possible changes in the climate, climate change models are used and they are forced to consider future scenarios. The B1 emission scenario (SRES), developed by the IPCC Special Report on Emissions Scenarios [29], was used for the prediction of climate change in this study. The B1 scenario describes a convergent world with a global population that peaks in mid-century and declines thereafter but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies [29].

In this study, the CGCM3.1/T63 [30] which is a Coupled Atmosphere-Ocean General Circulation Model (AOGCM) developed at the «Canadian Centre for Climate Modelling and Analysis» (CCCma) was used and considered as significantly more sophisticated than earlier versions. This model has a surface grid whose spatial resolution is roughly 2.8 degrees lat/lon and 31 levels in the vertical. The ocean grid shares the same land mask as the atmosphere and there are six ocean grids underlying every atmospheric grid cell. The ocean resolution is therefore approximately 1.4 degrees in longitude and 0.94 degrees in latitude. Weather data were obtained from the General Circulation Model (GCM) CGCM3.1/T63 for two time periods of climate change, 2020-2050 and 2070-2100 under SRES B1 and for the baseline period (1977-1997) for climate change impact assessment.

Stochastic models that generate a suite of long series synthetic weather data from observed weather data have become important to address the inadequacy of short-term observed weather data, for analysis of agricultural, hydrological, environmental and other weather-driven systems [31, 32, 33]. ClimGen [34], a daily time step stochastic model, generates daily precipitation (Pr in mm), maximum and minimum temperature (T_{max}, T_{min} in ^{o}C), solar radiation (R_s in MJ $m^{-2}d^{-1}$), maximum and minimum relative humidity (RH_{max}, RH_{min} in %) and wind speed (u_2 in m s^{-1}) data series with similar statistics to that of the historical weather data. The model requires inputs of daily series of these weather variables to calculate the parameters used in the generation process for any length of period at a location of interest. ClimGen preserves, in the generated weather data, the correlation among the weather variables as well as the seasonal characteristics in the actual weather variable at the site of interest and, thus, does not take into account the climatic extremes and climatic variability that are expected to be increased in the future [34].

Based on the data derived from the General Circulation Model CGCM3.1/T63, the downscaling of a 20-year data set (1977-1997) of daily climate variables performed using the weather generator GlimGen, which is embedded in CropSyst, for the generation of synthetic time series which depict the future change of the above climate variables. In the case of precipitation, a 25-year data set (1975-2000) was used in order to meet the model's requirements for the synthetic generation of precipitation. For the different climate variables, the change between the baseline period and the period of climate change was calculated. According to that change, the historic data series of the study area was perturbed. The perturbed time series then was used by ClimGen for the generation of synthetic time series of the weather variables which preserve the statistic characteristics of the historic time series. The generated weather data series was compared with the observed weather data series

for their means, variance and skewness coefficient for the confirmation of the ability of the method in the synthetic generation of time series. The observed and generated weather data series were used as inputs to the CropSyst model to simulate potential cotton yields for the two periods of climate change 2020-2050 and 2070-2100 under B1 SRES.

CropSyst simulation model

CropSyst crop growth simulation model [15] was used to assess the response of cotton to climate change. CropSyst is a multi-year, multi-crop, daily time step crop growth/management simulation model with a link to GIS software and a weather generator and can serve as an analytical tool to study the effect of cropping systems management on crop productivity and the environment [14, 35]. For this purpose, CropSyst simulates the water and nitrogen budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition and soil erosion by water. The main inputs are weather variables (precipitation, maximum and minimum temperature and solar radiation) on a daily time step with the model allowing the user to specify management options, such as sowing, irrigation, organic and inorganic nitrogen fertilization, tillage, harvest, etc.

The model was selected for its robustness and relative ease of application, using commonly available data. Also, CropSyst is credited with the capability to simulate the growth of many crops from a uniform structure and a common set of parameters. This represents an advantage over separate model representations of crops in simulating the productivity of agricultural systems where multi- and inter-cropping rather than mono-cropping systems are dominant. CropSyst has data requirements that can be reasonably met and provides support utilities to fill in missing inputs based on well-established procedures (e.g., pedotransfer functions to derive soil hydraulic parameters). It therefore provides a conceptually unified modelling system for many crops, minimizing the dangers of structural uncertainty in making both cross crop and inter-spatial comparisons [18]. As such, it is able to well represent the variation in yield determined by weather-driven environmental conditions and respond to specific management regimen. The evaluation of CropSyst model for simulating the potential yield of cotton in Uzbekistan showed that early cotton growth and leaf area index development could be simulated with sufficient accuracy while final aboveground biomass was slightly overestimated because some unaccounted plant stress at the sites diminished actual aboveground biomass [36]. Simulations of early cotton aboveground biomass development in India matched the field data reasonably well [37].

Multiple linear regression models

There are a number of climate variables impacting crop yield, with temperature, precipitation, and solar radiation being the most widely used to assess climate change and its impact. Generally, at any time (year), crop yield can be expressed as the sum of management and climate contributions which can be described as [38, 39]:

$$y = y_c + y_m \quad (1)$$

where y is the crop yield; y_c is the climate induced crop yield; and y_m is the crop management (including technology and any other non-climate factor) induced crop yield. Crop management induced crop yield, is mainly determined by the development level of productive forces (science and technology) and the climate induced crop yield mainly reflects the short-term yield fluctuation caused by climate change factors [23].

Crop yield, due to the influence of technological and environmental factors, shows increasing trends. For separating the contributions of climate and crop management, the trends in crop yield can be extrapolated using smoothing techniques, such as moving average which reveal more clearly the underlying trend, seasonal and cyclic components. A moving average is taken to estimate the current value of the mean and then is used as the forecast for the near future and is often called a "smoothed" version of the original series. Moving average techniques include the simple (SMA), the weighted (WMA) and the exponential moving average (EMA). In this

study, the simple moving average was used to extract the crop yield that reflects the climate effects, and is calculated as follows:

$$y'_c = \frac{1}{k}\sum_{n=0}^{k-1} y_{c-n} = \frac{y_c + y_{c-1} + y_{c-2} + \ldots + y_{c-k+1}}{k} \quad (2)$$

where y'_c is the series of climate induced crop yield, n is the sample number and k is the sliding length.

Finally, in order to establish the relationships between climate variables, potential evapotranspiration and climate induced crop yield, multivariate linear regression was used. The climate induced crop yield is a result of comprehensive climate conditions. The multiple linear regression model is described as follows [23]:

$$y = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \ldots + \alpha_k x_k \quad (3)$$

where y is the climate induced crop yield; α_0 is the regression constant; α_1, α_2, …, α_k are the partial regression coefficients; and x_1, x_2, …, x_k are the different climate variables.

A regression model selection was performed, considering cotton yield as the dependent variable and climate variables (maximum and minimum temperature, precipitation, solar radiation, maximum and minimum relative humidity and wind speed) and potential evapotranspiration of the historical period (1977-1997) as the independent variables. The relationships between the dependent and independent variables were established using six multiple linear regression models.

According to the multiple regression models, the cotton yield was calculated for the two periods of climate change (2020-2050 and 2070-2100) and was compared with that derived from CropSyst. The models' performance was evaluated using a variety of standard statistical criteria including the correlation coefficient (R), the root mean square error (RMSE), the relative error (RE), the mean error (ME), the mean percentage error (MPE) and the coefficient of residual mass (CRM). The above statistical criteria are given by the mathematical equations [40, 41, 42]:

$$R = \frac{\sum_{i=1}^{n}\left(y_{o,i} - \bar{y}_o\right)\left(y_{s,i} - \bar{y}_s\right)}{\sqrt{\sum_{i=1}^{n}\left(y_{o,i} - \bar{y}_o\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_{s,i} - \bar{y}_s\right)^2}} \quad (4)$$

$$RMSE = \frac{\sqrt{\left(\sum_{i=1}^{n}\left(y_{o,i} - y_{s,i}\right)^2\right)/n}}{\bar{y}_o} \quad (5)$$

$$RE = \frac{\sqrt{\sum_{i=1}^{n}\left(y_{o,i} - y_{s,i}\right)^2}/n}{\bar{y}_s} \quad (6)$$

$$ME = \frac{\sum_{i=1}^{n}\left(y_{o,i} - y_{s,i}\right)}{n} \quad (7)$$

$$MPE = \frac{\sum_{i=1}^{n} \frac{(y_{o,i} - y_{s,i})}{y_{o,i}} 100}{n} \quad (8)$$

$$CRM = \frac{\sum_{i=1}^{n} y_{s,i} - \sum_{i=1}^{n} y_{o,i}}{\sum_{i=1}^{n} y_{s,i}} \quad (9)$$

where $y_{o,I}$ is the simulated yield by CropSyst at year i; $y_{s,i}$ is the calculated yield by the multiple linear regression models at year i; $\bar{y}_o$ is the mean simulated yield by CropSyst; $\bar{y}_s$ is the calculated yield by the multiple linear regression models and n is the total number of years. If the model performs well, the values of R should be close to unity. The RMSE values show how much the calculated under- or over-estimate the simulated yield. A low RE implies good model performance and vice versa. ME is used to measure how close the calculated yield is to the simulated by CropSyst and MPE is the percentage of ME. The CRM is a measure of the tendency of the model to overestimate or underestimate the simulated yield by CropSyst. Positive values for CRM indicate that the model underestimates the measurements and negative values for CRM indicate a tendency to overestimate. For a perfect fit between simulated and calculated data, values of RMSE and CRM should equal zero.

Results and Discussion

Projected climate change

This study was mainly focused on the impact of changes in temperature and precipitation and the CGCM3.1/T63 model predicted that the average temperatures during the periods 2020-2050 and 2070-2100 will be above the average temperatures recorded during the 1977-1997 baseline period, an indication that the future climate will be warmer than the past. The simulation results indicate that future annual maximum air temperature is projected to increase by 1.83°C and 2.70°C, while annual minimum air temperature will increase by 0.88°C and by 1.67°C under SRES B1 during the periods 2020-2050 and 2070-2100, respectively. The annual precipitation is predicted to decrease by 8% and 3% during the periods 2020-2050 and 2070-2100. The yearly changes in the climate variables for the baseline period and the periods of climate change are depicted in Figure 2. The median value of climate change projections showed a warming trend and decreased precipitation during the cotton growing season (Apr. to Sept.). The seasonal (during the growing season) maximum temperature increased by 1.74°C and 2.46°C and the minimum temperature by 1.74°C and 2.22°C in the years 2020-2050 and 2070-2100 under SRES B1, respectively and the precipitation of the growing season decreased by 18% and 19%, correspondingly. As expected, the warming trends in the cotton growing season were moderately higher than in the annual and the decrease in the seasonal precipitation was higher than in the annual. The GCM produced lower changes in seasonal temperature and precipitation for the earlier planting date both during 2020-2050 and 2070-2100. The differences from 1977-1997 were as high as -0.65°C and 0.11°C for maximum temperature and 0.09°C and 0.51°C for minimum temperature during the periods 2020-2050 and 2070-2100, respectively. With regards to the changes in seasonal precipitation for the earlier planting date, the decrease was 2% and 12% in the periods 2020-2050 and 2070-2100. Potential evapotranspiration of cotton will increase by 3% and 15% during the periods 2020-2050 and 2070-2100, respectively. For the earlier planting date, the potential evapotranspiration is predicted to decrease by 3% during 2020-2050 and to increase by 9% during 2070-2100. The changes in the climate variables of the growing period and the potential evapotranspiration of cotton for the periods of climate change for the two planting dates are depicted in Figure 3.+

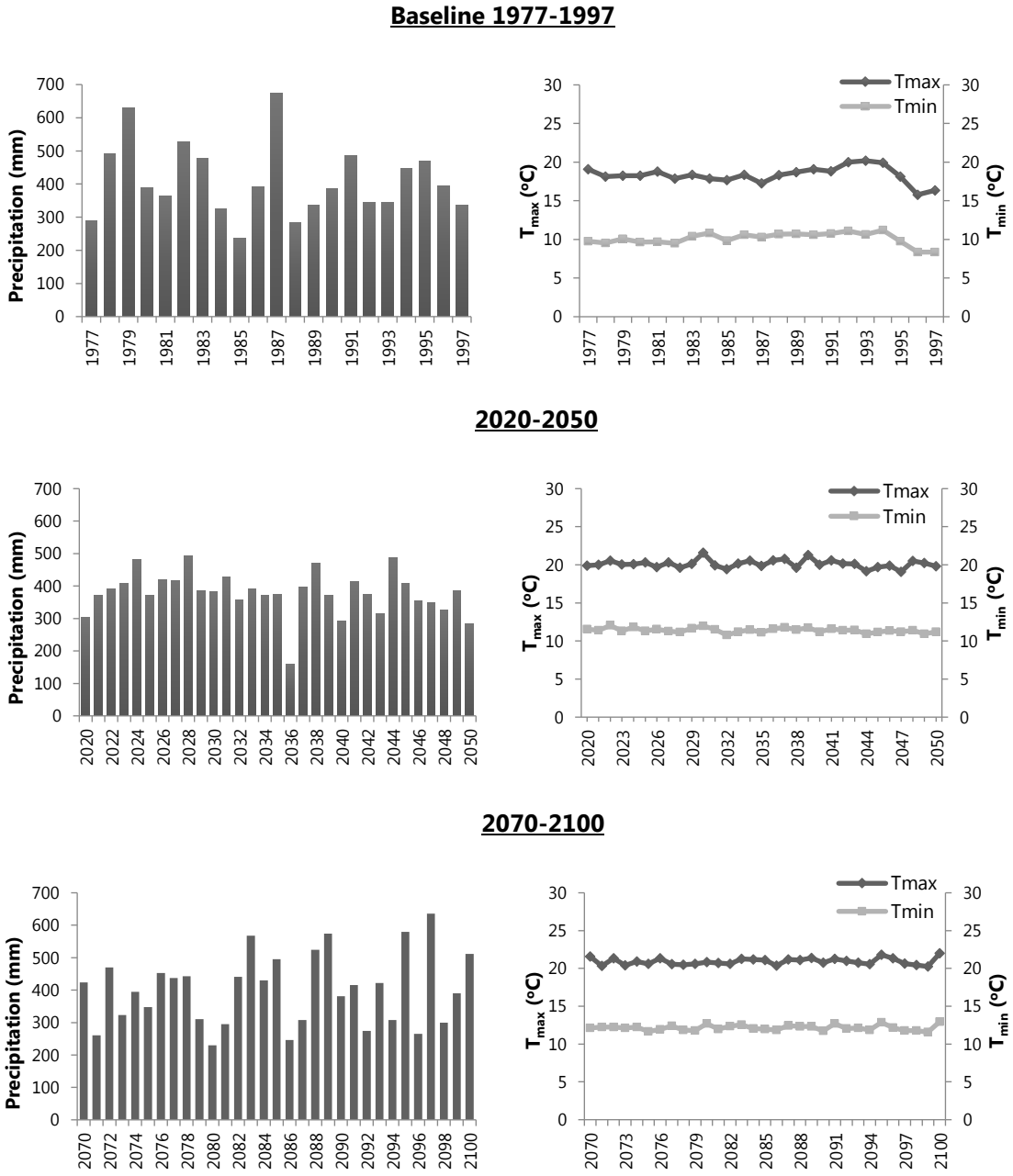
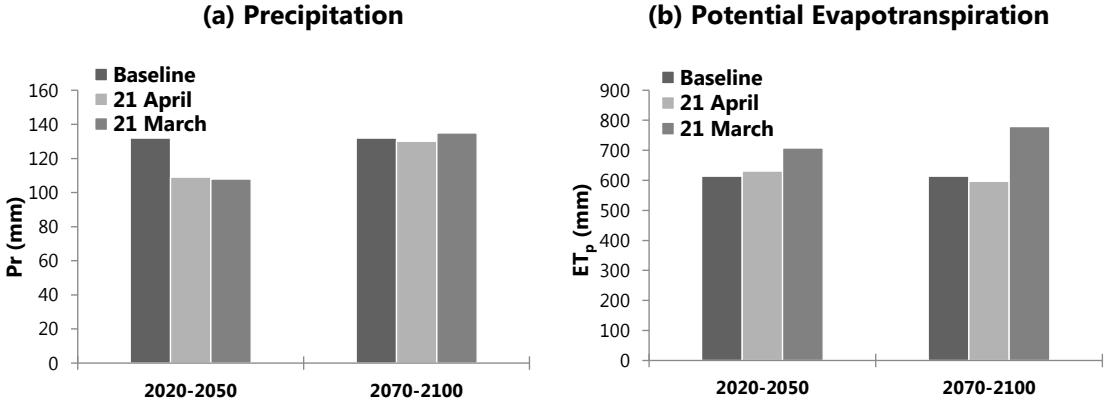


Figure 2. Differences in yearly precipitation, maximum and minimum temperature during 2020-2050 and 2070-2100, under SRES B1 in relation to baseline period 1977-1997.



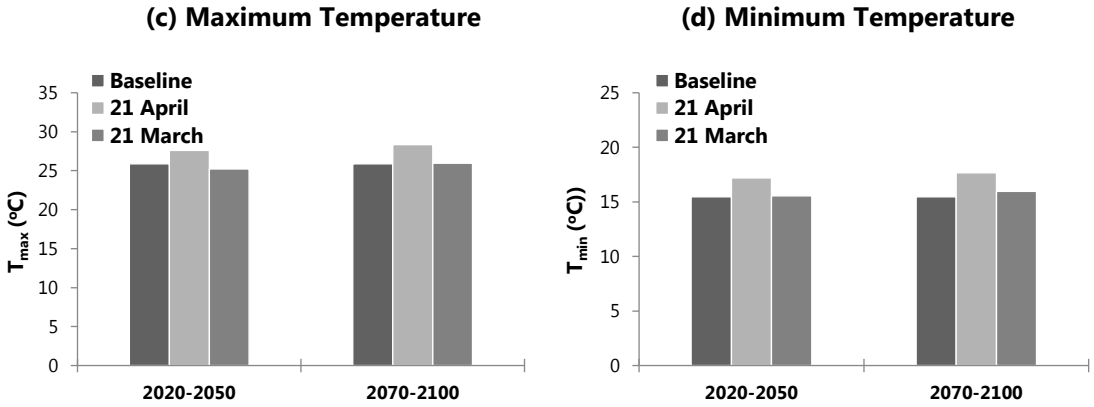


Figure 3. Differences in seasonal (a) precipitation, (b) potential evapotranspiration (c) maximum and (d) minimum temperature of cotton for two planting dates (21 April and 21 March) during 2020-2050 and 2070-2100, under SRES B1 in relation to baseline period 1977-1997.

Assessment of cotton response to climate change using CropSyst

Impacts on cotton yield

CropSyst model was run to predict cotton yield for the baseline period (1977-1997) and for the climate change periods 2020-2050 and 2070-2100 under SRES B1 scenario, respectively for two planting dates. The simulated results show the effect of precipitation and temperature changes on mean crop yield in future maintaining the irrigation in the same amounts with the baseline period. The crop yield which is based on the above ground biomass, increased by 6% under the climate medium-term projection (2020-2050) while decreased by 15% for the long-term projection of 2070-2100 compared to the present-day value. These results indicate that keeping the present irrigation practices might have beneficial effects on cotton in the medium-term due to the slight increase in temperature relative to the baseline period. The expected reduction of precipitation during the growing season of cotton for the period 2070-2100 which is higher than for 2020-2050 has a major impact on crop production. During 2070-2100 where the warming was higher than during 2020-2050 under SRES B1, crop yield was found to decrease significantly with the precipitation changes being able to modulate the magnitude of this negative impact. Based on the crop simulations some key processes and their interactions, account for the detrimental effect of temperature increase on crop yield, for long-term projections (2070-2100). First, the water stress is amplified with an increase of potential evapotranspiration (2070-2100) in water-limited soils, where the crop roots cannot take up more water. Second, a higher increase in temperature leads to a heat stress which when combined with the water stress results in a reduction in biomass production. Third, according to several studies, the number of maturity days (from sowing to harvest) is predicted to shrink, ranging from about 10 to 30 days shorter in the next few decades, which will also result in reduced biomass production [43]. Table 1 shows the differences in cotton yield for two planting dates in 2020-2050 and 2070-2100 relative to the baseline period.

Table 1. Differences in cotton yields (kg ha^{-1}) for two planting dates (21 April and 21 March) under SRES B1 during 2020-2050 and 2070-2100 relative to baseline period 1977-1997.

	Cotton Yield	
	CGCM3.1/T63	
Baseline	**SRES B1**	
period	**2020-2050**	**2070-2100**

	21 April	21 March	21 April	21 March
			kg ha^{-1}	
3493	**3685**	**4099**	**2963**	**3138**
	+192	+606	-529	-355
	+6%	+17%	-15%	-10%

Impacts on phenological dates

Climate change will have an impact on cotton phenology, since temperature changes influence the schedule of cotton germination, flowering and maturity. The phenological stages of cotton will slightly advance in the future due to the warming trend in spring. The projections revealed that the flowering and maturity date was 3 and 2 days earlier, respectively in 2020-2050 and 5 and 3 days earlier in 2070-2100, compared to the baseline period (Table 2).

Table 2. Phenological stages of cotton in 2020-2050 and 2070-2100 under SRES B1.

Phenological Stages	**CGCM3.1/T63**				
	Baseline period	**SRES B1**			
		2020-2050		**2070-2100**	
	Average Date	Average Date	Advance	Average Date	Advance
			days		days
Emergence	28 April	27 April	**1**	27 April	**1**
Flowering	9 July	6 July	**3**	4 July	**5**
Maturity	26 July	24 July	**2**	23 July	**3**

As discussed previously, the changes in temperature and precipitation are the main reasons why future cotton yield may decline for the climate long-term projection (2070-2100). In response to the future warmer climate, shifting to an earlier planting date may alleviate the negative effects of increased temperature on cotton yield. The study showed that the reduction in cotton yield for 2070-2100 will be 5% less if planting occurred 1 month earlier. By planting on 21th March, the production increase could be higher by 17% (than 6%) in 2020-2050 compared to the baseline period (Figure 4). The above can be atributed to the fact that, in the earlier planting date, plants avoid the negative effects of very high temperatures during the growing season [5]. Also, the early planted cotton uses the early rainfall resulting in a vivid vegetative growth during the stage of active growth and consequently to an increased leaf area for photosynthesis. Therefore, a potential adaptive strategy of crops to future climate change can be achieved by changing the sowing schedule.

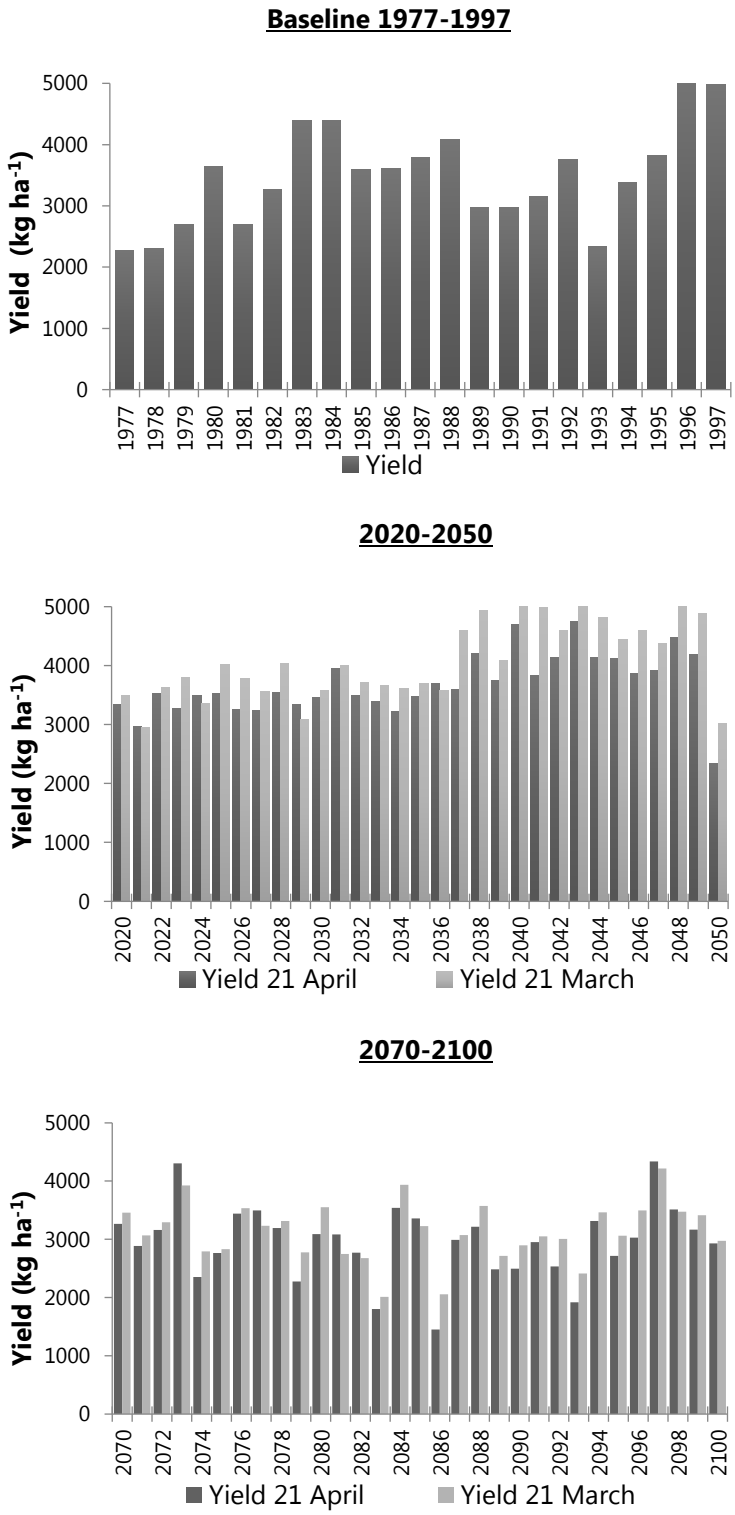


Figure 4. Differences in cotton yields for two planting dates (kg ha^{-1}) during 2020-2050 and 2070-2100, under SRES B1 relative to baseline period 1977-1997.

Evaluation of regression models predicting future cotton yield

An objective of the current study is to generate cotton yield prediction models with the use of climate variables and potential evapotranspiration. For assessing the relationships between climate induced crop yield, climate variables and potential evapotranspiration, a 2-year moving average separation method was used to decouple climate induced crop yield. Subsequently, according to the climate variables, the potential evapotranspiration

and the decoupled cotton yield of the historical period (1977-1997), a regression model selection was performed. The relationships between cotton yield (dependent variable) and climate variables and potential evapotranspiration (independent variables) were established using six multiple linear regression models according to the selected regression model. Table 3 shows the six models which give the highest R^2 values with the equations and the validation results. For the observed yields, there were remarked significant correlations for the six models with a maximum coefficient of determination (R^2) of 0.904 (eight independent variables) and a minimum coefficient of determination of 0.889 (five independent variables). Since the P-value is less than 0.0001, there is a statistically highly significant relationship between the climate variables, potential evapotranspiration and the observed yield. The correlation between the observed cotton yield and the ones predicted by the linear regression models is depicted in Figure 5.

Table 3. Multiple linear regression models and the validation results.

Symbol	Multiple Linear Regression Models	R^2	P-value
Y_a	$Yield = 9307.48 - 3.37861 \times Pr - 443.1 \times T_{max} + 662.058 \times T_{min} - 100.354 \times R_S + 127.901 \times RH_{max} - 130.092 \times RH_{min} + 849.586 u_2 - 11.6481 \times ET_p$	0.904	P<0.0001
Y_b	$Yield = 6025.21 - 3.25447 \times Pr - 192.841 \times T_{max} + 420.992 \times T_{min} + 34.187 \times RH_{max} + 967.192 \times u_2 - 12.3307 \times ET_p$	0.896	P<0.0001
Y_c	$Yield = 7553.82 - 3.50517 \times Pr + 256.982 \times T_{min} - 153.658 \times R_S + 32.2047 \times RH_{max} + 1071.67 \times u_2 - 13.7406 \times ET_p$	0.895	P<0.0001
Y_d	$Yield = 6403.48 - 3.64082 \times Pr + 347.131 \times T_{min} + 9.8507 \times RH_{max} + 19.6663 \times RH_{min} + 1280.07 \times u_2 - 17.9378 \times ET_p$	0.890	P<0.0001
Y_e	$Yield = 6106.3 - 3.55765 \times Pr + 314.961 \times T_{min} + 36.0108 \times RH_{min} + 1217.87 \times u_2 - 16.5918 \times ET_p$	0.889	P<0.0001
Y_f	$Yield = 7051.39 - 3.79393 \times Pr + 390.888 \times T_{min} + 20.0418 \times RH_{max} + 1371.09 \times u_2 - 19.9393 \times ET_p$	0.889	P<0.0001

Note: Pr is the precipitation; T_{max} is the maximum temperature; T_{min} is the minimum temperature; RH_{max} is the maximum relative humidity; RH_{min} is the minimum relative humidity; R_s is the solar radiation; u_2 is the wind speed; and ET_p is the potential evapotranspiration.

Baseline 1977-1997

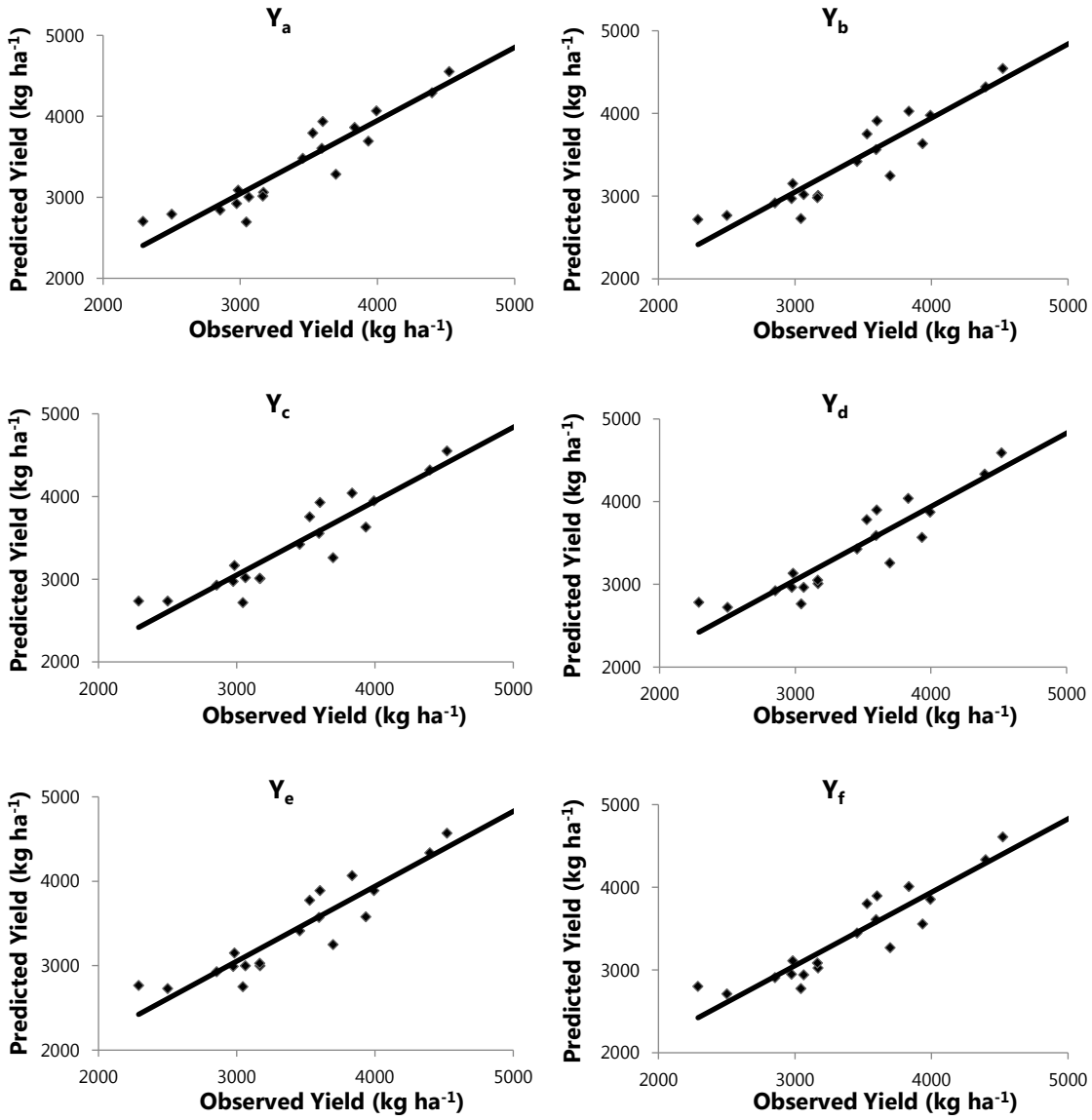


Figure 5. Correlation between observed and predicted cotton yield (kg ha^{-1}) for the historical period (1977-1997).

There were differences between the selected variables impacting cotton yield. Table 3 shows that the variables varied from five to eight in the regression models, resulting in six different multiple linear regression models. However, the differences in the coefficient of determination (R^2) were very small, indicating that the use of five variables is sufficient for the prediction of cotton yield. Cotton yield was affected by precipitation (Pr), temperature (T_{max}, T_{min} or both), relative humidity (RH_{max}, RH_{min} or both), wind speed (u_2) and potential evapotranspiration in all models. Solar radiation (R_s) was present in only two of the six models indicating that is not a key climate variable affecting cotton yield.

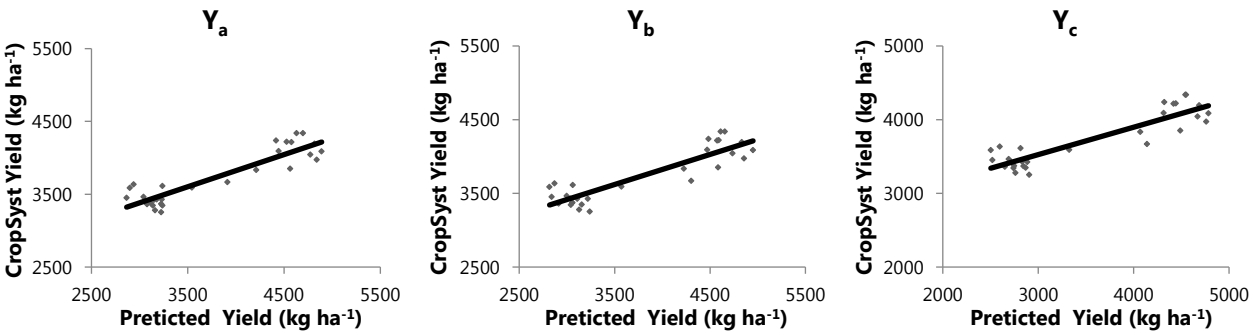
For the evaluation of the six multiple linear regression models in representing the cotton yield response to climate change, the models were tested against the simulated yield by CropSyst model. For this purpose, cotton yield was calculated for the two periods of climate change 2020-2050 and 2070-2100 under SRES B1 according to the six linear regression models and was compared with the future yield simulated by CropSyst. The statistical evaluation criteria are given in Table 4 and the correlation between predicted cotton yield and simulated by CropSyst in Figure 6.

Table 4. Statistical evaluation criteria.

Statistical criteria	2020-2050					
	Multiple Linear Regression Models					
	Y_a	Y_b	Y_c	Y_d	Y_e	Y_f
R	0.907	0.894	0.899	0.906	0.903	0.909
RMSE	0.119	0.133	0.161	0.221	0.198	0.256
RE	0.022	0.025	0.030	0.041	0.037	0.047
ME	-51.815	-32.815	187.585	-115.673	-56.793	-188.794
MPE	-0.619	-0.012	6.155	-1.451	-0.049	-3.143
CRM	0.014	0.009	-0.053	0.030	0.015	0.048

Statistical criteria	2070-2100					
	Multiple Linear Regression Models					
	Y_a	Y_b	Y_c	Y_d	Y_e	Y_f
R	-0.709	-0.716	-0.726	-0.740	-0.736	-0.743
RMSE	0.216	0.226	0.265	0.295	0.281	0.318
RE	0.040	0.042	0.049	0.055	0.052	0.059
ME	-27.999	33.180	309.685	259.462	242.263	302.271
MPE	-3.085	-1.073	8.241	6.189	5.709	7.491
CRM	0.09	-0.011	-0.117	-0.096	0.281	-0.114

(a) Climate change period 2020-2050



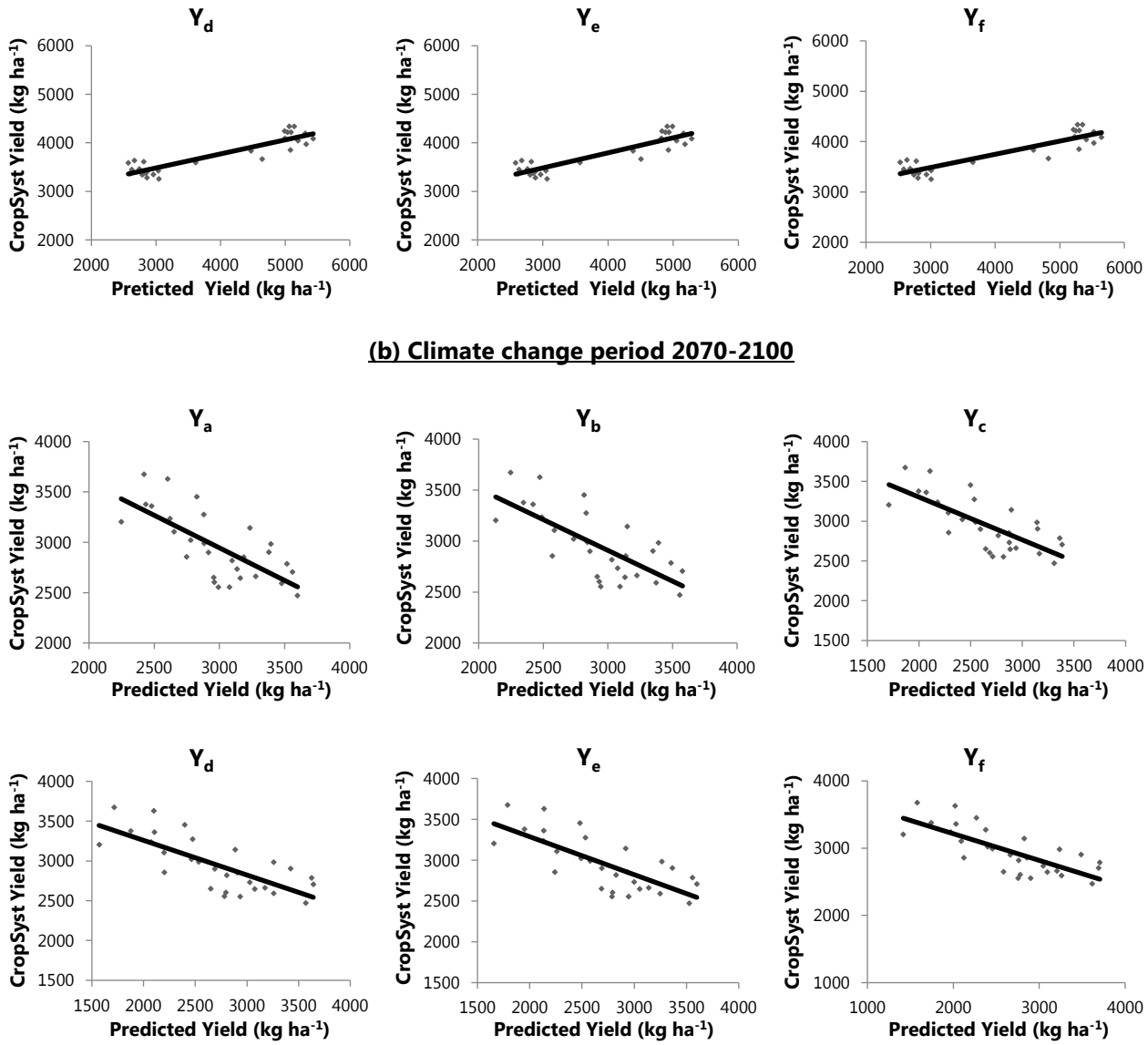


Figure 6. Correlation between cotton yield (kg ha^{-1}) predicted by the six linear regression models and simulated by CropSyst for climate change periods (a) 2020-2050 and (b) 2070-2100.

The statistical criterion R is close to unity for the period 2020-2050, showing that the regression models perform well in that period. R is close to -1 for the climate change period 2070-2100 indicating a good, linear negative correlation which is similar to the positive correlation coefficient with the relative strengths being the same. The RMSE values are small, indicating small deviations between calculated and simulated cotton yields for both periods. The RMSE ranges from 0.119 to 0.256 (2020-2050) and from 0.216 to 0.318 (2070-2100). The RE values are low for both climate change periods indicating a good model performance. The ME is -188.794 to 187.585 kg ha^{-1} for 2020-2050 and -27.999 to 309.685 kg ha^{-1} for 2070-2100. MPE ranges from -3.143% to 6.155% and from -3.085% to 8.241% for climate change periods 2020-2050 and 2070-2100, respectively. The values of CRM are close to zero which demonstrates that there is a good fit between calculated and simulated cotton yields. CRM is mainly positive for the period of climate change 2020-2050 and negative for the period 2070-2100. This indicates that the regression models underestimate the yield compared to the simulated yield for 2020-2050 while they overestimate the yield for 2070-2100. Generally, the multiple linear regression models have a better performance for the period 2020-2050 than 2070-2100, demonstrating their ability in representing the future cotton yield response to climate change in short-term projections.

Conclusions

In this study, the effects of climate change on cotton yield in the area of Agios Mamas in Northern Greece were assessed. Simulation results suggested that temperature and precipitation could have a significant effect on cotton production. The CGCM3.1/T63 model indicates an increase in future maximum and minimum air temperature while precipitation is expected to decrease for both periods of climate change relative to the baseline period (1977-1997). The yields predicted by CropSyst, maintaining the irrigation and other management practices of the baseline period, revealed positive impacts of climate change on cotton yield in the medium-term projection (2020-2050) and negative impacts in the long term (2070-2100) under, SRES B1. Cotton yield was projected to decline by 15% during 2070-2100 compared to the current yield, induced by higher temperatures leading to increased potential evapotranspiration. A second simulation scenario was designed to investigate the utility of an earlier planting date as an adaptive strategy to climate change. Early planting date resulted in a slighter yield reduction in 2070-2100 and in a higher increase in 2020-2050 relative to the present planting date, indicating that could serve as possible means of mitigating impacts of climate change. Multiple linear regression results showed that there is a relationship between climate variables, potential evapotranspiration and cotton yield. Comparing the estimated yield from the regression models with the simulated cotton yield by CropSyst for the climate change periods, we can conclude that multiple linear regression models could serve as a simple tool for predicting crop yields in the future with the use of climate variables and potential evapotranspiration. Previous research on the effect of climate change on agriculture suggested that improving irrigation efficiency, introducing new cultivars or changing planting date could be used as adaptation options to reduce the crops' vulnerability to climate change. A change in the planting date seems to be feasible and easy to implement adaptation option to reduce the negative effect of climate change. Therefore, it is important to develop adaptation strategies, which could reduce the vulnerability of cotton to climate change, without large increase in the applied irrigation water. The changes in climate will have serious impacts on the agricultural sector and our analysis indicates that adaptation and mitigation measures can and should play an important role in reducing the impacts of climate change on agriculture. An improved agricultural water management aiming at raised productivity will ensure global food supply and global food security. High priority should be given to sustainable management practices for adaptation and associated mitigation of climate change. Conservation agriculture could conduce to efficiency in water use, soil quality, capacity to withstand extreme events and carbon sequestration.

In summary, useful information was generated from this study for the development of effective and sustainable strategies for cotton production in Northern Greece under climate change. The results also have important implication for the improvement of climate change impact studies on agricultural production to cope with the future change of climate. In addition, more sophisticated models should be undertaken so as to allow a more complete assessment of the relationships between climate change and crop yields.

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