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Optimizing the Sowing Date and Irrigation Strategy to Improve Maize Yield by Using CERES (Crop Estimation through Resource and Environment Synthesis)-Maize Model

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Abstract: Summer maize (*Zea mays* L.) is a widely cultivated crop in the arid and semi-arid Guanzhong region of China. However, due to the spatial and temporal variation in rainfall, the seasonal maize yield varies substantially and occasionally is not economical for poor farmers to produce. Recent water-saving agricultural practices were developed by the government to make it possible to apply supplementary irrigation at optimum sowing dates to maximize maize production under limited rainfall in the region. CERES (Crop Estimation through Resource and Environment Synthesis)-maize model was used to identify the appropriate irrigation strategies, crop growth stages and sowing dates for sustainable maize production. Model calibration process were carried out for full irrigation treatments of four growing seasons, (2012–2015). The data used for calibration included: Crop phenology, grain yield, aboveground biomass and leaf area index. The calibration phase model showed good agreement between simulated and observed values, with normalized root mean square error (nRMSE) ranging from 4.51% to 14.5%. The performance of the calibrated model was evaluated using the field data of grain yield, aboveground biomass, leaf area index and water use efficiency. The performance of the model during evaluation was satisfactory with acceptable nRMSE error ranging from 7% to 10%. Soil moisture content was evaluated for full irrigation treatments for both 2012 and 2013 seasons. With results showing that soil moisture content below 35 cm layer was well simulated with nRMSE, 0.57 to 0.86 respectively. Appropriate simulated sowing dates for higher production and water productivity were from 14 to 24 June. The proper amount and timing of irrigation water application was 100 mm at the flowering stage, and 100 mm at the grain filling stage respectively. Summer maize yield can be improved by adjusting the sowing date and applying supplementary irrigation when precipitation cannot meet the crop water demand in the Guanzhong Plain.

Keywords: CERES-maize; Summer maize; Sowing date; Irrigation strategy; Guanzhong Plain

1. Introduction

The scarcity of water resources is one of the major challenges in the world, particularly for the main fresh water consumer, i.e., agriculture. In the context of the increasing shortage of water resources, improving crop water productivity (producing more crop per drop) will contribute to alleviating the water crisis, especially in arid and semi-arid regions [1]. In the Guanzhong region, water resources are limiting for crop growth and are mainly dependent on monsoon precipitation, where above 60%–70% of the precipitation comes in around June and August. This is not an appropriate time to meet water demands from a corn crop [2]. With the variability and uneven distribution of precipitation in China [3], the rainfall pattern is also irregular in the Guanzhong plain [4]. This insufficient and irregular rainfall generally results in water scarcities and droughts. Therefore, water scarcities and uneven rainfall distribution are the primary limitations on the growth of agriculture in northwest China. In the arid and semi-arid region, the farmers can apply supplementary irrigation at different crop growth stages to fulfill the deficiency of rainfall and avoid the effects of water stress on the plants. Irrigation scheduling based on supplementary irrigation can increase grain yield under scarce water conditions [5–7]. Supplementary irrigation provides the required amount of water at different crop growth stages to reduce the impacts of water shortage on plants. However, irrigation planners have no precise methodology to determine the amount of irrigation water to apply at which specific crop stage. Previous studies showed that supplementary irrigation amount was selected based on previous experiences. Currently this practice has been replaced by crop system models to improve the estimation of irrigation amount.

Many crop system models have been developed, such as FAO Aqua Crop model [8], Crop System [9], APSIM (Agricultural Production Systems Simulator) [10], RZWQM (Root Zoon Water Quality Management) [11], and DSSAT (Decision Support System for Agro-Technology Transfer) [12]. These crop system models have been used for the simulation of agriculture practices, with DSSAT widely used in the world for the simulation of biomass and grain yield production. CERES-maize model [13–15] included in DSSAT is a multi-purpose model that has been used to evaluate crop growth and development, such as phenology (mainly anthesis and physiology maturity dates), biomass production and yield [12]. CERES-maize model predicts yield and soil moisture at different depths accurately under full irrigation treatments [16–20]. CERES-maize model has also been used for determining optimum sowing dates using long term weather data and for yield prediction under different climate scenarios [21–24], and yield prediction response to the variability of climate [25–27]. DSSAT has been extensively used for multiple purposes in some regions of China, such as Northeast China, [28], in Northern China [29] and in Northwest China [30,31].

There are no studies conducted in the Guanzhong region of northwest China for maize crop production using the irrigation strategy scenario and sowing date under different climatic condition. Thus, it is necessary to identify the irrigation strategy, critical crop growth stages and sowing date under the variation of precipitation amount during the growing season for securing crop productivity. In this area, the main aim is to reduce crop water stress and improve agricultural production by employing supplementary irrigation. The objectives of this study were thus (1) to calibrate and evaluate the CERES-maize model in the Guanzhong Plain. (2) to determine the optimum sowing date, crop growth stages and irrigation amount to improve maize yield under rain-fed and irrigation conditions using the CERES-maize model.

2. Materials and Methods

2.1. Field Experiment

The experiment was conducted at the Key Laboratory of Agricultural Soil and Water Engineering (Figure 1) (34°18′ N, 108°24′ E, 506 m above sea level), Northwest A&F University, Yangling, Shaanxi Province, China. The study area is in a sub-humid to a semi-arid climate zone with a mean annual temperature of 12.9 °C and a mean annual maximum and minimum air temperatures of 40 °C and −17.4 °C, respectively. The total annual sunshine duration was 2196 h, with annual precipitation of 548 mm. Daily maximum and minimum air temperature (°C), precipitation (mm d^{-1}), and sunshine hours for years 2012 to 2015 were obtained from the Yangling meteorological station (Figure 2a), which is located beside the field experimental site. Historical weather data (1961–2011) was collected from the Chinese meteorological administration [32] against the weather station Wugong, located beside the research station (Figure 2b).

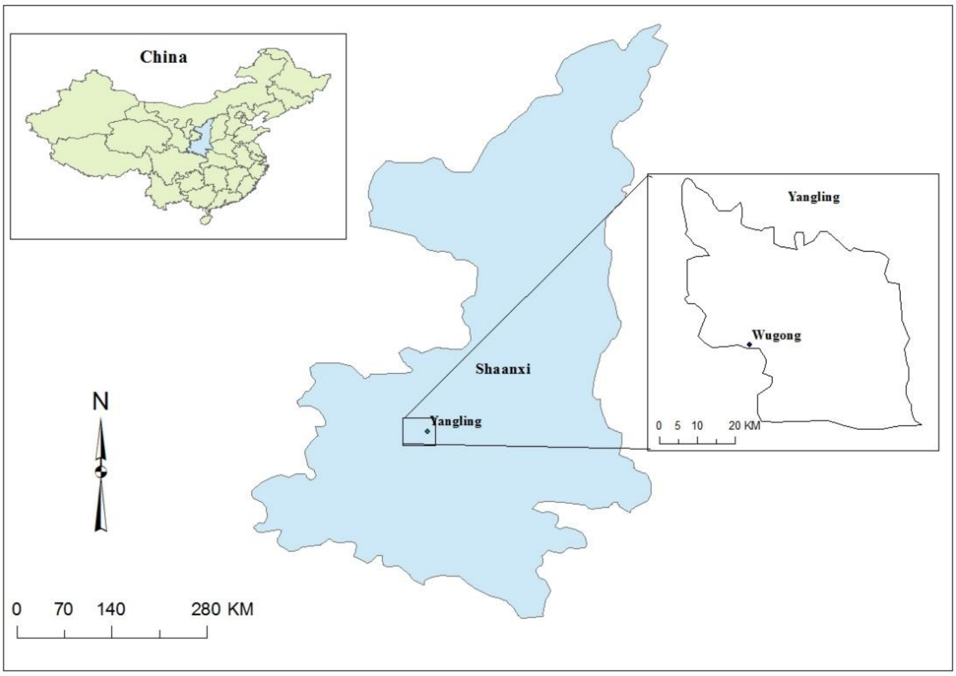


Figure 1. Map location of Yangling field experiment & Wugong weather station in China.

The soil properties were determined by collecting the soil samples from the different locations of the experimental plots at five soil depths between 0 and 250 cm depth.

The soil was a brown loess loam, with on an average 26% sand, 51% silt and 23% clay content. Average soil bulk density was 1.36 g cm^{-3}, average phosphorus (P) was 0.016%, average potassium (K) was 1.46%, and average nitrogen (N) was 0.056%. The average field capacity (FC) and permanent wilting point (PWP) of the root zone soil profile were 27.9% and 12.7%, respectively. Further detail of soil properties information is mentioned in Table 1.

Table 1. Physical and chemical properties of the soils at five depths at the experimental site in Yangling, Shaanxi Province, China.

Soil Property	Soil Layers (cm)				
	0–23	23–35	35–95	95–196	196–250
Texture	silty clay loam	silty clay loam	silty clay loam	silt loam	silty clay loam
Sand %	26.71	24.98	24.11	21.32	30.64
Silt %	50.85	52.78	54.75	48.60	47.55
Clay%	22.10	22.10	20.90	30.10	21.60
Bulk density, g cm^{-3}	1.32	1.40	1.41	1.36	1.32
Wilting Point %	10.8	10.9	12.8	14.5	14.5
Field Capacity %	28.2	27.6	27.9	28	27.8
Organic matter %	1.17	0.65	0.55	0.64	0.39
Total N, % (*w/w*)	0.09	0.06	0.05	0.05	0.03
Total P, % (*w/w*)	0.02	0.02	0.02	0.01	0.01
Total K, % (*w/w*)	1.74	1.25	1.20	1.39	1.75
pH	8.00	8.20	8.20	8.20	8.20

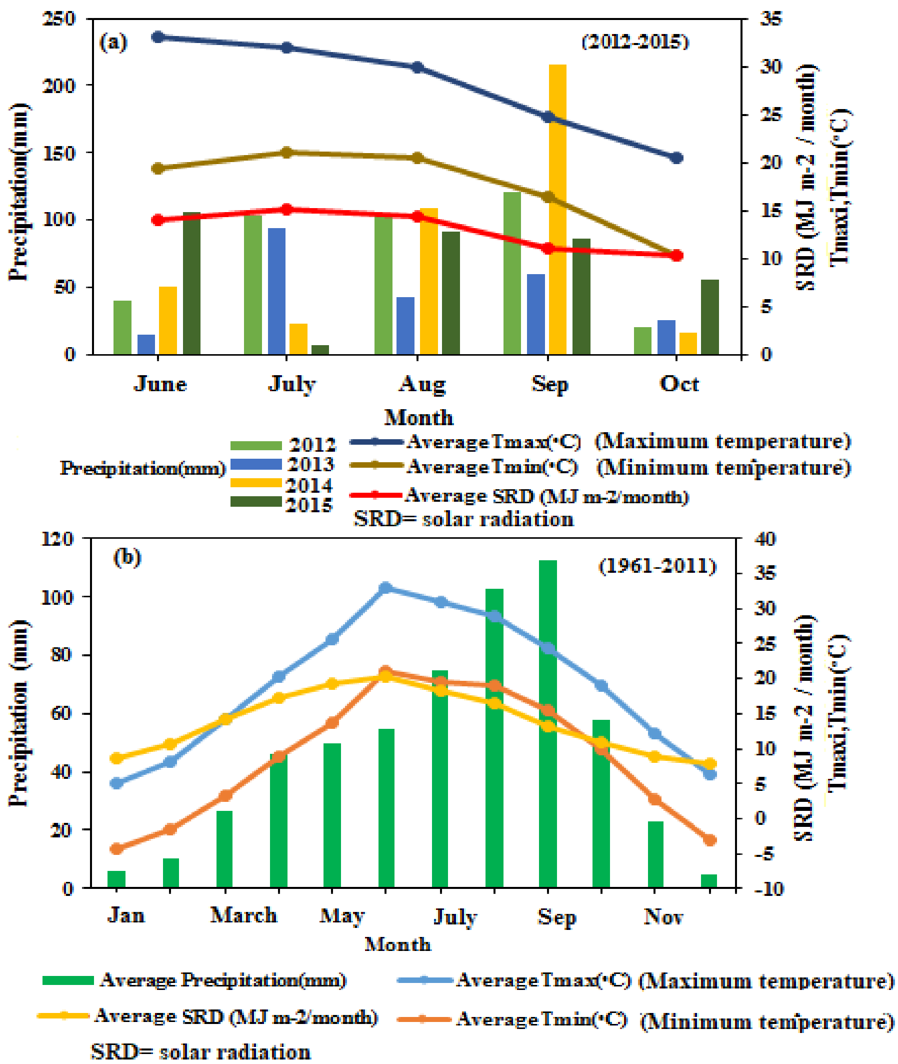
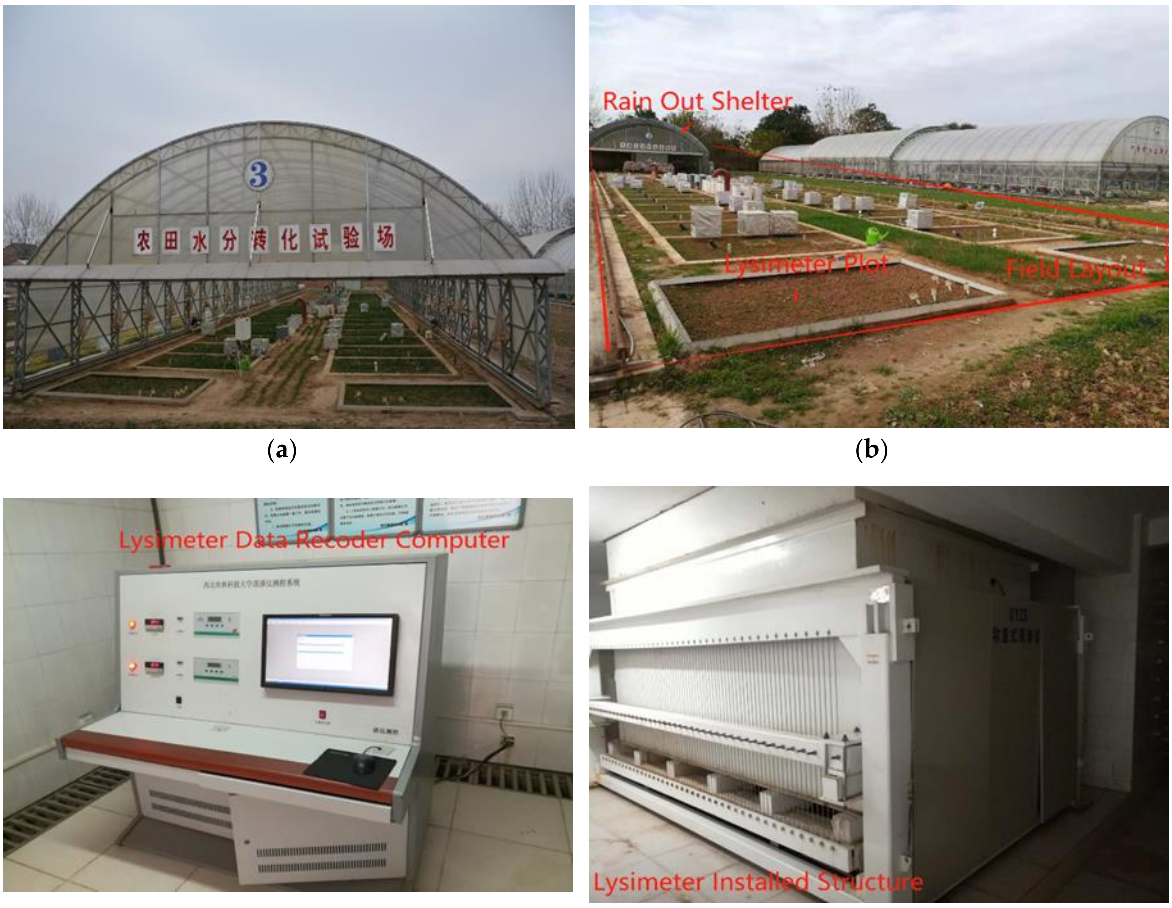


Figure 2. (**a**) Average monthly maximum, minimum temperature (°C) and rainfall (mm) during maize growing season (2012–2015) (**b**) Historical weather data (1961–2011) for Yangling, China.

2.2. Crop Management and Irrigation

The Maize cultivar Wuke-02 that is commercially cultivated in the area was used in the experiments. Crop sowing during 2012, 2013, 2014 and 2015 growing season were carried out on 19th, 23rd, 20th, and 15th of June respectively. The seeding density was six plants m^{-2} with row spacing of 50 cm. The dimensions (length × width × depth) of the experimental plot are 3.0 m × 2.2 m × 3.0 m. According to the local agricultural management, 180 kg N ha^{-1} and 120 kg P_2O_5 ha^{-1} were applied during crop planting.

The experiment was performed under moveable rainfall out shelter. Large weighing lysimeter (3 m × 2.2 m ×3 m) fitted with data loggers were installed in experimental plot to measure crop evapotranspiration (ETc) (with precision of 0.021 mm) (Figure 3). Soil and crop management conditions in the lysimeter were similar to other experimental plots. The ETc from the lysimeter was measured on hourly basis and then added to get the daily value. The irrigation was scheduled when soil moisture content of the lysimeter dropped to 65% of field capacity. The lysimeters received the full irrigation (CK), whereas other irrigation treatments received, i.e., 80% and 60% of the CK full irrigation which represents a moderate and severe soil moisture deficit condition. The flood irrigation method was used in this study. However, irrigation application was carried out with pump fitted with flow meter to ensure the same quantity of irrigation application applied to each experimental plot. Nine deficit irrigation treatments were designed with three replicates for experiments in 2012 and 2013 using the partial orthogonal experimental design method. The design scheme and irrigation amount are specified in Table 2a,b.



(**a**) (**b**) (**c**) (**d**)

Figure 3. (**a**–**b**) Field layout with and without rain-out shelter, (**c**) Lysimeter data recorder computer (**d**) Lysimeter installed structure

Table 2. (**a**) Irrigation scheduling based on evapotranspiration (mm) in 2012 and 2013, growing season. (**b**) Total irrigation amount (mm) applied during 2012, 2013, 2014 and 2015 growing season.

Treatments	2012			2013			
	23 June	29 July	25 August	13 July	8 August	15 August	08 September
CK	1.0 a	1.0	1.0	1.0	1.0	1.0	1.0
T2	1.0	0.8 b	0.8	1.0	0.8	0.8	0.8
T3	1.0	0.6 c	0.6	1.0	0.6	0.6	0.6
T4	0.8	1.0	0.8	0.8	1.0	0.8	0.6
T5	0.8	0.8	0.6	0.8	0.8	0.6	1.0
T6	0.8	0.6	1.0	0.8	0.6	1.0	0.8
T7	0.6	1.0	0.6	0.6	1.0	0.6	0.8
T8	0.6	0.8	1.0	0.6	0.8	1.0	0.6
T9	0.6	0.6	0.8	0.6	0.6	0.8	1.0

(**a**)

CK: Control treatment, T2–T9: Irrigation treatments a—100% of ET b—80% of ET c—60% of ET.

Treatments	2012	2013	2014	2015
CK	175	262	179	192
T2	149	220		
T3	123	178		
T4	152	205		
T5	126	213		
T6	142	211		
T7	129	198		
T8	145	196		
T9	119	204		

(**b**)

2.3. Water Use Efficiency

Water use efficiency calculated by a given formula

$$WUE = \frac{Y}{ETc} \tag{1}$$

where, *WUE* is defined as (Y) grain yield (kg ha^{-1}) per unit seasonal crop evapotranspiration *ETc* (mm). Seasonal crop evapotranspiration calculated for every irrigation treatment using water balance approach [33], which was analyzed seasonally and annually using the following equation

$$ETc = I + P - R - D \pm \Delta S \tag{2}$$

where I is the irrigation amount (mm), P is precipitation (mm), R is the surface runoff (mm), which was considered negligible, due to the cemented boundary constructed on each side of plot for the remote rainfall shelter experiment, D is the downward flux below the crop root zone (mm), which was ignored because the bottom of each plot was waterproofed in the rain-out shelter, and ΔS is the change in soil water storage (mm).

2.4. Field Measurements

Plant leaf area index was determined by using the SunScan-SS1 canopy analyzer (Delta-T Company, Burwell, Britain). Leaf area measurements were made eight times during the growing season at different growth stages. For each irrigation treatment phenology was recorded by visiting the fields four times a week. The emergence phase was observed by the visual number of plant leaf in the field. Emergence, anthesis, and maturity stages were noted in the form of the day of the year. Data on grain yield and aboveground biomass at maturity was also collected. All the cobs from each treatment plot were harvested at maturity, air dried and threshed to obtain the grain yield. Finally, yield was converted kg ha^{-1}. For aboveground biomass, all the plants were harvested closer to the ground and fresh weight was measured. Sub samples was taken and dried at 75 °C for 48 h to get the dry aboveground biomass. Soil moisture content was determined by Theta Probe ML2x (Delta-T Devices Ltd., Cambridge, UK) installed at different soil depths from 0–250 cm.

2.5. CERES-Maize Model Description and Calibration

In the present study, the CERES-maize crop simulation model (CSM) was used, which is part of the Decision Support System for Agro Technology Transfer (DSSAT) Version 4.6 [34]. DSSAT models can simulate the growth of 30 different crops [12,35,36]. The model takes the input, which includes cultivar type with specific coefficients, [12], weather data on a daily basis, soil property information, initial soil conditions, agronomic practices, including planting density and planting dates among others. The basic crop data, emergence, anthesis and physiological maturity dates, leaf area index, final grain yield and aboveground biomass, were selected from the full irrigation treatment (CK) during the four growing seasons of 2012, 2013, 2014 and 2015 for model calibration and the estimation of cultivar coefficients of the maize crop. DSSAT-GLUE (generalized likelihood uncertainty estimation) [37] package was used to determine the genetic coefficient for summer maize Wuke-02. GLUE tool was run 3000 times to obtain the best cultivar coefficient. If these coefficients are not satisfied with the result of simulated and observed values, then trial and error method [38] was used to improve the simulation results, based on statistical indices (R^2, RMSE, nRMSE and d-index).

2.6. Statistical Model Evaluation

The performance and evaluation of the DSSAT model was evaluated using the remaining irrigation treatments (T2–T9) during the 2012–2013 growing season. In this study the evaluation of the model was generally determined by different statistically analysis R^2, d-index value [39], and (nRMSE) normalized root mean square error between simulated and observed data.

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (|P_i'| + |O_i'|)^2} \right], \; 0 \le d \le 1 \tag{3}$$

where, n = number of observations, P_i = predicted value for the ith measurement, O_i = observed value for the ith measurement, $\overline{O}$ = the overall mean of observed values, P_i' = $P_i - \overline{O}$ and O_i' = $O_i - \overline{O}$. The normalized root mean square error (nRMSE) calculated by using the following equation

$$nRMSE = \frac{RMSE \times 100}{\overline{O}} \tag{4}$$

where $RMSE$ = root mean square error, which was calculated by using the following equation:

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

Higher d-index value and the lower nRMSE value indicated a good fit between the simulated and observed data.

Generally criteria of nRMSE are categorized in four standards for understanding relationship between simulation and observed data: nRMSE < 10% was considered excellent, 10% < nRMSE< 20% was considered good, 20% < nRMSE < 30% was considered fair, and nRMSE > 30% was considered poor [40].

2.7. Crop Cultivar Coefficient

In this study, the calibration of six cultivar coefficients obtained from the GLUE program for maize cultivar Wuke-02 are described in Table 3. P1: Degree days (base: 8 °C) from emergence to end of the juvenile phase, P2: Photoperiod sensitivity coefficient (0–1.0), P5: Degree days (base 8 °C) from silking to physiological maturity, G2: Potential kernel number, G3: Potential kernel growth rate mg/(kernel day), PHINT: Degree days required for a leaf tip to emerge (phyllochron interval) (degree days). The cultivar coefficient values are in the ranges found in different studies of maize crop [29,41].

Table 3. CERES (Crop Estimation through Resource and Environment Synthesis)-maize calibrated coefficient of maize crop wuke-02 under the experiments of 2012, 2013, 2014 and 2015.

Parameters	Values	Description
P1	164.6	Degree days (base 8 °C) from emergence to end of juvenile phase
P2	0.551	Photoperiod sensitivity coefficient
P5	780.3	Degree days (base 8 °C) from silking to physiological maturity
G2	808.0	Potential kernel number
G3	8.425	Potential kernel growth rate mg/day
PHINT	50.22	Degree days required for a leaf tip to emerge (phyllochron interval) (degree days)

2.8. Scenario Simulation

2.8.1. Optimum Sowing Date Treatments

The seasonal program was used to simulate the grain for different sowing dates [42]. The seasonal analysis was conducted using the long-term 55-year climatic data (1961 to 2015), with different crop parameters, such as crop management data, cultivar, fertilizer application rates and others to analyze the grain yield for multiple sowing dates. In this study, the purpose of seasonal analysis is to determine the best sowing date in response to different irrigation strategy scenario in Guanzhong plain climatic condition. Sowing dates were selected from 19 May to 28 July with 10 days intervals for the analysis of suitable sowing date. Box plots were used for the representation of simulation results.

2.8.2. Irrigation Strategy

The adjustment of irrigation treatments was based on the different crop growth stages emergence, flowering, grain filling, and physiology maturity stage with different irrigation treatments. Six irrigation scenarios with different combinations of crop growth stages were carried out in the simulation: Rain-fed, single irrigation, double irrigation, triple irrigation, quadruple irrigation and automatic irrigation. Each irrigation contained 100 mm of water, and automatic irrigation was 80% of the deficit level (Table 4). Crop management practices in the simulation option were kept as standard practice in the local field.

Table 4. Irrigation strategies scenario (I1–I12) simulation with CERES Maize-Model.

Crop Growth Stages and Irrigation Amount (mm)				
Irrigation Treatments	**Emergence**	**Flowering**	**Grain Filling**	**Maturity**
I1	Rainfed	Rainfed	Rainfed	Rainfed
I2	100			
I3		100		
I4			100	
I5				100
I6	100	100		
I7		100	100	
I8		100		100
I9	100	100	100	
I10	100	100		100
I11	100	100	100	100
I12	Automatic irrigation 80%	Automatic irrigation 80%	Automatic irrigation 80%	Automatic irrigation 80%

3. Results and Discussion

3.1. Calibrated Parameters Output

The different parameters of the full irrigation treatment (CK) simulated during the calibration of the model under the growing seasons from 2012–2015 and its comparison with the observed values can be found in Table 5. The simulation period of emergence to the observed period was not different. The simulated anthesis date had a slight difference ranging from 1–3 days from the observed period with relative absolute error (RAE) <1.3% and maturity date prediction varying between 1–6 days and a percent error from 0.72 to 2.11%. Simulated result of grain yield, aboveground biomass and leaf area index were in good agreement to the observed grain yield. Calibrated results are in line with the results reported by [17].

Table 5. CERES-maize model results between simulated and observed data of full irrigation treatments for the experiments 2012–2015.

Parameters	Year	Simulated	Observed	RAE%
Emergence date (d.o.y)	2012	176	176	0.00
	2013	179	179	0.00
	2014	177	177	0.00
	2015	172	172	0.00
Anthesis date (d.o.y)	2012	220	221	−0.45
	2013	224	225	−0.44
	2014	219	222	−1.33
	2015	217	218	−0.45
Maturity date (d.o.y)	2012	278	284	−2.11
	2013	274	275	−0.36
	2014	276	274	0.72
	2015	270	273	−1.09
Grain Yield (kg ha^{-1})	2012	8001	7700	3.89
	2013	9004	8400	7.60
	2014	7800	7600	2.60
	2015	7000	7400	−5.40
Aboveground Biomass (kg ha^{-1})	2012	14,200	15,500	−8.38
	2013	16,780	17,800	−5.73
	2014	15,400	16,100	−4.3
	2015	15,670	14,710	−6.52
Maximum LAI	2012	4.34	4.53	−4.19
	2013	4.73	5.0	−5.40

d.o.y: Day of the year, LAI: Leaf area index, RAE: Relative absolute error.

3.2. Model Simulation Evaluation

3.2.1. Grain Yield and Aboveground Biomass

The performance of the CERES-maize model was evaluated by comparison between simulated and observed grain yield and aboveground biomass under different irrigation treatments (T2–T9) (Figure 4). The observed yield ranged from 5600 to 9300 kg ha^{-1} during the 2012 and 2013 growing seasons respectively. The statistical analysis indicated that RMSE of simulated and observed grain yield was 970 kg ha^{-1}, with nRMSE = 9.91%, d = 0.80, and R^2 was 0.62 respectively. Aboveground biomass at maturity showed good agreement between simulated and observed data with RMSE = 1500 kg ha^{-1}, nRMSE = 9.6% and *d*-index = 0.82. The range of observed data of aboveground biomass was between 12,610 and 18,910 kg ha^{-1}. Simulated grain yield and aboveground biomass results are similar to the result obtained by [29,43]. The purpose of this evaluation was to investigate how the model predicts the effects of different irrigation treatments on the measured data of yield and aboveground biomass. The good fit between observed and simulated values results showed that the CERES-maize model could successfully simulate and predict the performances of yield and biomass for the different irrigation treatments.

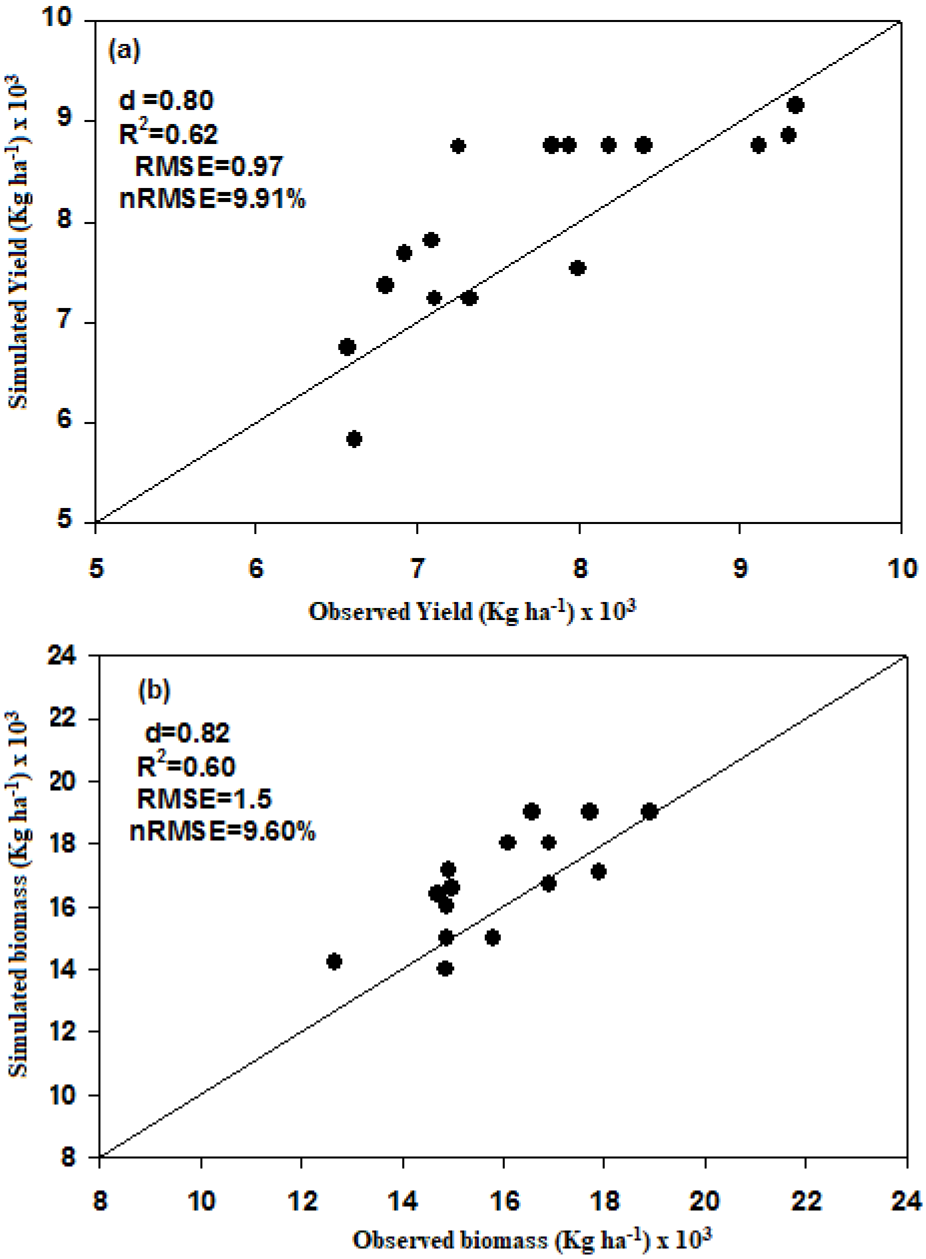


Figure 4. Comparison between simulated and observed (**a**) grain yield (**b**) aboveground biomass under different irrigation treatments for 2012 and 2013 growing season.

3.2.2. Soil Moisture Content

The CERES-maize Model was also used to simulate and predict the effects of full irrigation of 2012 and 2013 growing seasons on soil moisture contents at different soil depths (0–23 cm, 23–35 cm, 35–95 cm and 95−120 cm). The performance of the CERES-maize model for soil moisture content ranged from moderate to good for the two growing seasons (Figure 5). Results showed that the top soil layer (0–35 cm) and lower soil layers (35−120 cm) had nRMSE from 25.6% to 51% and nRMSE from 8.8% to 13.61% in both season 2012 and 2013, respectively. The d values for the two seasons were 0.57 to 0.86 for lower soil depth and 0.37 to 0.79 for top soil depth. Soil moisture content was well simulated for the growing season in 2012 in comparison to the 2013 growing season. Simulated soil moisture content showed a good relationship with observed soil moisture contents for lower soil depths compared to the top depth, as reported in previous studies [40,44]. Overall, similar studies showed that CERES-maize model can accurately simulate soil moisture content at different soil layers.

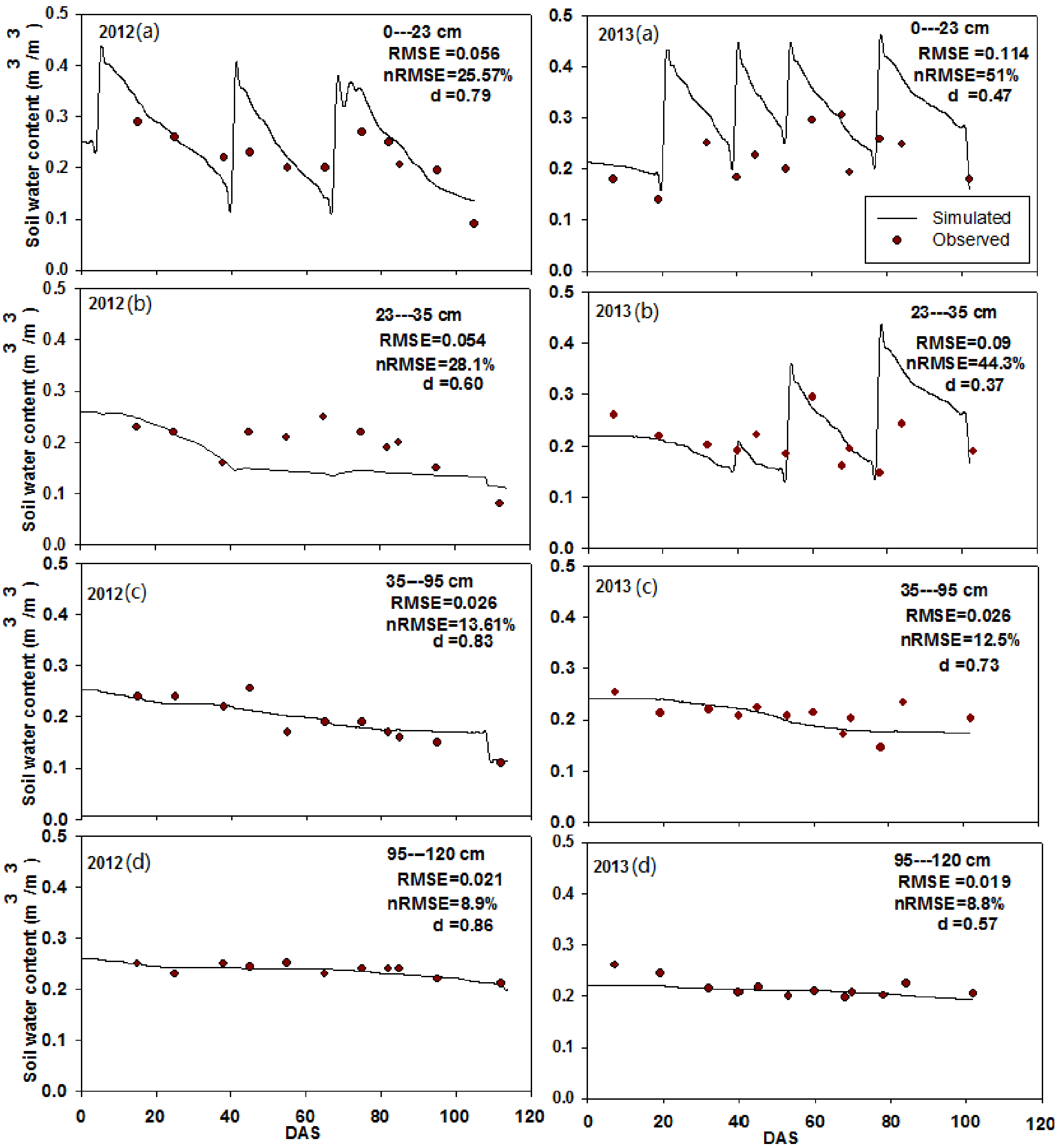


Figure 5. Simulated and observed soil moisture content at different soil depth for (**a**–**c**) 2012 and (**a**–**c**) 2013 growing season. DAS: Days After Sowing.

3.2.3. Leaf Area Index

The performance evaluation of the CERES-maize model for the LAI (Leaf Area Index) was made by using the 16 limited irrigation treatments (T2–T9) of 2012 and 2013 growing season (Figure 6). Observed and simulated leaf area index is in good agreement with nRMSE at 15% and 19%, for growing season 2012 and 2013, respectively. Simulation of LAI in the initial growing season is very close to observed LAI, from 50 days after sowing. It appeared that differences between simulated and observed slightly increased for both growing seasons. Model prediction for maximum LAI for the whole growing season is under-estimated. However, the underestimation is less in 2012 compared to 2013. This was discussed earlier by [29], who observed LAI being greater than simulated. Model results showed that LAI reduced during the growing season under limited irrigation treatments. Our results are consistent with a previous study conducted using CSM-CERES-maize model [18,23,45] which proposed that non-stress irrigation treatment's LAI was comparatively better than stress irrigation treatment's LAI for specific environments.

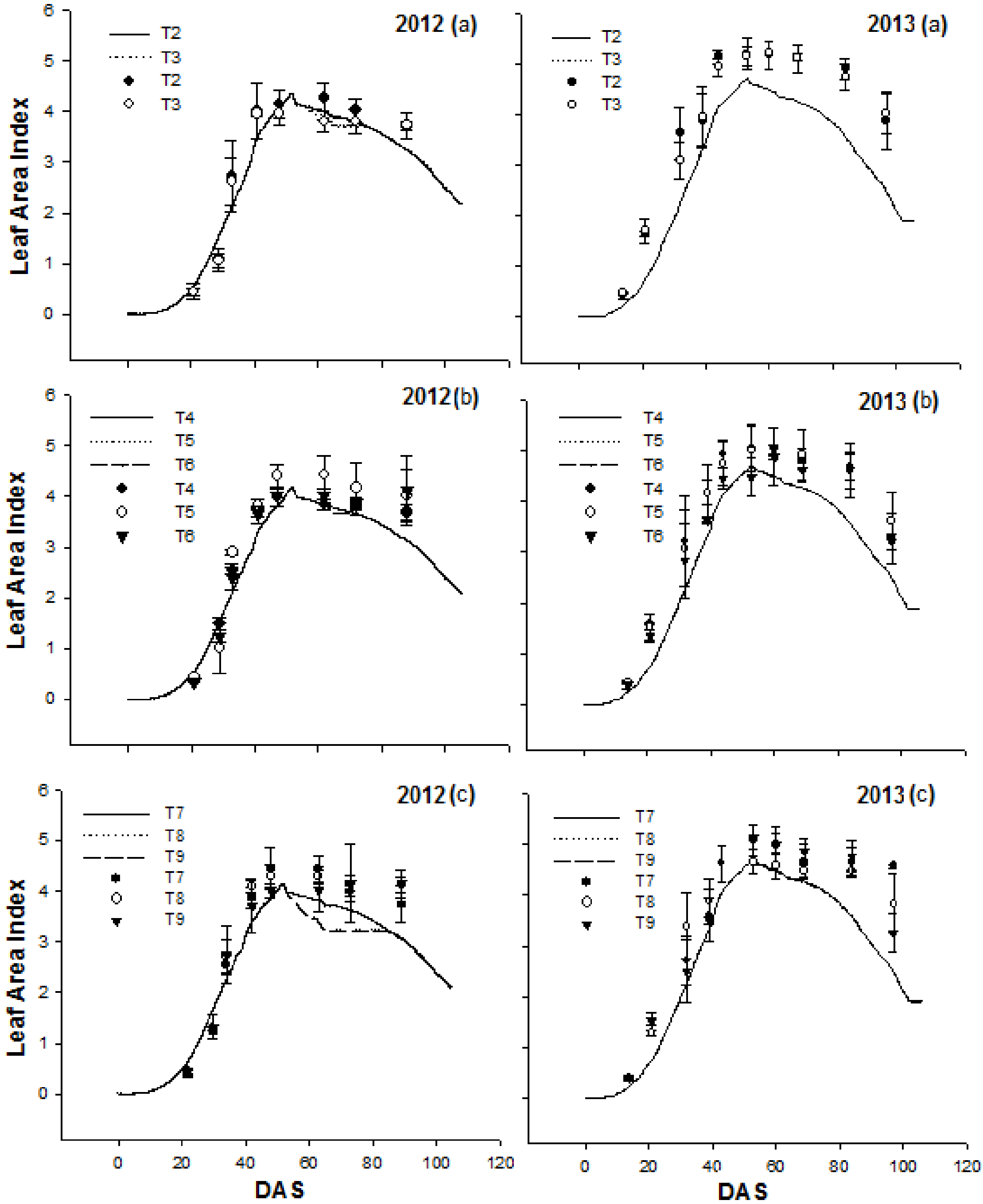


Figure 6. Simulated and observed leaf area index growing season (**a**–**c**) 2012 and (**a**–**c**) 2013. Horizontal bars are standard deviations DAS: Days After Sowing.

3.2.4. Water Use Efficiency

Simulated and measured water use efficiency (WUE) for the 2012 and 2013 growing seasons examined and showed a goodness of fit with nRMSE of 6% and 7%, respectively. The values of simulated WUE for full irrigation are very close to the observed value of WUE in both growing seasons as was previously reported [46]. Water use efficiency for full irrigation was reasonably simulated as compared to limited irrigation. Water use efficiency simulated and observed for 2013 growing season was higher in the deficit irrigation (T3), as compared to the non-stressed irrigation (T1) [46]. Simulated WUE for (T1) in both 2012 and 2013 growing seasons had similar results compared to the irrigation treatments (T4) and (T5) WUE respectively, indicating that deficit irrigation could raise the WUE (Table 6).

Table 6. Observed and simulated water use efficiency for maize crop during the 2012–2013 growing season.

Treatments	2012 Growing Season WUE (kg ha^{-1} mm^{-1})		2013 growing season WUE (kg ha^{-1} mm^{-1})	
	Observed	Simulated	Observed	Simulated
T1	26.4	25.4	25.9	26.5
T2	23.2	22.8	30.8	31.1
T3	20.7	17.5	34.9	32.4
T4	20.9	19.7	30.5	26.0
T5	26.1	25.2	28.8	25.6
T6	21.4	20.3	27.0	27.4
T7	21.9	21.2	28.9	29.2
T8	20.3	20.1	29.7	28.3
T9	21.8	18.8	27.0	25.3

T1–T9: Irrigation treatments, WUE: Water use efficiency.

3.2.5. Optimum Sowing Date

The application of seasonal analysis of the CERES-maize model indicated that grain yield was affected by the different irrigation strategies and planting dates at different crop growth stages. Simulated seasonal grain yield results summarized in Figure 7 showed that under all scenarios of irrigation strategy, changing sowing date from 15 May to 4 June resulted in increased yield from 3750 to 8750 kg ha^{-1}, but with a lower median yield compared to sowing dates between 14 to 24 June which had highest median yield ranged 6000 to 10,500 kg ha^{-1}. Delayed sowing dates from 24 June showed decreasing yields, with lower median a yield than the median yield of earlier sowing dates. In this region sowing dates were recommended on the basis of local farmer's field knowledge for several years without considering local climate conditions. The finding of this study showed that variations occurred between locations and irrigation strategies with respect to optimum sowing dates and climate conditions.

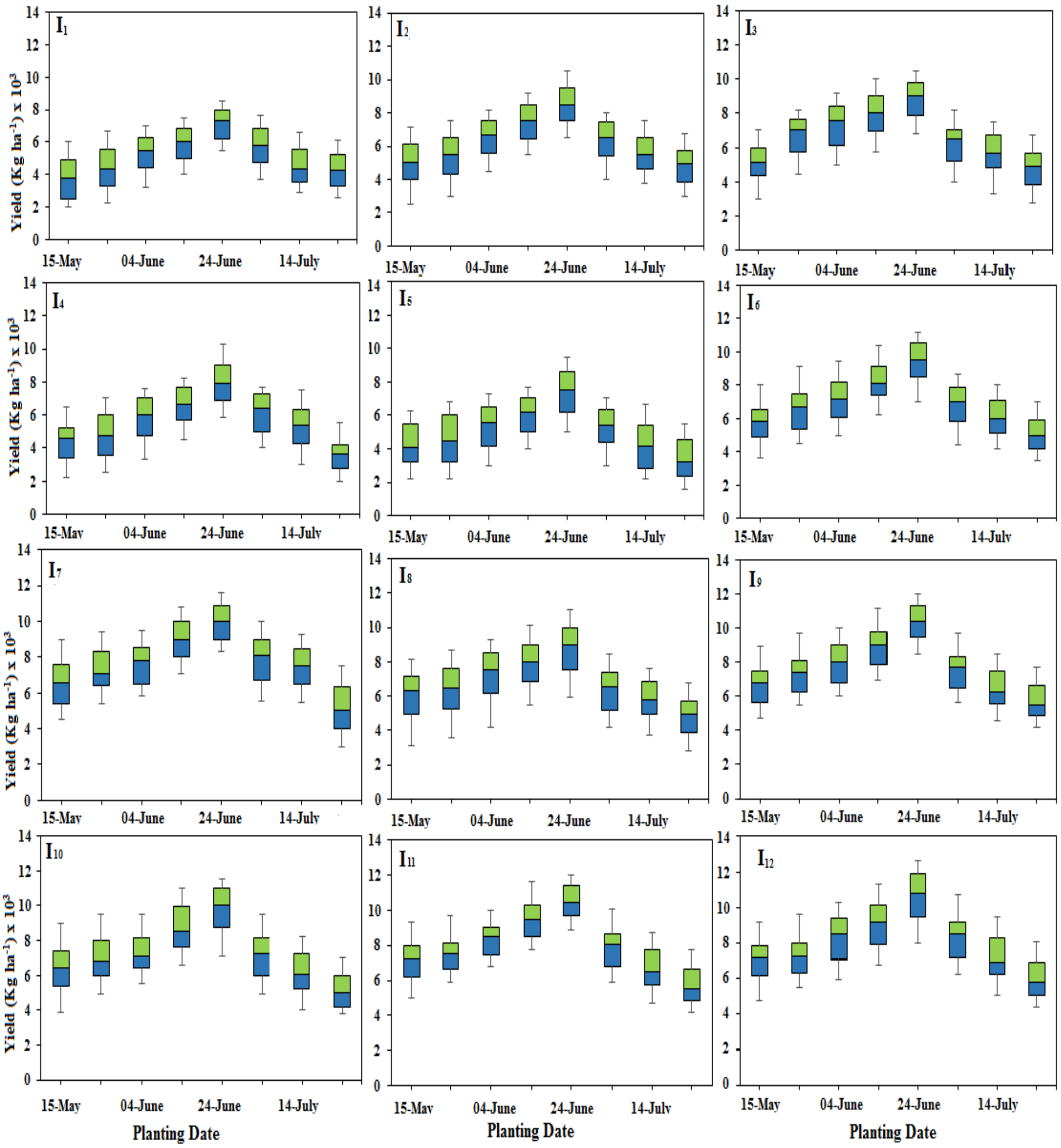


Figure 7. Simulated maize yield under different irrigation scenario (I1–I12) using historical weather data with different sowing dates.

3.2.6. Irrigation Strategy

After confirming the optimum sowing date of 24 June, further analysis was conducted by splitting the crop growing period on the basis of precipitation quantity P < 200 mm, 200 mm< P < 300 mm, 300 mm < P < 400 mm and P > 400 mm (Figure 8) using the long-term historical weather data. The purpose is to determine the best-growing stages for the appropriate amount of irrigation application during the entire crop growing season. Maize grain yield increased with increasing supplementary irrigation amount in the four growing period precipitation quantity scenarios.

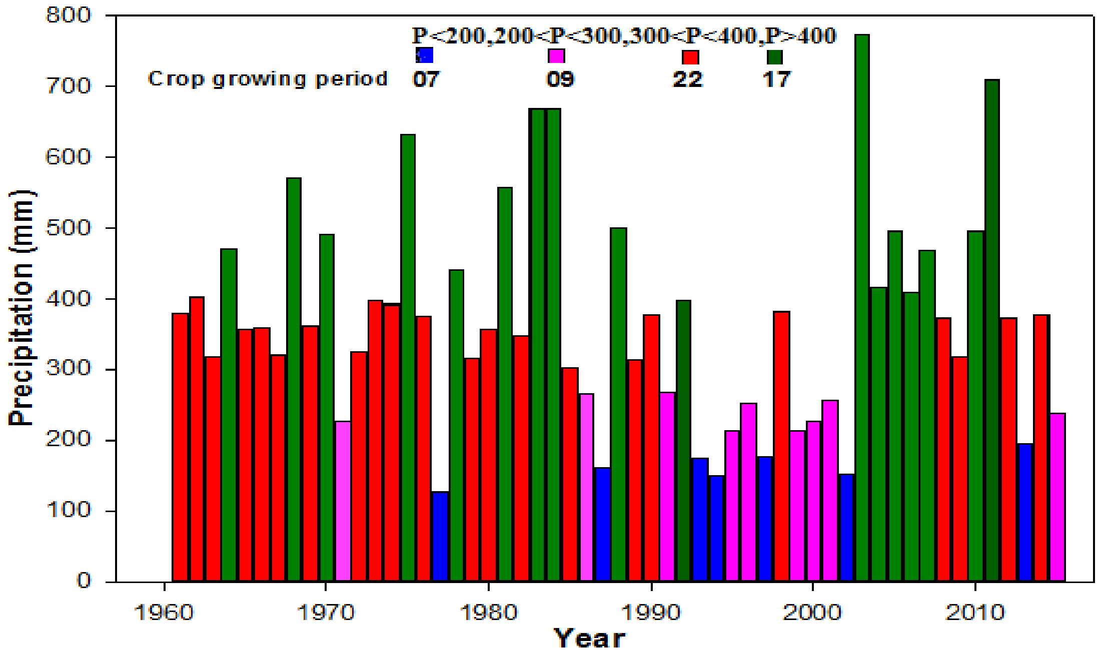


Figure 8. Summer maize crop growing period Categorized based on the precipitation quantity using the historical weather data.

The rain-fed yield ranged from 5600 to 7600 kg ha^{-1} in all four growing seasons (Figure 9). The application of single irrigation (100 mm) at emergence and flowering stages considerably increased yields from 6600 to 9650 kg ha^{-1} and 7800 to 9800 kg ha^{-1} respectively. While, the grain yield was not increased at grain filling and maturity stage as compared to irrigation applied at emergence and flowering stage. In the grain filling and maturity stage irrigation scenario, the crop may remain under stress, due to the interval of irrigation prolonged compared to the emergence and the flowering stage. In the double irrigation (I7) scenario, in which irrigation was applied 100 mm at the flowering stage and 100 mm at the grain filling stage, the yield was between 9680 and 10,900 kg ha^{-1}.

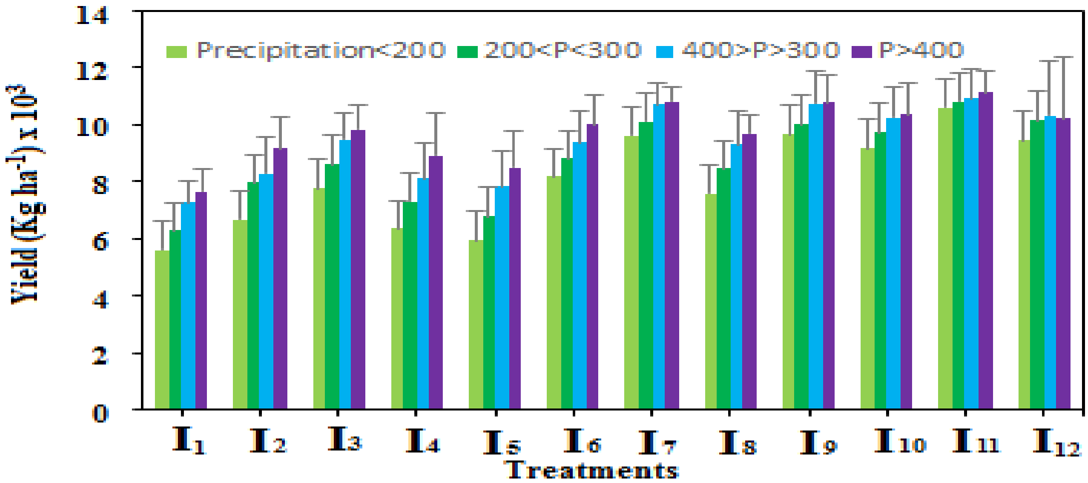


Figure 9. Simulated maize yield different irrigation scenario (I1–I12) based on the precipitation quantity using the historical weather data.

In addition, irrigation scenario (I7) yield was significantly different from the three irrigation (300 mm) and four irrigation application (400 mm) scenario. Double irrigation treatment (I7) (200 mm) is more beneficial for obtaining higher yield compared to scenarios of higher irrigation (I9, I10 and I11).

The median yield analysis carried out using the historical weather data of 55 years (1961–2015) showed that there was not much difference in yield from double irrigation scenario (I7) than full irrigation application (Figure 7). These results show that the application of irrigation has an important impact on grain yield under the limited availability of irrigation water in the Guanzhong Plain. If irrigation water resources are limited, then it is essential to consider these two stages (flowering and grain filling) for irrigation application during the crop growth season. These two stages are more critical during the growing season. When irrigation is not applied at these two stages of crop growth, plant stress and low yield are the result (Figure 9) [47]. Our results are in agreement with these findings.

3.2.7. Seasonal Water Use Efficiency

Simulated water use efficiency (WUE) was determined by dividing grain yield with seasonal evapotranspiration (ETc) in the different irrigation strategy scenarios (I1–I12). When the growing seasons were classified on the basis of precipitation (P < 200 mm, 200 mm < P < 300 mm, 300 mm < P < 400 mm and P > 400 mm) using historical weather data (1961 to 2015), the response of water use efficiency to irrigation treatment varied. In comparison, of single irrigation treatments (I2, I3, I4, I5), water use efficiency of 24.35 kg ha^{-1} mm^{-1} in irrigation treatment (I3) at flowering stage is higher compared to the rain-fed (I1) water use efficiency 20 kg ha^{-1} mm^{-1}, which was between the other single irrigation treatments (I2, I4, I5) in all four growing periods. (Figure 10) In the double irrigation treatment, the growing season had significantly higher WUE than all other irrigation treatments. In the full irrigation treatments I10 and I11, WUE is lower and produced yields that were higher, resulting in higher water use compared to double irrigation (I7). Summer maize WUE was found to increase with deficit irrigation in southern Taiwan [48]. This study is in agreement with the study of Kird [49] who stated that water productivity can be increased by reducing the number of irrigation applications.

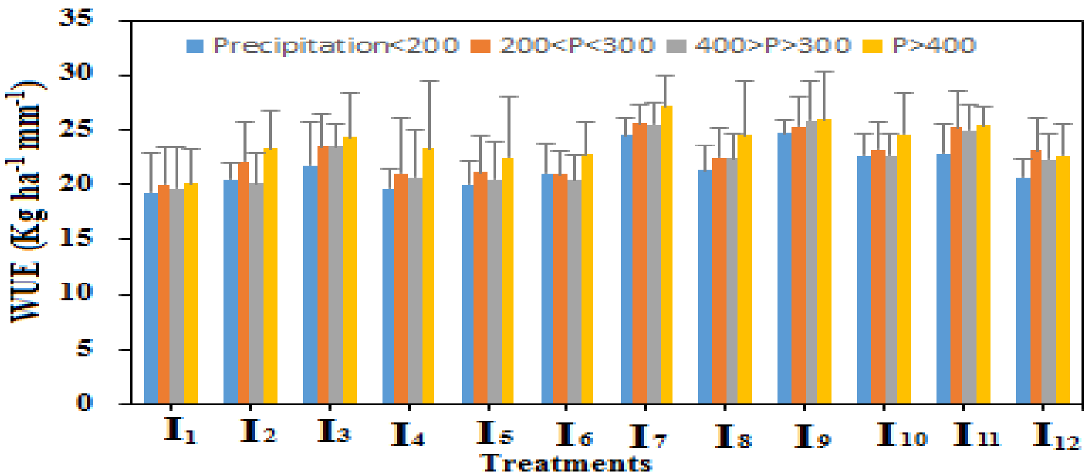


Figure 10. Simulated water use efficiency of different irrigation scenario (I1–I12) based on the precipitation quantity using the historical weather data.

4. Conclusions

CERES-maize model proposed that early and delayed sowing date from 24 June is not beneficial for maximum yield production. The model simulation for optimum time and irrigation amount was carried out with different irrigation scenarios at different growth stages resulting in the optimum timing of irrigation application. This is during the flowering and grain filling period with optimum irrigation amount of 200 mm during the crop growing season. It is important for the crop to have access to water during these two stages as lower irrigation or precipitation leads to crop stress. Two irrigation applications for these crop growth stages are essential and could lead to the similar yield obtained from 3 or 4 irrigation applications that have no crop stress. The long-term simulation of water use efficiency is higher in a single irrigation of 100 mm at the flowering stage and also higher in two irrigation application when applied 100 mm at the flowering stage and 100 mm at grain filling stage.

Overall, the application of the CERES-maize model demonstrated that the negative effects of less rainfall or water availability on the agricultural production can be controlled by the systematic consideration of critical crop growth stages, sowing date and amount of irrigation water. Furthermore, this study serves to improve our understanding of how different irrigation strategies can be used to optimize sowing date, crop growth stages and maize yield within the region.

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