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RESEARCH ARTICLE

Modeling the response of sesame (*Sesamum indicum* L.) growth and development to climate change under deficit irrigation in a semi-arid region

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Data Availability Statement: The software (AquaCrop) was used in this study is available on the FAO website(http://www.fao.org/aquacrop/software/aquacropstandardwindowsprogramme/en/) and after the second author's registration; the latest version (6.1) of the model was downloaded and employed. The authors had no special access or privileges that others would not have. All used and created data are available on demand.

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Abstract

The future climate outlook was based on a combination of CCMs based on three Representative Concentration Pathway (RCP) scenarios including RCP 2.6, RCP 4.5 and RCP 8.5 for the future period of 2021–2051. The results showed an increase of the average Tmax in June, July and August (averaged by 1.8˚C compared to the observed period) and a decrease in rainfall in May to September (averaged by 30.76 mm compared to the observed period under all three scenarios. Estimation of phenological stages of sesame under different scenarios showed that with increasing Tmax in April and May, the beginning of flowering, grain filling and physiological maturity was accelerated, also with increasing temperature from June to August the duration of the phenological stages was decreased. The effect of deficit irrigation (DI, supplying of 50% plant water requirement) on sesame phenological stages was not significantly different from full irrigation (FI). Simulation of canopy cover evolution (CC) and dry matter accumulation using the AquaCrop model revealed that the length of the late-season and the mid-season stages, have the greatest liability to be changed under the future climate change. Under the studied scenarios, the beginning of sesame growing season will accelerate from 9 to 11 days, which makes possible delayed sowing of sesame. The average of biomass (B) produced under three scenarios in DI and FI conditions were 17920 and 17241 kg ha^{-1}, and the average of grain yield (GY) was 2905 and 3429 kg ha^{-1}, respectively, which shows an increase by 31.5% and 28.7% of B, 18.4% and 39.5% of GY, compared to the observations (year 2016). The results revealed that under the future climate (except for RCP8 scenario), DI strategy can be used without reducing the GY of sesame due to the very little reduction (1.2%) in GY under DI compared to FI.

1. Introduction

Climate change has become increasingly recognized as a global phenomenon with the possibility of extensive implications [1, 2]. Global warming is an important aspect of climate change [3]. According to the Intergovernmental Panel on Climate Change (IPCC), global warming

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will increase by about 1.5 to 4˚C by the end of the 21st century, compared to the base period (1850–1900), and will continue after 2100 [4]. Agriculture is expected to be negatively impacted in many regions through the greater occurrence and extent of excessive weather events like droughts and floods [5, 6]. It is anticipated that in developing countries which are mostly located in arid regions, the climate change impact on low-income people living in agricultural communities will be worse [7]. Climate change is the most important threat to sustainable development, agriculture and food security in these regions. As a strategy to protect and improve livelihoods and guarantee food security, the top concern for agricultural development is to reduce the vulnerability of agricultural systems to climate change [8, 9]. A large body of literature has recognized adaptation as one of the policy alternatives in response to climate change [10, 11]. It is defined as adjustment of natural or human systems to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities [12, 13]. It was reported that increased adaptive capacity of farmers can reduce negative impacts of climate variability and change [14].

Several potential adaptation alternatives have been recommended for developing countries. For instance, soil and water conservation practices have been suggested in response to the soil erosion crisis caused by climate change [15]. Similarly, the application of different agronomic practices like planting drought-resistant crop varieties, crop diversification, and improved crop varieties are potential adaptation practices [16]. Moreover, studies have showed the importance of adoption of small-scale irrigation schemes to overcome the impact of the unpredictable and irregular trends of rainfall and frequent drought [17]. Employing DI management in growing crops tolerant to semiarid conditions may save irrigation water without significant yield penalties. There are many studies that have been performed in relation to DI and its useful application in agriculture [18–20]. The results of Pabuayon et al. [21] demonstrated that sesame, safflower, and sunflower are potential low-input oilseed crops that can grow under deficit irrigation conditions without significant reductions to yield and oil content. The effects of climate change on growth and production of crops such as wheat, corn and rice have been studied across the world. These effects vary based on the type of plant, its photosynthetic pathway and the study site geographical conditions, so comments on the response of different species to climate change require case studies.

Regarding the importance of climate change, various tools have been developed to measure its effects. One of the relatively low cost, accurate and fast solutions is the use of modeling approaches, including crop growth simulation models [22, 23]. General circulation models (GCMs), also called climate coupled models (CCMs), are mathematical models that simulate atmospheric-oceanic properties and processes aimed at describing the earth's climate system [24]. Crop growth models predict the growth and yield of crops and can be used to explore the effects of climate change on agriculture through options to mitigate the negative effects such as setting the date of planting, changing the cropping pattern, cultivation of high temperature resistant cultivars and promotion of new crops including neglected and underutilized crops, and improved adaptive rural capacity managements [14, 25]. Rahimi Moghaddam et al. [23] by using the APSIM model under two climatic scenarios (RCP4.5 and RCP8) and using AgMIP data studied the effect of climate change on corn production in Khuzestan province, Iran. They reported that increasing the temperature increases the production risks and decreases the yield of corn, so with increasing the temperature by 2.33 and 3.29˚C, the grain yield of corn under the two scenarios of RCP4. 5 and RCP8 decreased by 13.7% and 22.8%, respectively. In another study, the CERES model and AgMIP data were used to assess the future climate of Panama on corn yield and the effect of end-season water stress on this crop. The results showed that increasing the temperature reduces the length of the growing season and accelerates the ripening period, and this reduces the end-season stress in the corn plant and also lowers the yield [22]. Zhang and Tao [26] modeled the response of rice phenology to climate change using five crop models in different climatic regions in China. The results showed that these models after calibration can satisfactorily simulate the phenological stages of rice. Under climate change conditions the length of the rice growing season will decrease by 0.4 to 5.7 days, but in northern China the length of the growing season will increase with increasing temperature.

Iran is located in an arid and semi-arid region and due to its biophysical structure, is vulnerable to environmental changes, and climate change is expected to have a significant effect on agricultural production systems [27]. Achieving more accurate information about climate change and its consequences in Iran requires extensive studies on a regional scale and predicting the response of agricultural production systems in each region to these changes [28]. In Iran, sesame is known as the highest quality oilseed crop, although it ranks third after canola and soybean mainly because of its expensive price. Total cultivated area in 2017–18 cropping year was 31,012 ha with 28,430 ha under irrigation and 2,581 ha as rainfed. The corresponding production of irrigated and rainfed systems was 30,468 ton and 551 ton, respectively [29]. In Iran, eastern, northeastern and central provinces are among the most important areas under sesame cultivation. Climate factors (water scarcity, high temperature widely coincide in midsummer) are the main reason for the continuously declining amount of sesame production in the cultivation area of sesame across the country. It was reported that drought and inadequacy of irrigation water are the most important production problems for many crops including sesame [30]. It has been reported that in Ethiopia sesame farmers employ small-scale irrigation managements (12.75%) over their farm as an important strategy to mitigate the consequences of climate change. As another strategy, half of them adopt sesame as a main crop diversification practice in adjustment to climate change [31]. Cagirgan et al. [32] studied the impact of climatic variability on the occurrence of sesame phyllody and symptomatology of the disease and suggested that climate change and variability may also offer some positive impact to be exploited for the benefit of food security and such cases should be considered in the crop management tactics and strategies as well as in modeling studies aiming to forecast the impact of climate variability. In arid environments, due to scarcity of water which usually coincides with high temperature, the need for a practical decision-support tool to help assess irrigation management methods, strategies and practices, is urgent [14, 33]. Simulation models provide a low-cost means for investigating a wide range of management options, enabling policy environments to guarantee food security. The Food and Agriculture Organization of the United Nations (FAO) has developed a field-crop-water-productivity simulation model named AquaCrop, which could be employed as a robust decision-support tool in planning, analysis and prediction of growth and development of many crops [34]. It was reported that to design and optimize DI strategies, crop water productivity (WP^*) modeling is a useful tool [35].

The phenology and growth period of the sesame plant are the main factors determining the agroecological suitability of this plant in the cultivated area. Correct prediction of crop phenological stages is very important for optimizing farm management activities and better adaptation of the crop calendar to specific agroecological systems, especially in order to mitigate the negative effects of climatic and environmental factors [36].

This study aimed to assess and simulate the critical phenological growth stages of sesame in response to increased temperature derived by climate change using a modeling approach. It is also the goal of this study to assess the effects of application of DI on phenological stages of sesame compared with FI, and its feasibility as alternative irrigation management under future climate change conditions.

2. Materials & methods

2.1. Study site

In this study, in order to simulate and investigate the effect of future climate change on sesame crop, Mashhad regional synoptic station (latitude: 36˚ 15′ N; longitude: 59˚ 28′ E; elevation: 985 m asl), with 69-year meteorological data and long history of sesame cultivation in semi-arid region was selected. The average maximum temperature is 11 to 30˚C and the minimum temperature is between 6 to 26˚C. The station was located in the Kashaf River watershed in the northeast of the country in an arid region with a mean annual precipitation of 256 mm that occurs mainly in winter and spring. The climate of the region is arid (BWh) according to the Koppen classification method [37].

The data required for this study include weather, soil and crop management factors. Weather data including daily data of minimum temperature (Tmin), maximum temperature (Tmax), radiation and precipitation of Mashhad station for the observed period of 1985–2015 were prepared by the Climatology and Aerology Organization (CAO), Iran. Data required to map the future climate were generated and extracted by simultaneously simulating four CCMs from paired oceanic atmospheric models including BCC-CSM1-1, GFDL-CM3, IPSL-C-M5A-LR, MIROC5 using web version of MarkSim DSSAT weather file generator. Also, monthly temperature and precipitation data were generated for the statistical period of 1985–2015 as a base (observed) period to evaluate the accuracy of the CCMs.

2.2. Field experiments

Field studies were conducted in 2015 and 2016 at the Research Farm of Agriculture Faculty, Ferdowsi University of Mashhad, Iran (The full description of the experimental design can find in Nassiri-Mahallati & Jahan, 2020). Soil data including soil class, soil moisture holding capacity at field capacity point, organic carbon, hydraulic conductivity, acidity and bulk density are shown in Table 1.

Crop management data including planting date, plant density, fertilizer management, irrigation, date of occurrence of phenological stages and duration of each stage, and harvest date, were obtained from 10 field experiments conducted at the research farm of Ferdowsi University of Mashhad, in addition to two experiments conducted by the authors in 2015 and 2016 during sesame growing season (May to October). The full description of the weather data, experimental design, planting and management, sampling, measurement and calculations were provided by Nassiri-Mahallati & Jahan [38].

Table 1. Soil physicochemical properties of the experimental field (mean of two years).

Soil depth (cm)	Total N (%)	Available P (ppm)	Available K (ppm)	EC[a] (dS m^{-1})	pH (Saturation extract)	C/N ratio	OC[b] (%)	Bulk density (g cm^{-3})	Water content at FC (vol.%)	Texture grade
0–15	0.076	22	460	1.3	7.3	12.7	0.55	1.45	27.3	Silty Loam
15–30	0.069	19	446	1.3	7.2	12.3	0.53	1.49	29.7	Silty Loam
30–60	0.041	21	435	1.5	7.2	11.6	0.43	1.51	29.3	Loam
60–90	0.022	20	431	1.6	7.1	10.7	0.39	1.52	29.0	Clay Loam

[a] EC: Soil electrical conductivity;

[b] OC: Organic carbon;

[c] FC: Field capacity.

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Table 2. Recorded growing degree day (GDD) and the days number to reach out each development stage of sesame under two irrigation regimes during the growing seasons of 2015–2016 (mean of two years).

Phenology	Full irrigation		Deficit irrigation	
	Accumulative GDD (˚C d^{-1})	Days after planting	Accumulative GDD (˚C d^{-1})	Days after planting
Flowering	790.6±112	41±0.89	782.4±131	38±0.96
Length of flowering	1105.1±85	16±0.84	1098±97	15±0.93
Grain filling	1106±72	56±1.1	1097.3±89	52±1.3
Length of grain filling	2268.7±142	53±1.4	2260.6±153	50±1.6
Physiological maturity	2270.5±88	105±1.2	2266.4±97	101±1.5
Length of maturity	2648.4±275	24±1.5	2637±291	22±1.8

Each value is averaged of six measurements ±standard deviation (SD)

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2.3. Developmental stages of sesame

Developmental stage indicates the physiological age of a given plant and is characterized by the formation and emergence of various organs. The most important phenological change of the plant is switching from the vegetative to reproductive stage, which causes a change in allocation of dry matter between plant organs. The main development stages of sesame plant include seedling emergence, flowering, grain filling and maturity. The required growing degree day (GDD) for three development stages of sesame including flowering, grain filling and maturity under two irrigation levels (FI, DI) for two years of experiment (2015–2016) were calculated (based on the photothermal model developed by the authors in MS-Excel spreadsheet software) using Eqs 1 to 4 [39] (Table 2):

$$\mathrm{DAP} = \mathrm{DAP}_{i-1} + 1 \quad (1)$$

$$\mathrm{TMP}_i = (\mathrm{Tmax}_i + \mathrm{Tmin}_i)/2 \quad (2)$$

$$\mathrm{DTT}_i = \mathrm{TMP}_i - \mathrm{Tb} \quad (3)$$

$$\mathrm{TT}_i = \mathrm{TT}_{i-1} + \mathrm{DTT}_i \quad (4)$$

Where, DAP is the day after planting; TMP: average of daily temperature; Tmax: daily maximum temperature; Tmin: daily minimum temperature; DTT: daily thermal time; Tb: base temperature of sesame crop; TT: accumulated thermal time; i: the number of the day used in calculation.

2.4. Outlook of climate projection

In recent years, the use of couple ocean-atmosphere models to identify climate change and its future consequences, at scales of decades and centuries, has attracted much attention [28, 39]. Hence, to predict the future climate in the study area an ensemble of CCMs included of BCC-CSM1-1, GFDL-CM3, IPSL-CM5A-LR, MIROC5 of MarkSim DSSAT weather file generator was employed. This is the MarkSim web version for IPCC AR5 data (CMIP5). Employing MarkSim, it is possible to use 17 available CCMs individually or in combination. When several CCMs are selected, the MarkSim creates a combination pattern based on averaging. The resolution of MarkSim simulations is 2.5×2.5 degree pixels, and therefore does not require downscaling. The general assumption is that if the model can simulate the long-term average of climatic parameters in the base period with appropriate accuracy, it is expected to have more or less the same accuracy in simulation future conditions.

In the latest report of the IPCC (IPCC AR5 2013), the future climate is predicted based on four scenarios: RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5. The RCP scenarios include a low-forcing scenario (RCP2.6), two moderate-forcing stabilization scenarios (RCP4.5 and RCP6), and a high-forcing scenario (RCP8.5). In the present study, the three RCP 8.5, RCP 4.5, and RCP 2.6 were selected on the basis that they represent all three scenarios of prediction.

2.5. Tuning of crop model parameters to local conditions

In the AquaCrop model, constant and variable plant parameters (also called conservative and non-conservative parameters, respectively) should be adjusted under water stress through the influence of plant sensitivity factors to drought (Ks_{sen}, Ks_{exp}, Ks_{sto}). This is because plant parameters have different values under different conditions and their values depend on farm management factors as well (Table 3). The AquaCrop required parameters for the study area conditions have already been tuned, calibrated and validated [38]. In addition to the data measured at field experiments in the present study, data from 10 experiments on sesame between 2010 and 2018, all of which were conducted at the research farm of Ferdowsi University of Mashhad (as the same site of the present study), were used for tuning of crop parameters to local conditions.

Table 3. Sesame crop parameters affected by deficit irrigation, used in AquaCrop model under Mashhad conditions.

Crop parameter	value	unit	Source
Non- conservative crop parameters			
Reference harvest index	23	%	Measured
Canopy cover per seedling at 90% emergence (CC_o)	4.5	cm^2	Measured
Maximum effective rooting depth	90	cm	Measured
Time to maximum rooting depth	82	day	Measured
Time from sowing to emergence	11	day	Measured
Time from sowing to flowering	55	day	Measured
Time from sowing to maximum canopy cover (CC_x)	64	day	Measured
Time from sowing to senescence	89	day	Measured
GDD from 90% emergence to start of flowering	785	˚C day	Measured
GDD for flowering period length	317	˚C day	Measured
Plant density	400000	plant ha^{-1}	Measured
Maximum canopy cover (cc_x)	95	%	Measured
Conservative crop parameters			
Low threshold of salinity	2	dS m^{-1}	default
Aeration stress	Sat-5	%	default
Base temperature	10	˚C	default
Upper temperature	40	˚C	default
Soil water stress coefficient of canopy expansion (Ks_{exp}) Upper threshold	0.15	-	default
Soil water stress coefficient of canopy expansion (Ks_{exp}) Lower threshold	0.65	-	default
Soil water stress coefficient of stomata closure (Ks_{sto})	0.60	-	default
Soil water stress coefficient of canopy senescence (Ks_{sen})	0.70	-	default
Normalized crop water productivity (WP*)	18	g m^{-2}	default
Crop coefficient (Kc_{Tr})	1.05	-	default

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2.6. Sensitivity analysis of the crop model

Sensitivity analysis of the model was performed using the absolute value of the relative difference between biomass (B) and grain yield (GY) [40].

2.7. Calibration and validation of the crop model

Since the AquaCrop model uses different plant parameters to simulate plant growth and yield, the parameters were calibrated before running the model. Consequently, the model was validated using the data for the second year.

2.8. Estimation of sesame phenology

The calculated GDDs (based on the photothermal model) for each development stage of sesame under two irrigation levels (Table 2) were employed to identify the date of occurrence and the length of each development stage for the growing seasons of 2021–2051.

2.9. Simulation of sesame canopy cover (CC) and biomass (B)

Mean of Tmin, Tmax, and precipitation in Mashhad station based on the forecast of CCMs for the statistical period 2021–2051 were introduced to the AquaCrop model after preparation to crop model appropriate format. Soil and crop management data were obtained from field experiments. The evolution of sesame CC and B (dry matter accumulation) under two irrigation levels during the growing seasons for 2015, also for three scenarios (2021–2051) were simulated.

2.10. Model evaluation

To evaluate the AquaCrop model reliability in simulating sesame phenological stages, statistics of the goodness of fit including *RMSE* (Eq (5) [41]), coefficient of determination (R^2) (Eq (6) [42]), were employed.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n}} \tag{5}$$

$$R^2 = \frac{\left(\sum_{i=1}^{n} (P_i - \bar{P})(O_i - \bar{O})\right)^2}{\sum_{i=1}^{n} (P_i - \bar{P})^2 (O_i - \bar{O})^2} \tag{6}$$

3. Results

3.1. Temperature and rainfall during the sesame growing season

The average of Tmin, Tmax and precipitation during the sesame growing season for observed period (1985–2015) are shown in Fig 1. During the observed period, Tmin and Tmax had an upward trend, although the increase in Tmin was greater than Tmax. Precipitation fluctuations did not follow a definite trend, however, since 2000 to 2015 the amount of precipitation has decreased significantly compared to the previous fifteen years (1985–2000).

Outlook of the average of Tmax, Tmin and precipitation during the sesame growing season projected for the future (2021–2051) under three scenarios RCP 8.5, RCP 4.5 and RCP 2.6 compared to the observation period (1985–2015) shown in Fig 2.

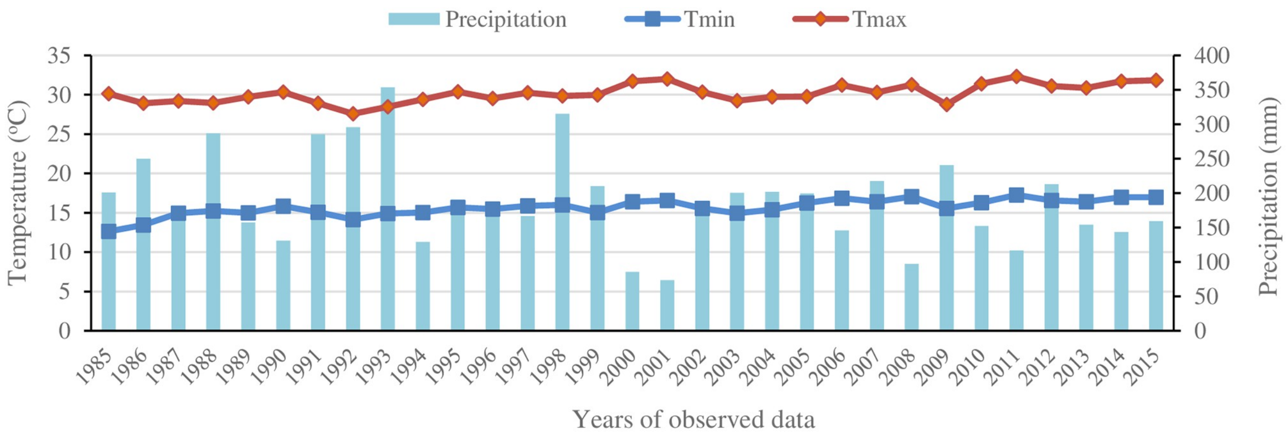

Fig 1. The average of minimum temperature, maximum temperature and precipitation during the sesame growing season for the observed period (1985–2015).

https://doi.org/10.1371/journal.pclm.0000003.g001

Projected Tmax by the ensemble models of GCMs during April to September showed that for April, May and September, the average Tmax under all three scenarios was lower than the same months in the observation period (as much as 0, 3.5 and 1.3 ˚C, respectively) and for June, July and August, were estimated more than the observation period (as much as 2.2, 4.2 and 1.4 ˚C, respectively) (Fig 2).

The average projected Tmin in April, May, June, August and September were lower than for the same months in the observation period (as much as 9.2, 3.8, 0.25, 0.4 and 4.3 ˚C, respectively), and only for July was estimated more than the related observed value (as much as 1.54 ˚C) (Fig 2).

The average total precipitation projected under the three scenarios during the sesame growing season, was higher only in April (as much as 18.8 mm), compared with the amounts of the observation period and it was estimated to be less than the observation period in May, June, July, August and September (as much as 13.9, 44.4, 37, 22.6 and 35.8 mm, respectively) (Fig 2).

Projected mean of Tmax was higher in June, July and August compared with observed related values. Projected mean of Tmin was only higher in July and was lower in April, May and September compared with observed values. Projected mean of rainfall was lower in May to September and was only higher in April compared with observed values (Fig 3).

A relative comparison of the mean of projected Tmax, Tmin and rainfall for three scenarios with related observed values indicated that all three projected values were lower than observed ones (Fig 4). However, the difference between projected and observed Tmax was not significant, but this difference was large and significant for Tmin and especially for rainfall.

3.2. Sesame phenology under climate change

Estimation of the length of flowering, grain filling and physiological maturity stages of sesame under three scenarios of RCP 8.5, RCP 4.5 and RCP 2.6 indicates that in future climatic conditions, the length of these stages will change (Table 4 and Fig 5). Linear relationships and negative correlations were found between the increase in the mean temperature and the beginning of phenological stages of sesame under three scenarios: RCP 8.5, RCP 4.5 and RCP 2.6 in the future period 2021–2051. The statistics were significant only for the beginning of grain filling stage.

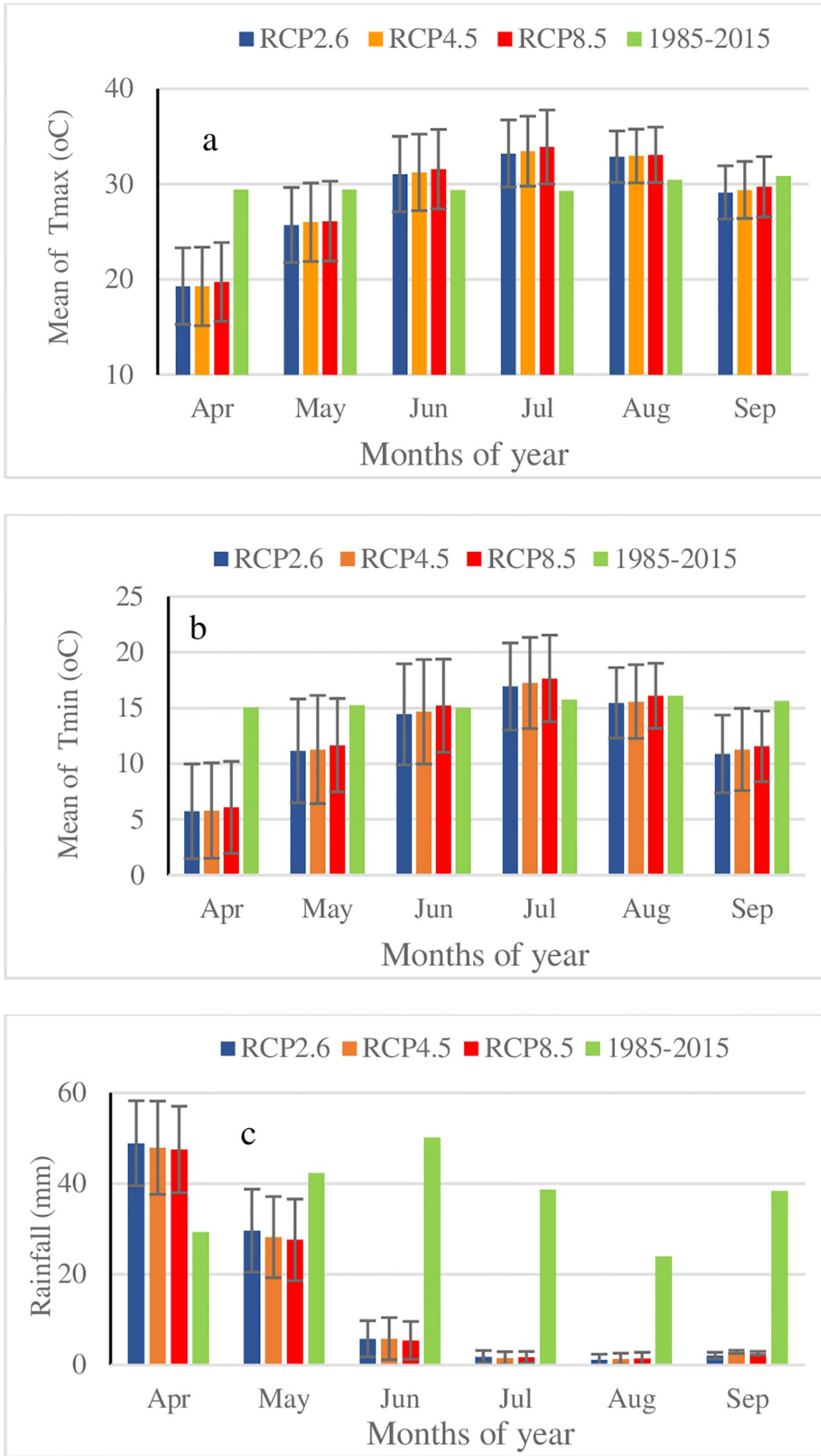

Fig 2. Observed and predicted of the mean of (A) Tmax, (B) Tmin, and (C) rainfall under three scenarios of climate change for Mashhad region.

https://doi.org/10.1371/journal.pclm.0000003.g002

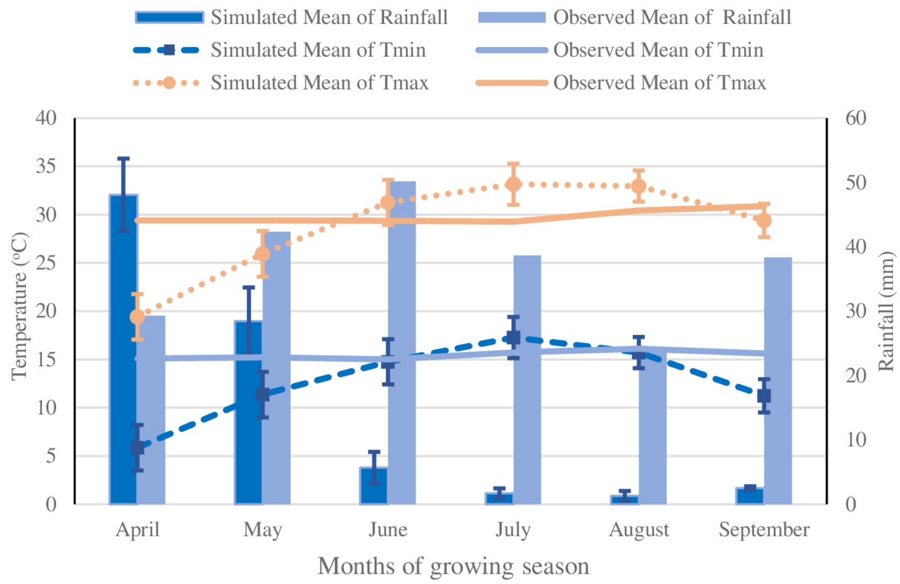

Fig 3. Observed and projected mean of temperature and rainfall under three scenarios of climate change for Mashhad region.

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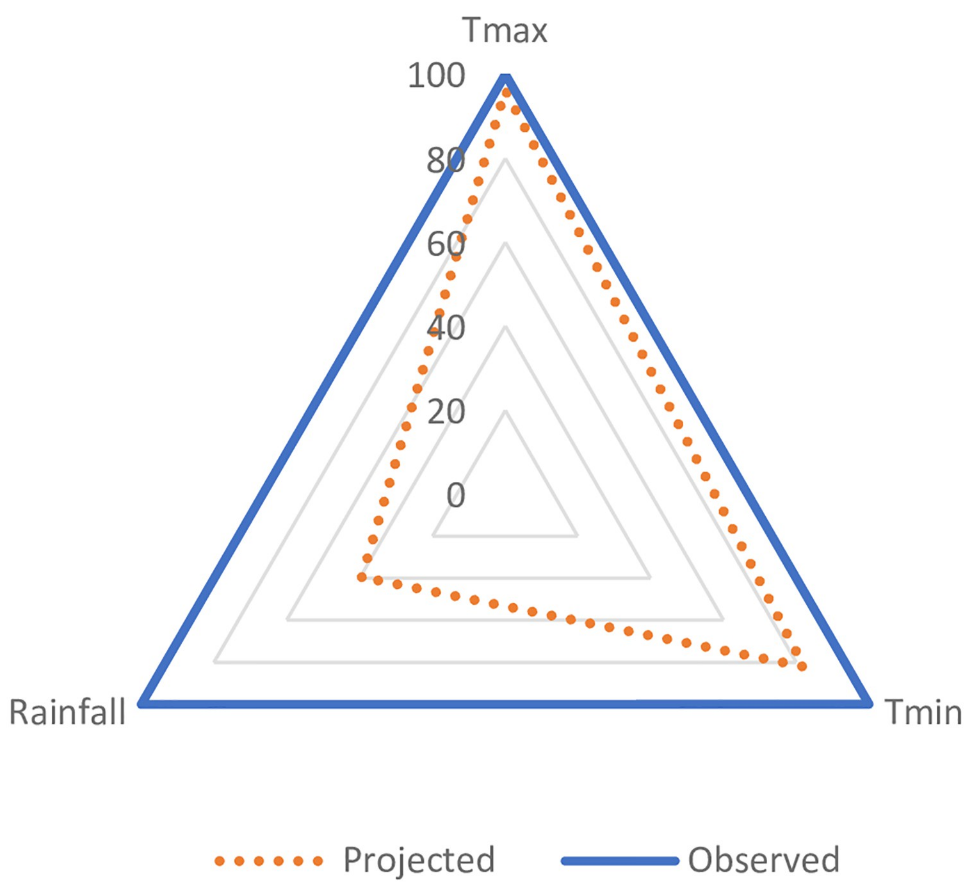

Fig 4. The relative comparison of the projected (averaged of three scenarios for 2021–2051) and observed (1985–2015) of Tmax, Tmin and rainfall.

https://doi.org/10.1371/journal.pclm.0000003.g004

Table 4. Mean comparisons of observed and estimated length of sesame phenological stages under two irrigation levels for 2021–2051.

Irrigation regime	Flowering (d)		Grain filling (d)		Physiological maturity (d)	
	Observed	Estimated	Observed	Estimated	Observed	Estimated
Full	12±0.84	10	55±1.1	67	24±1.3	27
Deficit	12±0.87	10	52±1.2	64	21±1.5	24
Mean	12	10	53.5	65.5	22.5	25.5

Each mean is averaged of six values ±standard deviation (SD)

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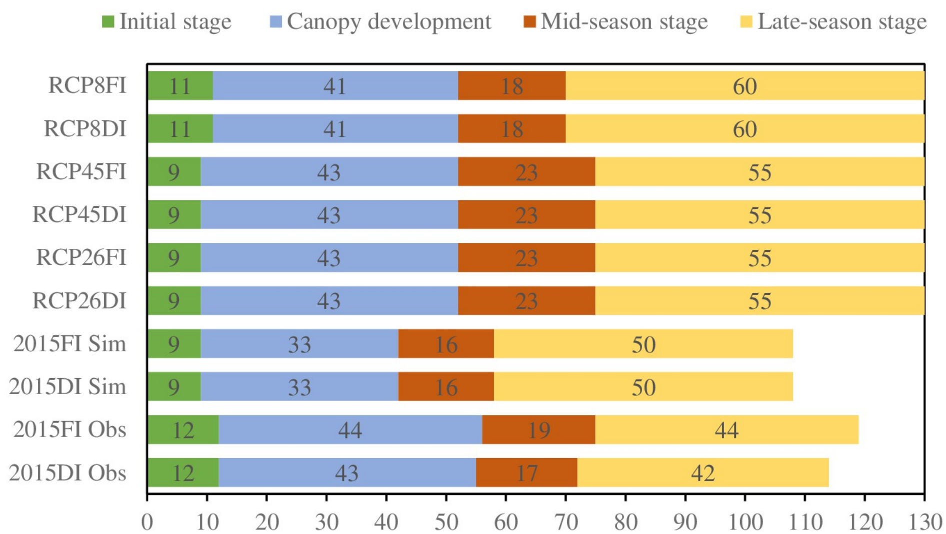

Fig 5. The beginning day and the length of sesame phenological stages under two irrigation levels and three climate scenarios simulated for 2021–2051 and 2015 (simulated and observed) based on FAO stages.

https://doi.org/10.1371/journal.pclm.0000003.g005

3.3. Evaluation of the phenology models

The statistical indices for the estimated and observed values of the length of the phenological stages of sesame (calculated using the photothermal model) are shown in Table 5. The *P-value* of *t-test* at 95% of probability level and the coefficient of determination (R^2) indicate that the model simulations had satisfactory accuracy. It is noteworthy that the difference between the observed and simulated values in all three phenological stages between FI and DI was insignificant.

AquaCrop simulates phenology stages based on FAO 56 stages guideline, including 1. Initial stage, 2. Canopy development, 3. Mid-season stage, and 4. Late-season stage. In Fig 6 these stages were shown for all combination of scenarios and irrigation levels. The projected predictions indicated that the length of initial stage (stage 1) will reduce (by 1 to 3 days). The length

Table 5. Statistical indices to evaluate the precision of the Excel developed phenology model in estimation of sesame phenological stages under future climate change.

Phenological stages	Number of data	P (t)	RMSE	R^2
Flowering	90	0.071	3.4	0.81
Grain filling	90	0.066	2.9	0.85
Physiological maturity	90	0.061	2.1	0.87

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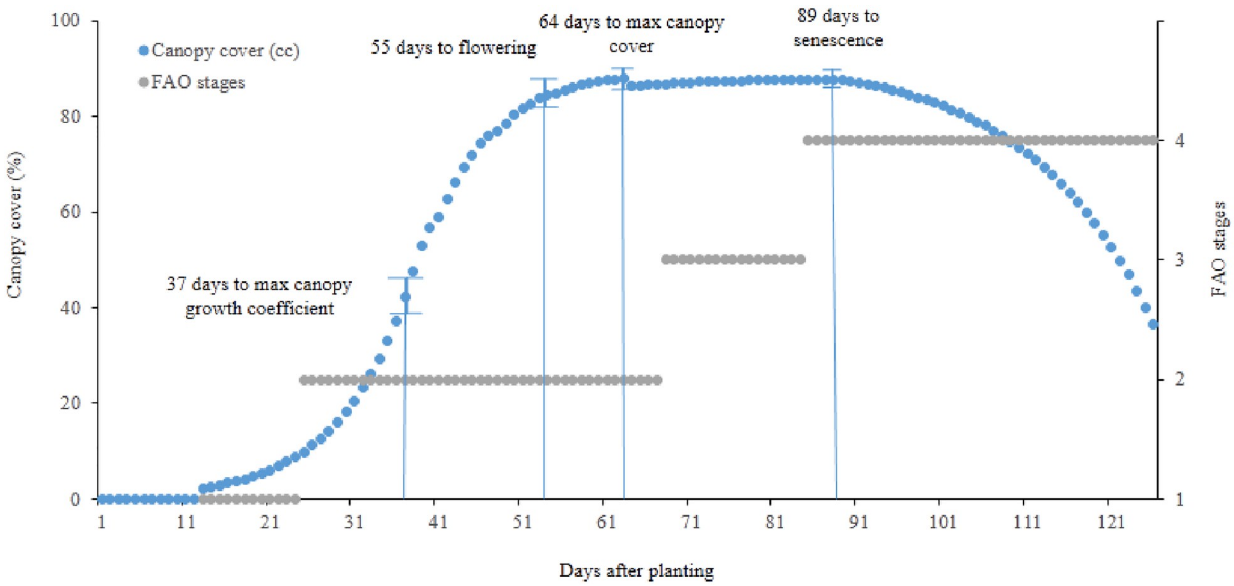

Fig 6. Observed sesame canopy cover evolution and critical development stages during growing season of 2015.

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of canopy development stage (stage 2) may reduce by 1 to 3 days under FI and from 0 to 2 days under DI. The length of mid-season stage (stage 3) will be reduced by 1 day in RCP8, but will increase by 4 days for RCP4.5 and RCP2.6 under FI. The same trend will be resulted for stage 3 under DI (Fig 6). The length of late season-stage (stage 4) may increase by 1 day in RCP8, by 16 to 18 days, and will increase by 11 to 13 days for RCP4.5 and RCP2.6, respectively (Fig 6).

3.4. Evaluation of crop model

Calculation of goodness of fit indices revealed that the AquaCrop model had high robustness to simulate canopy cover evolution and dry matter accumulation of sesame (Table 6). The values of *NRMSE* and R^2 were slightly higher for FI compared with DI regarding CC and B simulations.

3.5. Simulations of CC evolution, B accumulation, GY and water productivity (WP*)

AquaCrop simulations of B, GY and WP* for three scenarios are shown in Table 7. To better understand the changes in the developmental stages of sesame under projected climate change conditions, first, the time of occurrence and the length of three developmental stages were determined (using Eqs 1 to 4) and compared to FAO stages (Fig 6), then by inputting these

Table 6. Goodness of fit indices for sesame canopy cover (CC) and biomass (B) simulations under two irrigation levels.

Treatment	Parameter	Statistics		
		R^2	NRMSE (%)	EF
Deficit irrigation	CC	0.94	2.2	0.87
	B	0.95	3.4	0.81
Full irrigation	CC	0.95	2.1	0.91
	B	0.96	3.3	0.83

R^2: coefficient of determination, NRMSE: normalized root mean square error, EF: modeling efficiency

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Table 7. Observed and simulated biomass, grain yield and water productivity of sesame under the three scenarios of climate change.

		Biomass (t ha^{-1})		Grain yield (t ha^{-1})		Water productivity (WP*) (g m^{-2})	
		Deficit irrigation	Full irrigation	Deficit irrigation	Full irrigation	Deficit irrigation	Full irrigation
Observed	2015	13.622	13.390	2.543	2.458	18.3	18.3
Simulated (2021–2051)	RCP2.6	18.153	17.479	2.782	2.719	21	21
	RCP4.5	17.961	17.279	2.752	2.691	21	21
	RCP8	17.648	16.966	3.183	4.878	21	21

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values to the AquaCrop model, changes in sesame canopy cover and biomass accumulation were simulated during the growth period (Fig 7).

Simulation of canopy cover evolution and biomass accumulation under three scenarios, and also data for 2015 are shown in Fig 7.

4. Discussion

The future climate outlook of the region based on combined models showed that the Tmax in June, July and August at Mashhad station under the RCP 8.5, 4.5 and 206 scenarios will increase by 1.91 ˚C, 3.88 ˚C and 2.53 ˚C compared to the same months in observed period (1985–2015), respectively. The average total rainfall under the mentioned scenarios compared to observed period will decrease intensely except for April which showed an increase of 18.78 mm. The highest decrease in rainfall will be in July (36.96 mm) and the lowest will be in May (13.87 mm) (Fig 3). The effect of DI on the length of sesame phenological stages was not significantly different from FI (Table 4). In other words, application of DI did not make a difference during the phenological stages of sesame (Fig 5).

Interaction of increasing the mean temperature and irrigation level on the phenological stages of sesame crop under three scenarios in the future showed that at both levels of irrigation, the beginning of flowering, grain filling and physiological maturity stages occurred earlier with increasing temperature (Fig 5). It was reported that physiological maturity of wheat crop can be accelerated by increased temperature and drought stress any time during the crop life cycle [43]. Hailu et al. [18] reported that the highest sesame yield of 1846.7 kg ha^{-1} was obtained from application of DI by 50% of crop evapotranspiration (ETc) with the conventional furrow application method. DI as a valuable and sustainable strategy in dry areas has been widely investigated and employed where water is the limiting factor in crop cultivation [20, 35]. The purpose of DI is to maximize water productivity and stabilize yield rather than maximize it. Sesame adoption by farmers is mostly due to its drought and high thermal tolerance characteristics [44].

The evaluation results of the phenology model showed that there is a small difference between the measured and estimated values (Table 5). Considering the values of R^2 (0.81 to 0.87) and *RMSE* (2.1 to 3.4), it could be claimed that the model meets high precision for predicting the length of flowering stages, grain filling and physiological maturity stages of sesame crop under the projected climate change conditions. The model estimations are in agreement with the simulations obtained from the AquaCrop model (Fig 5).

The length of sesame growing season under three scenarios was increased by 11 to 16 days at both irrigation levels compared with observed period. Moreover, the increase in FI was about 5 days less than DI (Fig 5). The reduced length of initial stage for both irrigation level under RCP8 was 1 day, and under RCP4.5 and RCP2.6 was 3 days, compared with the observed period. The reduced length of canopy development for DI and FI levels under RCP8 were by 2 and 3 days, respectively, compared with the observed period. The length of canopy

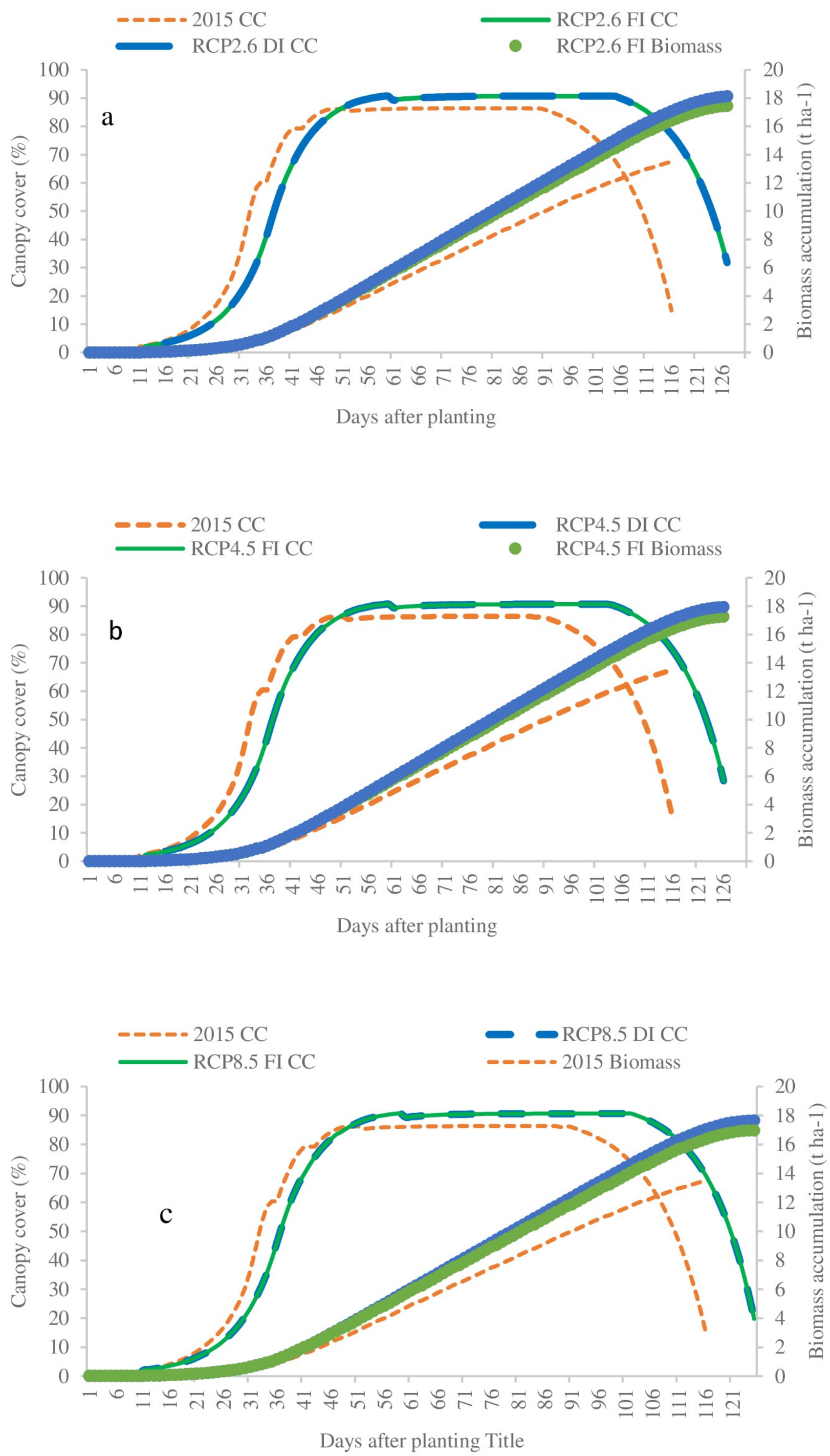

Fig 7. Sesame canopy cover evolution (lines) and accumulative biomass (dots) during growing season (127 days) under three scenarios of projected climate change (2021–2051).

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development for FI level under RCP4.5 and RCP2.6 was reduced 1 day, and did not change for DI level. The remarkable point is the length of mid-season stage under RCP4.5 and RCP2.6 increased by 5 days (on averaged for DI and FI levels), whiles under RCP8 no change was resulted (Figs 5 and 7). Another noteworthy point was that by 16 to 18 days increase in late-season stage under RCP8 compared to the observed period, whiles under RCP4.5 and RCP2.6 the regarding value was by 11 to 13 days (larger values are related to DI level). Considering these changes, it can be suggested that the late-season stage and the mid-season stage, have the greatest potential to be changed in the length of the period under the future climate, compared to the initial and canopy development stages. The increased length of the late-season stage under RCP8, resulted in increased SY by 15% (under DI) and 80% (under FI), compared with RCP4.5 and RCP2.6 (based on averaged of two scenarios) (Table 7). This improved SY obtained with no change in B under RCP8.

With increasing air temperature, averaged time of the beginning of phenological stages of sesame in DI showed a greater decrease than the FI (Fig 5). In other words, with increasing temperature and decreasing irrigation water, the beginning of phenological stages will delay, and decreasing the amount of irrigation water will exacerbate the effect of increasing temperature on the onset time of phenological stages. With decreasing irrigation water (application of DI) and increasing temperature (drought stress), the length of flowering period did not differ significantly compared to FI, although the length of grain filling and physiological maturity decreased significantly, which is probably due to higher Tmax and less rainfall in June, July, and August (Fig 3).

The relative comparison of the projected (averaged of three scenarios for 2021–2051) and observed (1985–2015) Tmax, Tmin and rainfall indicated that the projected value of Tmax were close to the observed value. Moreover, rainfall and Tmin will be decreased in the future studied period (Fig 4). In other word, under future climate, variability in rainfall and Tmin would be higher than Tmax which affects the agronomical management of sesame cultivation.

Increasing the length of the growing season, by providing an earlier planting date in early spring, when most of the rainfall occurs, can mitigate the effects of rising temperatures due to climate change and even lead to increased yields [25]. Existing reports on the longer length of the growing season vary widely depending on the region and the climate change scenario [28, 39]. However, studies in northern Europe have shown that future climate change will increase the length of the growing season and allow cultivation of late maturing cultivars of wheat, and as a result, wheat yields are predicted to increase significantly [45, 46].

Increasing the temperature under different scenarios shows that at higher temperatures (increasing temperature by more than 1 ˚C), the beginning of flowering, grain filling and physiological maturity will be accelerated. The length of the grain filling period and physiological maturity stages will be longer, even when the total plant water requirement (full irrigation) was provided (Fig 5, Table 4). Increasing the temperature may decrease the growth rate of the crop; however, experimental evidences have shown that under these conditions, the duration of grain ripening in cereals and grain crops will be longer [5, 47]. Since the optimum yield is, on the one hand, a function of dry matter accumulation during the growing season and, on the other hand, a function of sufficient time to transfer the assimilates to the grain, so increasing the temperature could extend the length of grain filling period in sesame and may result in higher yield (Fig 5). It has been reported that an increase in the length of the growing season in early spring may compensate or increase the yield [48]. It was reported that changing the planting date and breeding new cultivars with higher resistance to drought and high temperature will mitigate the reduction of wheat yield in Iran under the climatic conditions of 2025 and 2050 by 13 and 21 percent, respectively [25]. Studies on rice have also confirmed the increase in resistance to high temperatures through the improvement of new cultivars as one of the adaptation strategies to climate change [5, 49].

The length of phenological stages were not significantly affected by DI (Table 5). These results are in agreement with the results of research of Mohammadi et al. (2015) on the effect of climate change on rice phenology [50]. High values of R^2 have been reported in simulating the growth of different crops under DI conditions, e.g., Khorsand et al. [51] reported an $R^2 = 0.95$ in simulating wheat yield under drought stress conditions. To design and optimize DI strategies, crop water productivity modeling is a useful tool [35].

The average biomass (B) produced under three scenarios in DI and FI conditions were 17920 and 17241 kg ha^{-1}, and the average of grain yield (GY) was 2905 and 3429 kg ha^{-1}, respectively, which showed an increase of 31.5% and 28.7% for B, and 18.4% and 39.5% for GY, compared to the observational year (2016) (Table 7). Under the future climate change conditions (except for RCP8 scenario), DI strategy can be used without reducing the GY of sesame due to the very little reduction (1.2%) in GY under DI compared to FI. Andarzian et al. [43] reported that the AquaCrop model was accurately able to simulate soil moisture content of root zone, crop biomass and seed yield of wheat, with *NRMSE* less than 10%; analysis of irrigation scenarios also showed that the highest grain yield could be obtained by applying deficit water conditions (200 mm). Nath et al. [52] assessed the effects of macro and micro climatic variations on yield of sesame for various sowing dates and indicated that the average reduction in yield of sesame was 78.5 and 213%, respectively, for crops sown on 10th February and 28th April, compared with the crop sown on 19th February. Ambient temperature above 30˚C up to 100% flowering also had a direct positive effect on sesame yield. They reported that the temperature profile and photosynthetically active radiation within the sesame canopy produced 72 and 35% variation in yield, respectively. It was reported that nutrition resources affected the sesame growth indices, but had no effect on phenological stages of sesame [53]. Plant-response mechanisms for enhanced drought resistance interacted under robinin + chitosan treatment to improve plant performance under stress conditions [54]. Joyce et al. [55] reviewed agricultural water management strategies for adaptation to climate change using the WEAP model and suggested that the best adaptation strategies include improving irrigation technologies, and changing cultivation patterns to more valuable or less water consumable crops. Studies on the effect of climate change on rice production in India by Agrawal and Mal [56] also showed that increasing temperature will reduce flowering duration and that pre-flowering temperature change showed no effect on other phenological processes. Modeling the response of rice phenology to climate change using five crop models in China by Zhang & Tao [26] also showed that the rice growing season under future climate change scenarios will be reduced by about 0.4 to 5.7 days. Gohari et al. [57] studied the effect of climate change on four species of cereals in Zayandehrud basin and reported that with increasing temperature and decreasing rainfall, the crop growth period will decrease.

The AquaCrop model showed a fair performance in simulating the canopy cover evolution and biomass accumulation. The length of developmental stages determined by the model which is based on the FAO 56 stages, showed a slight difference with four calibrated stages for sesame [38]. The standard error of the means (SEM) for simulated canopy cover at the time of reaching the maximum canopy growth coefficient, flowering and the maximum canopy cover was more than the SEM at the time of canopy senescence. This is because canopy senescence occurs under the influence of high temperatures on the hottest days of summer and changes in the simulated Tmax under the three scenarios are less than the changes in Tmin (Fig 4). It seems (Fig 6) that the time of onset of the stages of emergence, rapid canopy development, flowering and the maximum canopy cover have higher sensitivity and therefore higher variability in future climate change compared to grain filling, ripening, and canopy senescence stages. Moreover, the length of grain filling and ripening and canopy cover senescence increased which in turn improved biomass by about 4 t ha^{-1}. Simulation of canopy cover evolution and biomass accumulation under three scenarios revealed the same trend (Fig 7), but showed no significant difference from the equivalent trend for the year 2015.

These findings call for policy and plans that promote and expand the practices of climate change adaptation strategies based on adaptive management capacity [14]. As water variability is a critical constraint to sesame production, risk-reducing measures and associated plans would be advantageous. Based on this study's findings, we further point toward management that should target increasing provision of relevant timely information on current as well as future climate forecasts. Introducing modern high-yield and climate-resilient crops, in turn, will inform farmers' climate adaptation decisions and help them reduce food insecurity and boost sesame production. Integrating the simulation models with regional early warning systems would improve yield stability by responding to farmers' need for agro-climatic information resources and climate risk management tools.

The present study has been conducted with respect to the current level of agriculture and without considering the development of future technology in the agricultural sector. In the context of changing climate conditions, adaptation to climate change by determining the optimum planting date and selecting the most suitable crop cultivar should also be considered to minimize plant stress at high temperatures. Given the rapid pace of change in various domains- including climate, environment, technology and social- as well as the uncertainty that exists in every forecast scenario, the authors strongly suggest that simulations of climate impacts on crop growth and development should be conducted for shorter periods of time such as between five and ten years. In this case, the results of such studies will not only be associated with less uncertainty, but also will be more applicable in practice, due to greater congruence with conditions over shorter time periods.

5. Conclusion

This study examined the implications of deficit irrigation under future climate change as an adaptation strategy for sesame production in a semi-arid region. Sesame phenological stages were exposed to climate change and have been tested for possible adaptation by applying different irrigation levels. The results of the future climate modeling showed an increase in the average Tmax in June, July and August (1.8˚C compared to the observation period) and a decrease in precipitation in May to September (average 30.76 mm compared to the observation period) under all three scenarios. The AquaCrop simulations showed that increases in temperature variability accelerated the beginning of sesame phenological stages along with longer length of phenological stages. The effect of deficit irrigation on sesame phenological stages was not significantly different from full irrigation. Simulation of the canopy cover development and biomass accumulation during the growing period confirmed the changes occurring through phenological stages. For reproductive growth stages, the length of grain filling period and physiological maturity increased, which in turn improved the final yield. This suggests that adaptation strategies are effective both in harnessing the effects of climate change and ensuring an optimum level of sesame production. Generally, it seems that sesame phenology will not negatively be impacted by climate changes, and may even provide higher production in response to future higher temperature.

Author Contributions

Conceptualization: Mahdi Nassiri-Mahallati.

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Formal analysis: Mohsen Jahan.

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Validation: Mahdi Nassiri-Mahallati.

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