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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

Evaluation of the Impacts of Climate Change on Sunflower with Aquacrop Model*

İklim Değişikliğinin Ayçiçeği Üzerine Etkilerinin Aquacrop Modeli ile Değerlendirilmesi*

Hüdaverdi GÜRKAN[1*]

Abstract

Climate change has become one of the most significant risk factors in agricultural production. Plant productivity declines caused by climate change pose a serious threat to food supply and security. Crop simulation models have been widely used in recent years for the assessment of the impacts of climate change on agricultural production. In Konya, there have been limited studies on the potential effects of climate change on sunflower production. Sunflower, the main crop of the most imported agricultural product group, in which the production amount is currently insufficient to cover domestic consumption demand, is strategically important for the Turkish economy. The goal of this study was to examine the effects of climate change on sunflower yield in Türkiye by using the Aquacrop model. The data of the field experiment carried out on the Ekllor sunflower cultivar for two years in Konya conditions were used as material. The daily projection dataset of three Global Climate Models (HadGEM2-ES, MPI-ESM-MR, GFDL-ESM2M) and two scenarios (RCP4.5 and RCP8.5) were used to analyze climate change impacts. The 1971-2000 period was considered as the reference period and the 2022-2098 period was selected as the future period. The results confirmed that the Aquacrop model was able to satisfactorily simulate yield with NRMSE 2.10 % for the rainfed condition and 10.55 % for the irrigated condition, a d-index of 0.97, and a modeling efficiency of 0.91. Aqaucrop climate change impacts simulation which was based on 3 global climate models covering with 2022 -2098 period simulations projected that sunflower yield would be decreased in a range of 21% to 44% for RCP4.5 and 18% to 50% for RCP8.5 scenarios under rainfed conditions. In contrast, the yield would be increased in a range of 11% to 23% for RCP4.5 and 10% to 33% for RCP8.5 scenarios under irrigated conditions. The findings point to the use of appropriate water management measures for future sunflower production as a means of adapting to climate change.

Keywords: Aquacrop, Crop simulation model, Climate change, Sunflower, Crop yield changes

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[1*] **Corresponding Author:** Hüdaverdi Gürkan, Turkish State Meteorological Service, Ankara, Türkiye. E-mail: hudaverdigurkan.tr@gmail.com OrcID: 0000-0003-1799-0090

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Öz

İklim değişikliği tarımsal üretim için en önemli risk faktörlerinden biri haline gelmiştir. İklim değişikliğinin neden olduğu bitki verimliliği düşüşleri, gıda arzı ve güvenliği için ciddi bir tehdit oluşturmaktadır. Bitki simülasyon modelleri son yıllarda iklim değişikliğinin tarımsal üretim üzerine etkilerinin değerlendirilmesinde giderek yaygın olarak kullanılmaya başlamıştır. Türkiye'de iklim değişikliğinin tarımsal üretim üzerine olası etkileri ile ilgili çalışma sınırlı sayıdadır. Üretim miktarı henüz iç tüketim talebini karşılayamayan ve en fazla ithalatı yapılan tarımsal ürün gurubunun temel ürünü olan ayçiçeği Türkiye ekonomisi için stratejik öneme sahiptir. Bu çalışmanın amacı, Türkiye'de iklim değişikliğinin ayçiçeği verimi üzerine etkilerinin Aquacrop modeli kullanılarak analiz edilmesidir. Konya koşullarında iki yıl süreyle Ekllor ayçiçeği çeşidi üzerine yürütülen tarla denemesine ait veriler materyal olarak kullanılmıştır. İklim değişikliği etki analizi için ise 3 Küresel İklim Modeli (HadGEM2-ES, MPI-ESM-MR, GFDL-ESM2M) ve 2 senaryoya (RCP4.5 ve RCP8.5) ait günlük veriler kullanılmıştır. 1971 - 2000 dönemi referans, 2022 – 2098 dönemi ise iklim değişikliği etki analizi dönemi olarak ele alınmıştır. Çalışma sonuçları Aquacrop modelinin susuz koşullarda %2.10 ve sulu koşullarda %10.55 NRMSE değeri, 0.97 d-indeks ve 0.91 model etkinliği istatistiksel analizleri ile verimi başarılı bir şekilde simüle edebildiğini ortaya koymuştur. 3 küresel iklim modeli ve 2022-2098 yılları arası dönem özelinde oluşturulan Aquacrop iklim değişikliği projeksiyon sonuçlarına göre ayçiçeği veriminin susuz koşullarda RCP4.5 senaryosuna göre %21-44, RCP8.5 senaryosuna göre ise %18-50 aralığında azalması öngörülmektedir. Bunun aksine sulu koşullarda RCP4.5 senaryosuna göre %11-23, RCP8.5 senaryosuna göre %10-33 aralığında verim artışı sağlanabilecektir. Bulgular, iklim değişikliğine uyum sağlamanın bir yolu olarak gelecekteki ayçiçeği üretimi için uygun su yönetimi uygulamalarının kullanılmasına işaret etmektedir.

Anahtar Kelimeler: Aquacrop, Bitki simülasyon modeli, İklim değişikliği, Ayçiçeği, Bitki verim değişimleri

1. Introduction

As stated in the World Meteorological Organization (WMO) reports, in comparison to the pre-industrial period, the global mean surface temperature has increased by around 1.1°C (1850-1900). The WMO affirms that the last decade, 2015-2021, was the warmest on record. (WMO, 2022). According to the Intergovernmental Panel on Climate Change (IPCC), the global surface temperature rising is projected to hit 1.5°C by 2050 (IPCC, 2018). Different parts of the world are affected differently by changes in the climate. While some locations will experience greater warming and rainfall than others, others will experience more severe droughts. Türkiye has a semi-arid climate and is one of the regions most vulnerable to climate change. Temperatures are anticipated to rise, and precipitation will decrease in the future, based on the most recent IPCC projections for Türkiye (Demircan et al., 2017). Furthermore, according to World Food and Agriculture Organization (FAO) assessments, crop yields will decline in several countries, including Türkiye, due to climate change between 2030 and 2100 years (FAO, 2016).

Like many crops, sunflowers grow under rainfed conditions. Sunflower is the world's third crop of oilseeds, after soybean and rapeseed (USDA, 2021). Türkiye ranks sixth (FAO, 2022) in sunflower seed production. The main source of vegetable oil consumed in Türkiye is sunflower (TURKSTAT, 2022). There are significant decreases in productivity depending on drought years. Sunflower production dropped by 23.8 percent in 2007 compared to the prior year. (TURKSTAT, 2022).

Changes in temperature and precipitation factors, vital to plant production, directly affect the productivity, and vegetation period, suited to the growing region (Bulut, 2015). Temperature and precipitation threshold responses significantly affect crop yields (Easterling et. al., 2007). It is not possible to directly interfere with climate factors in open-field agricultural conditions. For this reason, the climate is the most important unknown factor in crop growth and agricultural production (Hoogenboom, 2000). Experiments or statistical methods are used to investigate the probable influence of climatic conditions on crop productivity. Crop simulation models (CSMs) with adequate modeling capabilities have grown in popularity in recent years (Boote et al., 2010). CSMs predict crop development by using meteorological and soil variables, cultivar features, management activities, and modeling mechanisms in the soil-plant-atmosphere system (Jones et al., 2003; Hoogenboom et al., 2004). CSMs can be used to model how climate change would affect crop productivity (White et al., 2011). In addition, the insights provided by the CSMs have become critical data for the agriculture assessment reports produced by the IPCC (White et al., 2011; Easterling et al., 2007; Gitay et al., 2001; Reilly et al., 1996). Crop models are classified into three main categories according to the basic components they consider in the calculations: carbon-driven, radiation-driven, and water-driven (Steduto, 2003; Todorovic et al., 2009). The Aquacrop model is one of the common models with its simulation capability in water-limited conditions, less input parameter requisition, and climate change studies.

This study aimed to inform decision-makers by simulating possible outcomes to quantify uncertainty in climate change impact assessment on sunflower production in Konya where one of Türkiye's top sunflower-growing regions by using the Aquacrop Model. The objectives were a) calibration and evaluation of the Aquacrop Model and b) estimation of changes in sunflower yields in the future periods using three different climate projections datasets.

2. Materials and Methods

2.1. Study Area

The study site was the Konya Soil, Water, and Deserting Control Research Institute's field in Türkiye (37°48'N, 32°30' E, 1031 m a.s.l.). Konya province, located in Türkiye's semi-arid climatic zone, is one of the primary sunflower production locations. According to the Turkish Statistical Institute (TURKSTAT) crop production reports of 2022, Konya positions third in sunflower production (tonnes) in Türkiye (TURKSTAT, 2022). (*Figure 1*).

Figure 1. Study region

The study area has clay soil characteristics, according to the results of the analysis applied to soil samples taken from the study area. Because of its high infiltration capacity, surface runoff is minimal. The organic matter content of the soil is low. (*Table 1*).

Table 1. Soil profile features

Depth (cm)	**Clay (%)**	**Silt (%)**	**WP ($cm\ cm^{-1}$)**	**FC ($cm\ cm^{-1}$)**	**SP ($cm\ cm^{-1}$)**	**BD ($g\ cm^{-3}$)**	**OC (%)**	**pH in water**
0-30	59.3	21.1	0.26	0.42	0.48	1.42	0.44	7.6
30-60	61.7	21.1	0.27	0.44	0.50	1.47	0.30	7.9
60-90	63.8	21.1	0.29	0.46	0.53	1.54	0.19	7.9
90-120	64.0	21.0	0.29	0.45	0.52	1.46	0.12	7.9
120-200	64.0	21.0	0.29	0.45	0.52	1.46	0.09	7.9

WP= wilting point, FC= field capacity, SP= saturation point, BD= bulk density, OC= organic carbon

2.2. Field experimental data

The field experiment was carried out for two years between 2015 and 2016 in Türkiye's Konya province (Gunduz et al., 2018). The Ekllor sunflower cultivar was chosen for the study, which took place in 2015 and 2016. The experimental layout was a Randomized Complete Block, with three replications. Plant and row spacing was determined as 70cm and 25cm, respectively. The sunflower vegetation period in the first year was 136 days, and the following phenological and growth stages were noted: May 5 emergence, July 21 starburst, August 4 seed formation, and September 18 maturity. The second year's sunflower vegetative period covered 133 days, and the development stages identified were emergence on May 12, starburst on July 22, seed formation August 4, and maturity on September 21.

There were two treatments in the field experiment: rainfed and irrigated. The drip irrigation method was used as the irrigation system. A total of 428 mm of water was used in 10 irrigation applications in 2015, and 465 mm of water was used in 12 irrigation applications in 2016.

In both years, a certain amount of fertilizer was used. The followings are the types and amounts of fertilization that were used: Before planting, 200 kg ha^{-1} of Di-ammonium Phosphate (DAP), 300 kg ha^{-1} of 20-20-20 compound fertilizer at planting, 50 kg ha^{-1} of Urea, and 50 kg ha^{-1} of Ammonium Nitrate (AN) at hoe.

2.3. Weather and climate projections dataset

The study area, Konya, is one of the aridest provinces of Türkiye. The long-term average total precipitation of the study area is 323.3 mm and the average temperature is 11.6°C. In comparison to 2015, the growth cycle in 2016 was hotter and drier. During the 2015 sunflower growing season (May-September), total precipitation was 163.8 mm, whereas it was 98.1 mm in the growing season of 2016 (*Figure 2*).

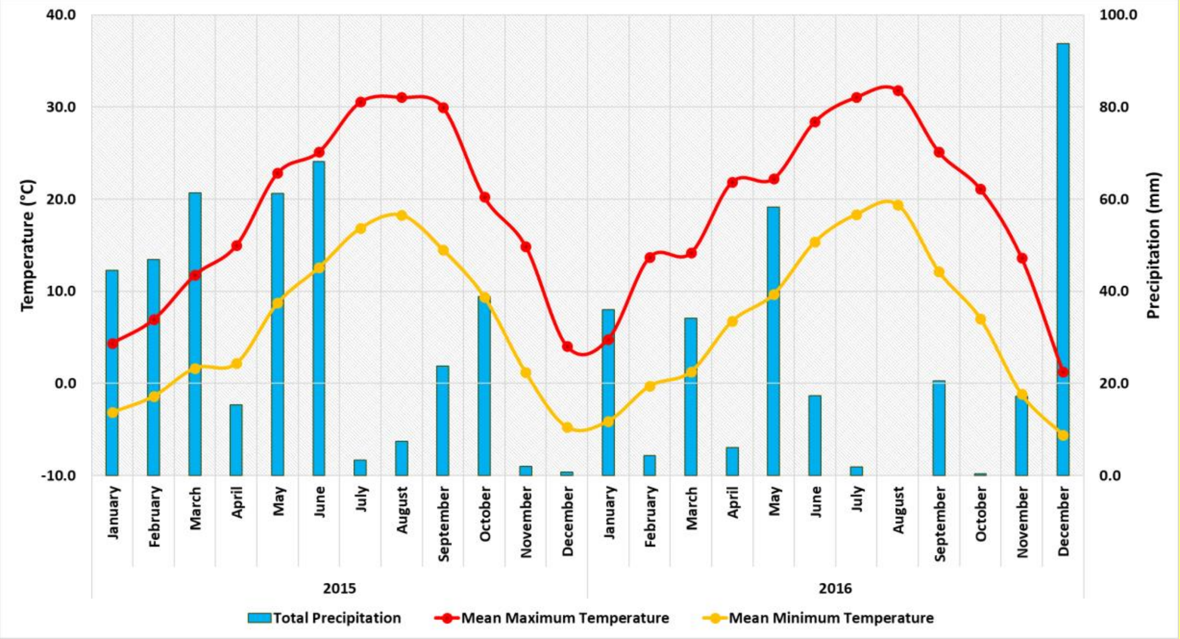

Figure 2. Observed monthly climate parameters at the research site in 2015 and 2016.

The observed daily weather dataset includes minimum and maximum temperature, total precipitation, average relative humidity, total radiation, and average wind speed parameters provided by The Turkish State Meteorological Service (TSMS). Due to the requirement for specific meteorological data for the Aquacrop model, observation data from a meteorology station 8 kilometers distant from the study area were used in the study.

The daily climate projections dataset downscaled by TSMS specifically for Türkiye was used for future climate change analyses. 3 GCMs (HadGEM2-ES, MPI-ESM-MR, GFDL-ESM2M) and two RCPs, i.e., 4.5 and 8.5 were selected for assessment of climate change impact. RCP4.5 reflects the most likely scenario, but RCP8.5 is referred to as the most catastrophic scenario due to the expected global temperature increase (Riahi et al., 2011; Thomson et al., 2011). The low-resolution GCMs dataset in the 130 - 220 km range was downscaled to 20 km resolution to conduct a detailed analysis specific to Türkiye conditions by TSMS. RegCM4.3.4 regional climate model and a nested dynamic downscaling approach were used to obtain a high-resolution climate projection dataset (Akcakaya et al., 2015).

For the 1971-2000 reference period, bias correction was performed between the model and observation data. Based on each parameter and each GCMs dataset, the bias adjustment was calculated for each day of the year. The bias correction results of each parameter was presented in *Table 2*.

For the climate change analysis study, the 1971-2000 period was considered as the reference period, and the 2022-2098 period was selected as the future period. The future term was divided into three segments: 2022–2040; 2041–2070; and 2071–2098.

Table 2. Daily average bias correction (observed-GCMs dataset) for each parameter

GCM	Tmin (°C)	Tmax (°C)	Precipitation (mm)	Wind (m/sec)	Rhum (%)	Radiation (w/m2)
HadGEM2-ES	0.1	1.0	-0.3	-1.1	-3.2	-2.5
MPI-ESM-MR	-0.1	1.1	0.3	-1.4	1.2	-1.1
GFDL-ESM2M	1.7	2.9	0.1	-1.2	-1.2	-1.2

Tmin: Minimum temperature, Tmax: Maximum temperature, Rhum: Relative humidity

The 2022-2098 climate projections of the study area were compared with the reference period of 1971-2000 specifically for the sunflower vegetation period. According to the climate projection results obtained for the sunflower vegetation period, based on the RCP4.5 and RCP8.5 scenarios, respectively, the total precipitation is projected to decrease by 18% and 21%, the minimum temperature is expected to increase in the range of 2.3°C and 3.6°C, and the maximum temperature is expected to rise by 2.5°C and 3.8°C.

2.4. The Aquacrop crop simulation model

The Aquacrop model produced by FAO aimed to increase water use efficiency in all irrigation conditions. Aquacrop mimics non-woody plant productivity reaction to water (Steduto et al., 2009; Raes et al., 2009; Hsiao et al., 2009). Since its creation in 2009, AquaCrop has been applied in a variety of regions all over the world. Aquacrop offers assistance with creating irrigation plans, identifying the best crop schedule, and estimating yield potential in various scenarios (including salinity and climate change). In the version of Aquacrop 7.0 released in 2022, simulations can be conducted for 17 different herbaceous crops. In this study, the previous version, Aquacrop v6.1, was used.

The model can visually present the estimation of yield and plant growth based on plant water consumption. The AquaCrop model calculates evapotranspiration separately as transpiration from the plant surface and evaporation from the soil surface. This distinction is of great importance on soil surfaces where there is insufficient vegetation and where soil water evaporation is too high. Another difference in the model compared to other models is that it uses the percentage of canopy cover instead of the leaf area index (LAI) in the calculations to better mimic the water deficit conditions. Aquacrop simulates the soil-water relationship in detail by considering capillary rise, deep infiltration, and groundwater level in the calculations.

Climate (daily, 10-day, or monthly), crop, soil, management (irrigation, tillage, etc.), and initial soil water content parameters are used as inputs in the model. Aquacrop stands out with its fewer input parameter requirements and modeling success in deficit water conditions compared to many other models. (Garcia-Vila et al., 2009; Todorovic et al., 2009; Stricevic, 2011; Kale et al., 2017; Elsheikh, 2015; Osman, 2018; Yigit and Candogan, 2019; Karimi, 2021).

In addition, the model is preferred in the studies of estimating the effects of climate change on crop yield productivity (Deveci et al., 2019; Gürkan, 2019; Konukcu et al., 2020; Raoufi et al., 2020; Yesilkoy, 2020; Stricevic et al., 2021). The Aquacrop model provides ease of use in climate change studies with the CO_2 projection data of IPCC's different climate scenarios (SRES and RCPs) presented in the database. Another superior feature of the Aquacrop model in climate change studies compared to other models is that it enables the automatic determination of parameters such as minimum temperature, average temperature, growing degree day, and precipitation, which are the determining factors of the planting window in line with the criteria determined by the user.

In this study, the future period simulations were carried out in the "successive years" mode. The start days of the next runs were linked to the crop maturity of previous years. Future sowing days were generated based on air temperature criteria. The minimum daily air temperature in 7 days of at least 5°C was determined as the threshold of the sowing date.

3. Results

3.1. Model calibration and evaluation

The data collected in 2015 were used to calibrate the Aquacrop Sunflower model, and the data obtained in 2016 were used to evaluate it. The calibration and evaluation procedures were conducted with the use of observed meteorological data. *Table 3* provided a list of the calibrated coefficients.

Table 3. The calibrated coefficients of the sunflower Ekllor cultivar

Parameter	**Coefficient**
Base temperature (°C)	5
Upper temperature (°C)	35
Initial Canopy Cover (CC_0)	0.29
Plant density (plants/ha)	57143
Canopy Growth Coefficient (CGC)	20.5
Maximum Canopy Cover (CC_x)	90
Canopy Decline Coefficient (CGC) (CDC)	0.401
Growing Degree Days (Sowing – Emergence)	147
Growing Degree Days (Sowing – Flowering)	1038
Growing Degree Days (duration of flowering)	268
Growing Degree Days (Sowing – Senescence)	1451
Growing Degree Days (Sowing – Maturity)	2233
Minimum effective rooting depth (Zr) - (m)	0.3
Maximum effective rooting depth (Zr) - (m)	2.0
Average root zone expansion (cm/day)	2.0
Crop transpiration coefficient (KcTr,x)	1.1
Crop water productivity (WP) g m^{-2}	20.5
Reference Harvest Index (HIo) (%)	37

Table 4 shows the findings of the phenological stage evaluation process. According to the vegetation period model simulation performance evaluation results, Aquacrop simulated the harvest period 6 days earlier.

Table 4. The model performance for evaluation of phenological stages

Phenological growth stages	**Observed**	**Simulated**	**Model Error (day)**
Emergence (DAP)	18	13	-5
Starburst (DAP)	71	66	-5
Maturity (DAP)	133	127	-6

DAP: days after planting

Before running the model for future periods, its performance under current conditions needs to be analyzed. Evaluation of the Aquacrop performance by comparing simulated data to field measurements was one of the primary goals of the research. This was accomplished using a statistical assessment approach that included relative error (RE), relative mean absolute error (RMAE), root mean square error (RMSE), normalized root mean square error (NRMSE), modeling efficiency (EF), index of agreement (d-index), and modified index of agreement (d1-Index). (Nash and Sutcliffe 1970; Willmott, 1982; Willmott et al., 1985). Inaccuracy is computed as the ratio in RE, RMAE, and NRMSE indexes. A lower number means a stronger connection, whereas zero symbolizes a great match. The RMSE methodology employs the unit used to compute the failure (in this case, kg/ha). A lower number means a closer link, while zero represents the perfect match. The d-index, d1-index, and EF indexes are dimensionless, with values ranging from 0 to 1. A perfect match is indicated by an index value of 1, and no match is indicated by a value of 0. A statistical examination of the simulations revealed that the model produced acceptable yield projected results. (*Table 5*).

Table 5. Evaluation of the Aquacrop for yield

Parameter		**Yield**								
Treatment	**Year**	**Observed (kg/ha)**	**Simulated (kg/ha)**	**RE (%)**	**RMAE (%)**	**RMSE (kg/ha)**	**NRMSE (%)**	**d-Index**	**d1-Index**	**EF**
Rainfed	**2015**	2388	2390	-2.3	-0.24	45.12	2.1	0.97	0.87	0.91
	2016	1913	2450	1.8						
Irrigated	**2015**	4361	4422	-12.8	-9.6	430.54	10.55			
	2016	3799	3759	-6.3						

3.2. Analysis of the impacts of climate change on sunflower vegetation duration

It is predicted that global warming and temperature increases will affect the sunflower vegetation duration. For this reason, the changes in the vegetation duration in the next periods were analyzed in the study. First, the reference period of 30 years (1971-2000) was analyzed for the assessment of the effects of climate change on the sunflower vegetation duration. 2022 and 2098 were chosen as prediction periods. Annual simulations of the Aquacrop model were performed for both the baseline and the future time frames.

The differences between the reference and the future periods were used to calculate the changes. The findings of the assessment showed that the sunflower crop will reach harvest maturity in less time due to climate change. Temperature increases caused by climate change would shorten plant growth durations, based on assessment results. The projection results of the RCP4.5 scenario revealed that the vegetation duration of the sunflower crop will be shortened by 8-14 days in the first period (2022-2040), 10-18 days in the second period (2041-2070), and 12-19 days in the last period (2071-2098) (*Figure 3*). For the overall 2022-2098 period, the average vegetation duration is expected to be shortened between 10-17 days. Sunflower vegetation duration will be shortened by 11-16 days in the first period, 16-20 days in the second period, and 23-25 days in the last period based on the RCP8.5 scenario. For the overall 2022-2098 period, the average vegetation duration is expected to be shortened between 17-20 days for the RCP8.5 scenario. (*Figure 3*).

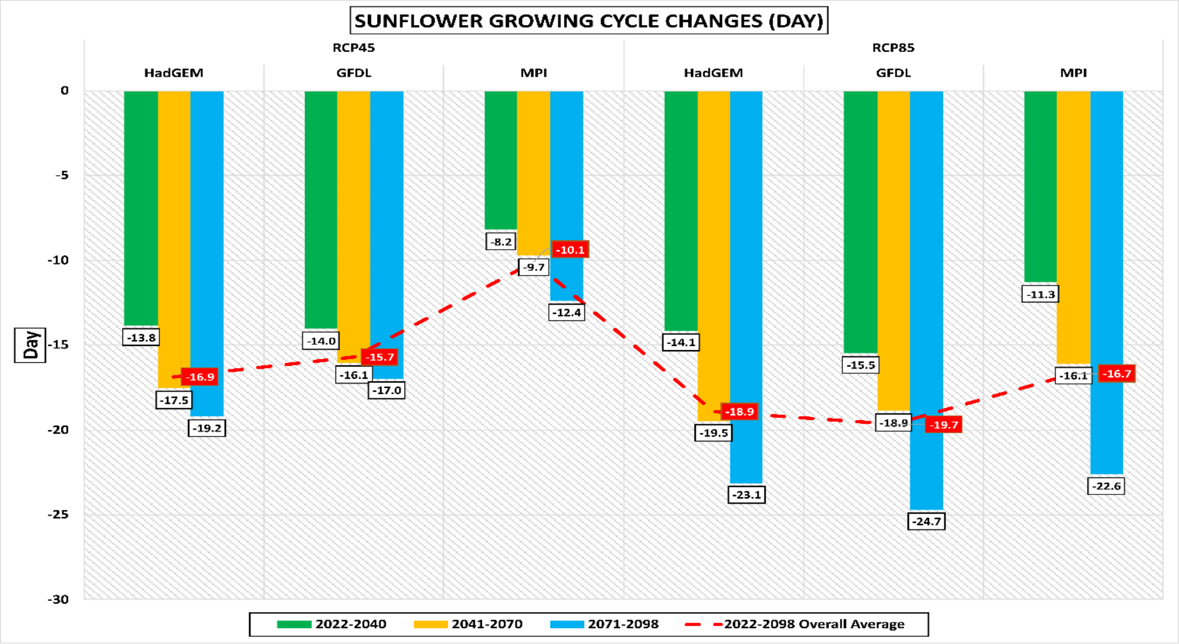

Figure 3. Changes in the length of the sunflower growth period (days)

3.3. Assessment of climate change impact on sunflower yield

Climate simulations for RCP4.5 were examined to determine how climate change may affect sunflower yield (*Figure 4*) and RCP8.5 scenarios (*Figure 5*). Rainfed and irrigated scenarios, as well as each GCM, were assessed independently for three periods (2022–2040, 2041–2070, and 2071–2098) and compared with the reference period (1971-2000) modeled yield results.

The 77-years (2022-2098) projections results based on the RCP4.5 scenario revealed the expectations of a decrease in yield under rainfed conditions and an increase in yield under irrigated conditions. For rainfed conditions, sunflower yield was simulated to decrease by 21% to 37% for the 2022-2040 period, decrease by 24% to 44% for the 2041-2070 period, and decrease by 23% to 42% for the 2071-2098 period. For irrigated conditions, it was proposed that sunflower yield will grow by 11% to 15% for the 2022-2040 period, increase by 14% to 23% for the 2041-2070 period, and increase by 18% to 22% for the 2071-2098 period (*Figure 4*).

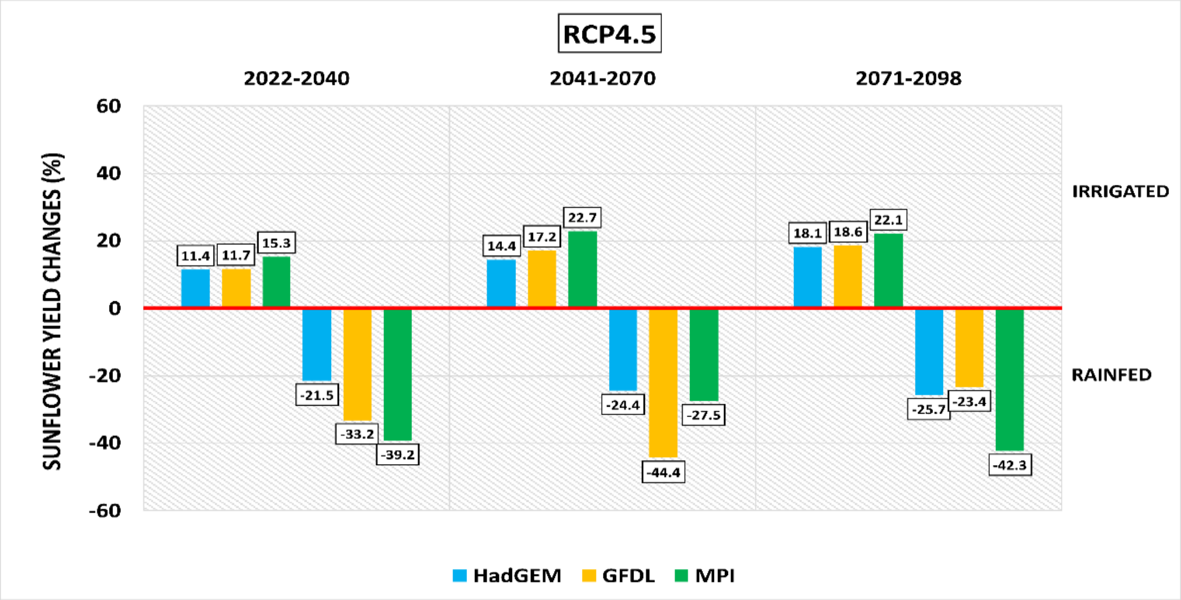

Figure 4. Sunflower yield changes based on RCP4.5 scenarios and three GCMs

Projection results of the RCP8.5 scenario revealed that the sunflower yield variation would be higher than the results of the RCP4.5 scenario in both rainfed and irrigated conditions. For rainfed conditions, sunflower yield was simulated to decrease by 18% to 44% for the 2022-2040 period, decrease by 23% to 40% for the 2041-2070 period, and decrease by 32% to 50% for the last period. For irrigated conditions, it was simulated that sunflower yield will rise by 10% to 14% for the 2022-2040 period, increase by 21% to 23% for the 2041-2070 period, and increase by 30% to 33% for the 2071-2098 period (*Figure 5*).

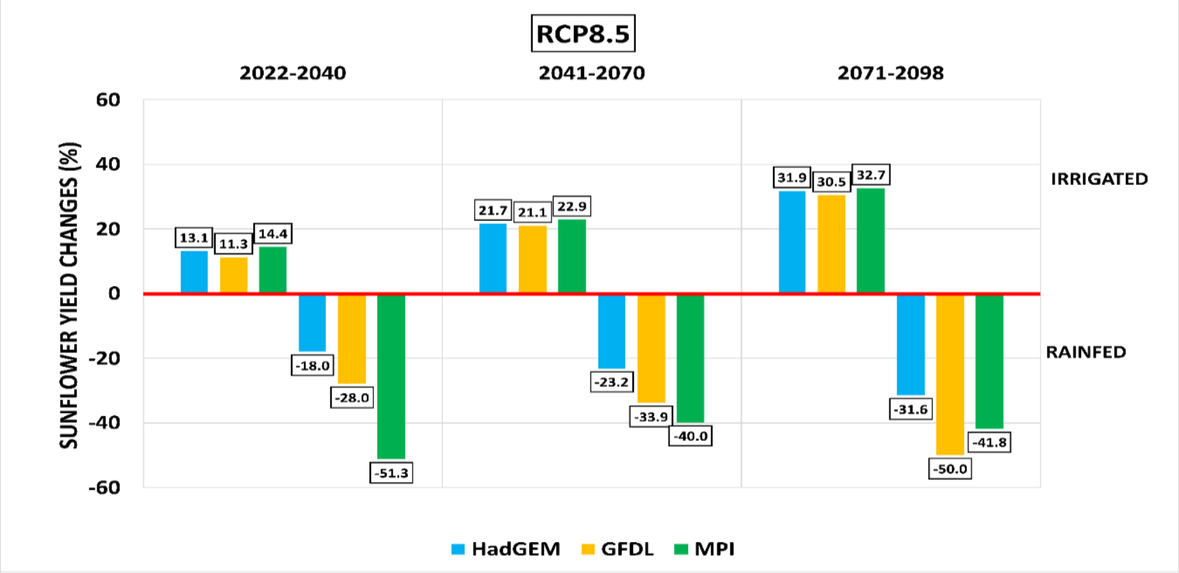

Figure 5. Sunflower yield changes based on RCP8.5 scenarios and three GCMs

3.4. Assessment of climate change impact on the total irrigation requirements of irrigated conditions

Due to climate change, it is predicted that temperatures will increase, and precipitation will decrease in the 2022-2098 period. According to the RCP8.5 scenario, precipitation decreases were expected to cause a greater negative impact in the 2071-2098 period. Precipitation is predicted to decrease by up to 25% in the RCP4.5 scenario and up to 41% in the RCP8.5 scenario (*Figure 6*).

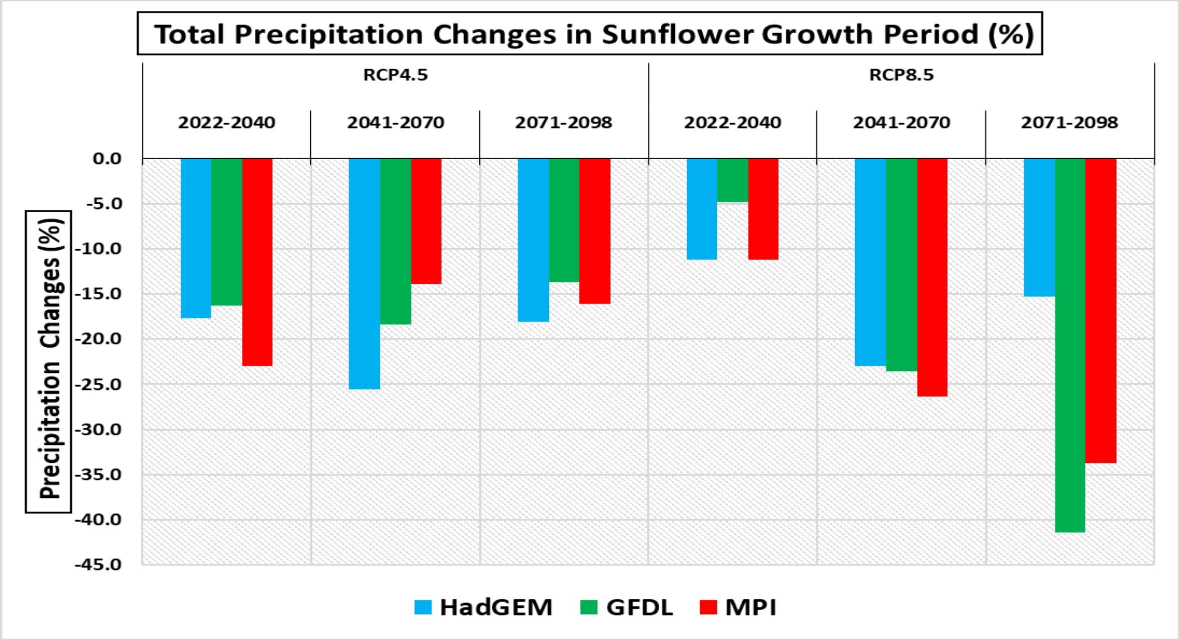

Figure 6. Konya sunflower growth period total precipitation projections

Temperature and precipitation changes will undoubtedly have an impact on sunflower growth and development. The projection results confirmed that and rising in temperature due to climate change would cause an increase in the water requirements for irrigated sunflower production conditions in future periods. The results of the research showed that the irrigation requirements will increase by 10% and 16% on average, respectively, in RCP4.5 and RCP8.5 scenarios in the 2022-2098 period under full irrigated conditions (*Figure 7*).

The results of the research indicated that if the rising irrigation requirements for the sunflower could be supplied, an enhancement in yield could be achieved. According to the RCP4.5 scenario, an average increase of 10% in irrigation water would contribute to an average 17% increase in the sunflower yield. The result for the RCP8.5 scenario projection indicated that an average increase of 16% in irrigation water would increase sunflower yield by 22% on average.

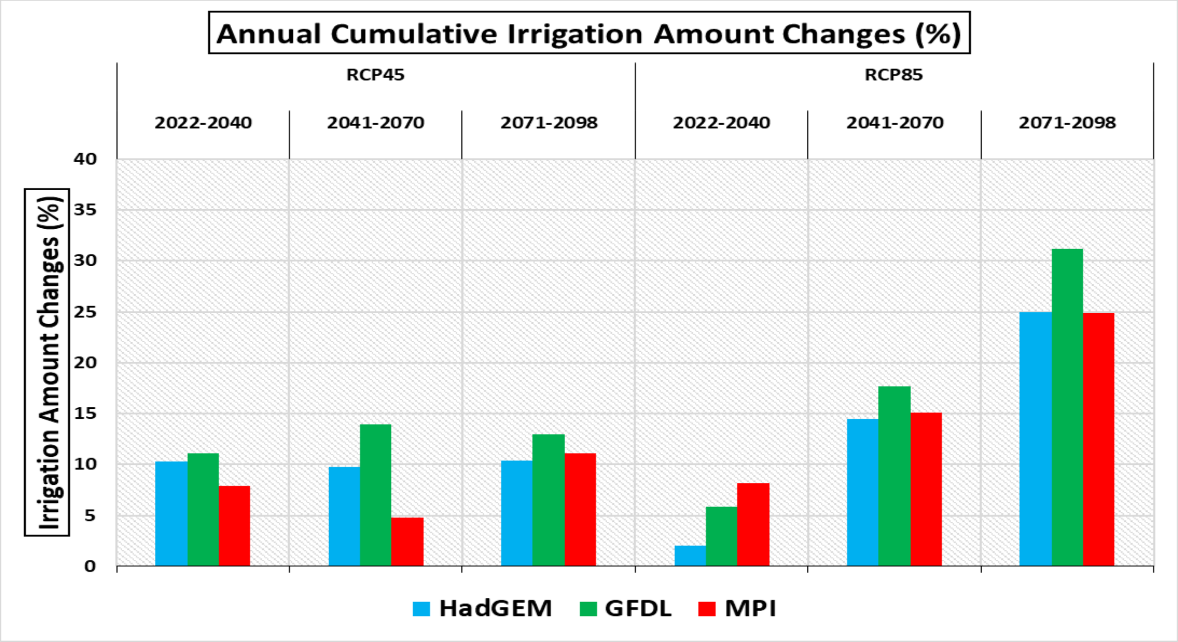

Figure 7. Konya cumulative irrigation requirement changes for irrigated conditions

4. Conclusion

The main objective of this study was the evaluation of the FAO Aquacrop model performance and the evaluation of how different climatic scenarios and GCMs simulations will affect sunflower yield. The yield and phenological stages were found to be faithfully predicted by the Aquacrop model. Under both rainfed and irrigated treatments, the model produced satisfactory simulation results. The Aquacrop model simulation ability was proven by statistical analysis.

The Aquacrop model achieved exceptional yield prediction ability under rainfed conditions with 2.10% nRMSE. Also, acceptable yield modeling findings in an irrigation environment with 10.55% nRMSE. The model's accuracy was comparable to earlier studies for conditions in Italy (Todorovic et al., 2009) with a 1.18% relative error and for conditions in Serbia (Stricevic et al., 2011) with a range of 0.3 to 5.0% relative error using the Aquacrop.

According to the findings of the climate change analyses, sunflower productivity in semi-arid regions will be severely affected under rainfed conditions. Obtained from two scenarios and three GCMs for rainfed situations, all yield estimates anticipated a yield loss ranging from 18 to 50 percent. Projection results revealed that there is a strong relationship between in-season total precipitation and yield. According to the simulation results, it is predicted that the maximum decrease in yield with 50% for the GFDL model on the RCP4.5 scenario will occur between 2071 and 2098 when the maximum decrease in precipitation with 48% is expected for the same model and scenario.

The results of the study match well with our earlier findings for the same location through the use of the DSSAT model (Gürkan et al., 2021). Obtaining results also outline similarities with other authors' research on climate change's effects on sunflower yield (Dellal, 2012; Demir, 2013; Deveci, 2015; Altürk et al., 2019; Gürkan, 2019; Gürkan et al., 2020; Yesilkoy, 2020) in Türkiye. Furthermore, the results are in line with previous studies conducted across Europe. In Southern and Eastern Europe, a decline in sunflower yield of between 10% and 30% was predicted for 2030. (Donatelli et al., 2015). Applying the ISAREG crop simulation model in Portugal environments, sunflower yield declines to deviate from 6% to 10% for the 2011–2041 timeframe and deviating from 11% to 19% for the 2041–2070 timeframe was calculated (Valverde et al., 2015).

According to the modeling results, sunflower yield would increase by 10% to 33% in both RCP4.5 and RCP8.5 scenarios. The findings revealed that providing enough water through further irrigation in the agronomic period increases sunflower production. However, in the Konya region, which lacks adequate irrigation facilities even today, the future irrigation requirement should not be ignored. Decision-makers should consider this situation in future agricultural production strategies. The importance of irrigation as a climate change adaptation technique for sunflower production in semi-arid environments is highlighted in the assessment of climate change risks.

The findings show that a rise in CO_2 levels caused by climate change can boost sunflower efficiency under irrigated conditions. Several studies have indicated that higher CO_2 concentrations enhance the productivity of C3 plants including the sunflower by allowing them to photosynthesize at a faster rate (Long et al., 2006; Reddy, 2010; Debaeke et al., 2017). For future climate predictions, the IPCC scenarios considered in this study, RCP4.5 and RCP8.5, anticipate a rise in CO_2 levels.

Assessment results of the impacts of climate change prove that especially due to temperature increases, the sunflower life cycle will shorten in future periods. For the overall 2022-2098 period, the average vegetation duration is expected to be shortened between 10-17 days for the RCP4.5 scenario, and between 17-20 days for the RCP8.5 scenario.

The Aquacrop Crop Model is a valuable technological tool to simulate the potential effects of climate change on future crop productivity. The Aquacrop model provides ease of use in research where data collection difficulties are experienced with its fewer input requirements and high success capability. The assessment of the effects of climate change on other herbal crops in other regions of Türkiye using the Aquacrop model could be the main subject of future research.

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