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Irrigation Schedule Optimization for Wheat and Sunflower Intercropping under Water Supply Restrictions in Inner Mongolia, China

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Abstract: Precise water management is essential for the efficient development of irrigated agricultural crops in the Hetao Irrigation Area of Inner Mongolia. Given the severe water scarcity in the region and the significant use of intercropping as a cropping method, the development of rational irrigation scheduling is crucial. The objective of this work was to combine the ISAREG model with wheat–sunflower intercropping crops in order to enhance the effectiveness of irrigation scheduling in intercropping systems. This was achieved by changing and verifying crucial parameters for simulating irrigation patterns in intercropping. We conducted an assessment of nine irrigation schedules for a wheat–sunflower intercropping system in order to provide a range of irrigation scenarios that effectively fulfill the water requirements of the system. In light of this, we suggested implementing restrictions on the dates and volumes of irrigation based on the demand for agricultural irrigation. This approach aimed to establish irrigation schedules that are highly efficient and tailored to the specific crops in the area. As a result, we achieved a water use efficiency rate of 100%, saved 28.78% of water resources, optimized crop irrigation schedules, and enhanced crop economics by 6.7%. This study presents a novel and efficient method to optimize agricultural irrigation schedules, boost agricultural water use efficiency, and maximize crop yields in order to promote sustainable agricultural development.

Keywords: efficient crop development; intercropping; irrigation schedules; ISAREG model; water usage efficiency

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Citation: Zheng, H.; Hou, H.; Wu, J.; Tian, D.; Miao, P. Irrigation Schedule Optimization for Wheat and Sunflower Intercropping under Water Supply Restrictions in Inner Mongolia, China. *Atmosphere* **2024**, *15*, 566. https://doi.org/10.3390/atmos15050566

Academic Editors: Gianni Bellocchi and Vijay P. Singh

Received: 21 January 2024
Revised: 25 April 2024
Accepted: 30 April 2024
Published: 3 May 2024

1. Introduction

The Hetao Irrigation District in Inner Mongolia is one of three major irrigation regions in China. This irrigation area spans 57.4 hectares and mostly relies on water sourced from the Yellow River. Recently, the imbalance between availability and demand for water resources has become noticeable, leading to water shortages. Asynchronous irrigation scheduling and varying water levels in the Yellow River have resulted in inconsistent irrigation dates and volumes, which are not aligned with crop water requirements, exacerbating the issue of water scarcity [1–3]. The irrigation schedules are not consistently optimized, resulting in water wastage and worsening the water shortage. Precision agriculture has posed solutions to this problem in terms of using alternative irrigation timings [4]. Intercropping is a significant practice in the Hetao irrigation basin. It is essential to improve the management of irrigation water resources to address the challenges of water shortages [5]. A thorough evaluation of water resources and their supply is crucial, and exploring alternative irrigation methods is recommended for the Inner Mongolia Loop Irrigation Area [6,7].

In recent decades, research has focused on the best use of irrigation water supplies. Multiple irrigation schedules and computer models have been extensively used to create and assess diverse irrigation techniques [8]. Huang et al. presented a strategy to enhance irrigation water usage efficiency by combining two-stage stochastic programming with imprecise quadratic programming to maximize the system's benefits [9]. The outcomes of this approach are crucial for developing effective water management strategies to optimize economic advantages and reduce the likelihood of system breakdown. Fu et al. introduced a comprehensive interval nonlinear planning model using Jensen's water production function to enhance water usage efficiency by distributing water throughout various crop development phases [10]. Yang et al. introduced a nonlinear fuzzy interval irrigation optimization model to optimize agricultural water distributions, analyzing three distinct situations [11]. Li et al. created a simulation optimization model to schedule agricultural irrigation efficiently, aiming to maximize net benefits and mitigate the adverse effects of water shortages [12]. The ISAREG model, created by Teixeira J. L. et al., is a simulation model for soil water balance that considers the size of the farm. The researchers conducted a simulation of irrigation scheduling for winter wheat and summer maize. They verified the correctness of the ISAREG model and used the FAO Penman–Monteith technique to compute reference evapotranspiration. Additionally, they determined crop coefficients suitable for the local conditions based on experimental data [13]. Experts have used the ISAREG model to explore scheduling possibilities to improve irrigation by simulating and evaluating the water balance and irrigation schedule in a wheat irrigation system in Beijing, China [14]. Li et al. used the ISAREG model after calibrating and testing it to simulate and assess various irrigation strategies for cotton [15]. The ISAREG irrigation scheduling simulation model, previously calibrated and verified for cotton in the Fergana area, was used in Zhang et al.'s work [16]. Their findings indicated that a substantial portion of the water delivered (an average of 20%) drains beyond the root zone in existing irrigation systems [17]. This discovery has resulted in the development of several options for creating and assessing irrigation systems [18]. Another study confirmed the model's efficiency in promoting water-saving and ecologically beneficial irrigation methods in the Trace area of southern Bulgaria [19,20]. The ISAREG irrigation scheduling simulation model was calibrated, validated, and tested using historical information from 19 years of maize experiments. Furthermore, these statistics were used to establish suitable crop characteristics [21–23]. The ISAREG approach was used to determine enhanced irrigation schedules for horticultural crops in Cuba. Implementing these enhanced schedules might boost water production by almost 30%. Deficit irrigation may lead to a water productivity improvement of up to 50%. These results were documented by Qian et al. (2018), Niu et al. (2016), Zhang, Li et al. (2021), and Zhang, Guo et al. (2021) [24–27].

Xie et al.'s study highlighted that effective precipitation is often disregarded in research on the distribution of agricultural water resources [28]. Effective precipitation greatly enhances irrigation water usage efficiency [29]. Crops need soil water for growth, and effective precipitation is the primary source of soil water [30]. Hence, including effective precipitation in the optimization model may lead to irrigation water savings [31]. When improving agricultural water resource management, individuals often utilize total irrigation instead of the real water requirements of crops, which might potentially reduce the irrigation efficiency and water conservation effects [32]. Total irrigation is the highest quantity of water required to provide adequate irrigation, leading to unavoidable waste of water [33].

This work aims to rectify the shortcomings of earlier studies in optimizing irrigation scheduling within the limitations of water supply. We carried out a two-year intercropping field experiment between wheat and sunflower at Dengkou Experimental Station, Hetao Irrigation District, Inner Mongolia. The ISAREG irrigation scheduling simulation model was used, taking into account both effective precipitation and the actual water requirements of the crops in the intercropping system. By conducting field experiments, we examined the attributes of nine irrigation treatments. Additionally, we included sunflower-wheat intercropping irrigation treatments into the model framework, resulting in enhanced irrigation efficiency and decreased water wastage. Through our intercropping studies, we have established the most optimal irrigation schedules by considering numerous irrigation scenarios. Additionally, we have defined the maximum limitations for agricultural water use in terms of individual irrigation dates and the overall amount of irrigation. This paper proposes novel concepts and methodologies for the sustainable management of water in agriculture.

2. Materials and Methods

2.1. Experimental Site and Field Trials

This research was carried out at the Dengkou Experimental Station in the Hetao Irrigation District of Inner Mongolia utilizing the border irrigation method (Figure 1). In 2018 and 2021, we assessed and confirmed the irrigation schedule parameters for two typical treatments for wheat intercropped with sunflower (p = 50%). We planted wheat using a stratified seeding method in 7 rows arranged in 2 bands, totaling 14 rows in a wheat–sunflower intercropping system. Each row was spaced 0.1 m apart, and each band had a width of 1.3 m. We planted sunflowers in 3 rows, each with a width of 1.07 m. The spacing between the side rows of sunflower and wheat, as well as between the sunflower rows, was 0.27 m. The planting date for wheat was 7 March and the harvest date was 25 July. Sunflower planting date was 21 April and harvest date was 13 September. We evaluated the wheat–sunflower intercropping irrigation system by analyzing the kinds of soil in the rhizosphere. The experimental setup was established in a 0.012 Km^2 region with an average distribution of nine treatments. The treatments included various irrigation schedules, crop planting patterns, etc., to investigate their impact on crop growth and output. The soil in the experimental locations was categorized into two layers: the topsoil layer (0 to 40 cm) was chalky loam with a soil bulk density of 1.43 g/cm^3, and the subsoil layer (40 to 100 cm) was chalky loam with a soil bulk density of 1.40 g/cm^3.

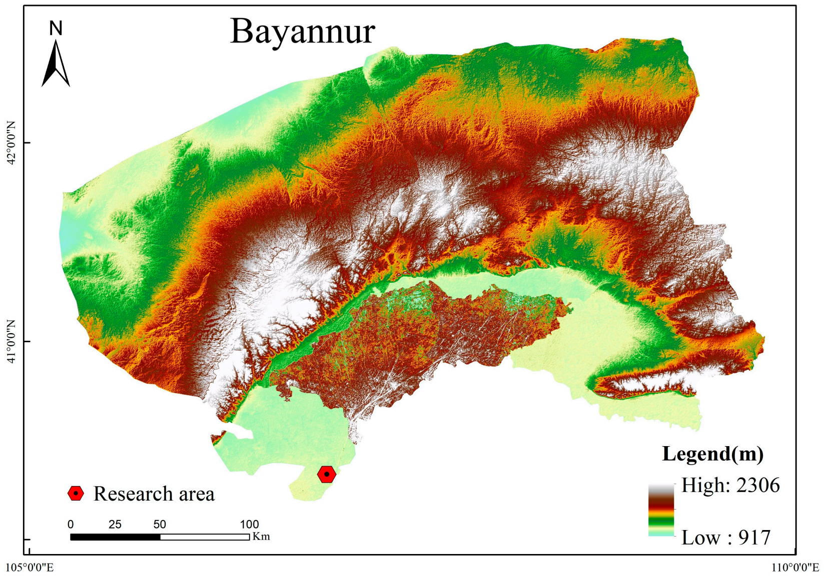

Figure 1. Elevation map of the research area.

We used time domain reflectometry (TDR), a common approach in soil physics research, to estimate the soil water content by analyzing the reflection and propagation duration of a pulse signal in the soil medium. The TDR soil moisture meter was arranged in three uniform methods for each treatment of TDR wheat and sunflower intercropping in the experimental site, which was arranged as a total of 27 TDR soil moisture test points and instrumented. The measurement depth ranged from 0 to 60 cm, covering the majority of the crop's root distribution region, aiming to provide a more comprehensive understanding of the crop's water requirements and water use. We calibrated the TDR probe to assure measurement accuracy, using the soil auger approach for calibration. For each treatment, we collected soil samples from three different locations. At each location, we extracted five soil samples from the 0–100 cm soil layer using a T-handle soil extractor. These samples were then placed in an aluminum box to measure their mass. Afterward, the samples were dried in a drying oven at 105 °C for 8 h, and their final weight was recorded. Based on this sampling technique, soil samples were gathered the day before irrigation and then once again 3 h after irrigation to ascertain the moisture content of the designated region. The conventional drying technique was used as a benchmark to assess the discrepancy of the soil moisture meter in determining soil moisture content. We used SPSS 27 to conduct a comparative study between the conventional drying technique and the instrumental technique. Additionally, we utilized a correlation and regression analysis to quantify the linear association between the two approaches. The research revealed a very significant positive correlation between the two approaches, with an R^2 value of 0.94 and a significance level ($p < 0.01$) (Figure 2). The soil was watered four times in total throughout the reproductive phase in the two studies. Treatment 1 received 75 mm of water, whereas Treatment 2 received 52 mm, as shown in Table 1. All other instances were identical. Table 1 displays the watering schedules for both treatments.

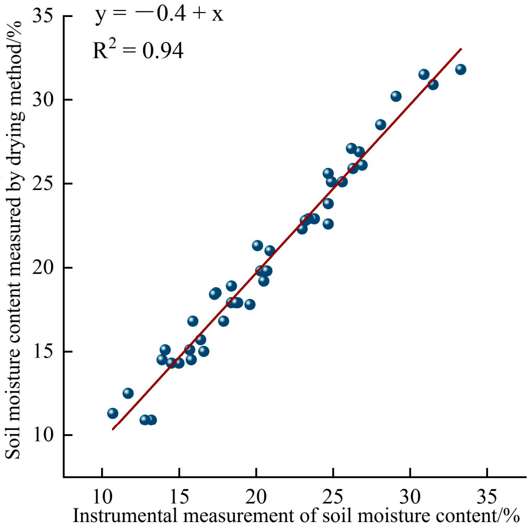

Figure 2. Calibration map of soil moisture content.

Table 1. Actual irrigation schedule for each project.

Irrigation Round	Treatment 1		
	Irrigation Date (m/d)	Irrigation Depth (mm)	Irrigation Amount (mm)
1	5/15	75	300
2	6/01	75	
3	6/12	75	
4	7/16	75	
Irrigation Round	**Treatment 2**		
	Irrigation Date (m/d)	**Irrigation Depth (mm)**	**Irrigation Amount (mm)**
1	5/15	52	208
2	6/01	52	
3	6/12	52	
4	7/16	52	

2.2. Reference Crop Evapotranspiration

Reference crop evapotranspiration, often referred to as ET_0, is a crucial element in modeling. ET_0 values may be derived using various computational methods, such as Evap56 in the ISAREG model, which uses the Monteith–Penman calculation approach [24].

2.3. Crop Coefficient

The crop coefficient is a numerical value that represents the water requirements of a certain crop with respect to the amount of water needed by a reference crop.

The crop coefficient (K_c) is a crucial factor used to determine the crop's real water needs by using the evapotranspiration (ET_0) of a reference crop. The crop coefficient in the wheat–sunflower intercropping system was determined in two phases. We first used the segmented single-value averaging approach, as suggested by FAO56, to determine the crop coefficients for wheat and sunflower. Nevertheless, these calculations might be inaccurate due to potential alterations to the aerodynamic characteristics of the surface due to intercropping. We performed trials on real fields to obtain precise data and confirm the accuracy of the generated crop coefficients (Table 2). The calculation was conducted using the FAO56 standard conditions for crop coefficients at various growth phases. The crop coefficient K_c was adjusted during the growth phase to match the particular climatic and soil conditions of the location. We computed the combined crop coefficient $K_{c(field)}$ for the intercrop. The coefficient was calculated by multiplying the weights of the two crops, the crop ratio f, and the crop height h [34]. The computation formula is:

$$K_{c(field)} = \frac{f_1 h_1 k_{c1} + f_2 h_2 k_{c2}}{f_1 h_1 + f_2 h_2} \tag{1}$$

where $K_{c(field)}$ is the integration crop coefficient, f_1 and f_2 are the plant proportions of the two crops, h_1 and h_2 are the height of the two crops (m), and k_{c1} and k_{c2} are the crop coefficients of the two crops.

Table 2. K_c calculated results and measured values.

Date (m/d)	Wheat Intercropping with Sunflowers	Wheat	Sunflowers	Measured Value
4/2	0.34	0.34		0.33
4/20	0.34	0.34		0.35
5/4	1.08	1.08		1.05
5/25	1.08	1.08	0.25	1.07
6/21	0.92	1.07	0.25	0.95
7/14	0.61	0.31		0.66
7/15	0.96		0.97	0.91
8/15	0.97		0.97	0.92
9/16	0.28		0.28	0.27

Figure 2 displays the ET_0 values computed using Evap56 based on the meteorological data recorded in 2018. ET_0 denotes the daily measurements of wheat growth when intercropped with sunflower during the whole duration (Figure 3).

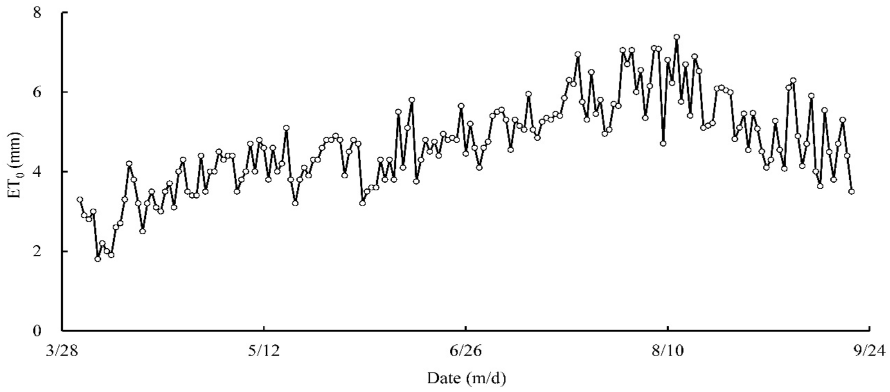

Figure 3. Calculation results of ET_0.

When determining the K_c value for wheat intercropped with sunflower, it is necessary to combine the development stages again. Due to the difference in planting dates between the two crops, there is a variation in the developmental phases and the growth period duration for each crop. We computed the ET_c (which represents the soil moisture dynamics monitored using TDR) and ET_0 (the actual local ET_0 determined using the PM formula and real-time meteorological data from the weather station at the Dengkou experimental site) for several treatments of wheat–sunflower intercropping in order to determine the K_c value. Based on the different attributes of wheat intercropped with sunflowers, the development process is categorized into six distinct phases [28]. Sunflowers are not planted during the first stage of wheat development; thus, the complete crop coefficients for early growth only apply to wheat. The initial sunflower growth throughout the first half of the mid-term period coincided with the developmental phase of wheat [35]. The latter half of the mid-term for wheat corresponds to the first half of the mid-term for sunflowers, during the growth anaphase. The comprehensive crop coefficients for sunflowers are determined at the later stages of their development, namely during the middle and anaphase stages after the wheat has been harvested. The crop coefficients for wheat, sunflower, and the wheat–sunflower intercrop are shown in Figure 4.

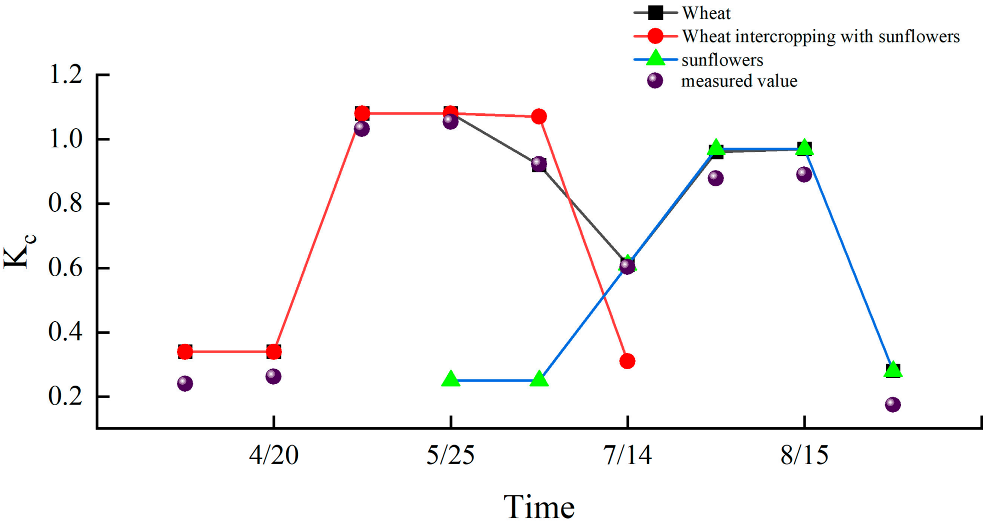

Figure 4. Calculation results of K_c.

2.4. Yield Response Coefficient

The FAO56 guidelines suggest using yield response coefficients (K_y) to evaluate crop water requirements. The yield response coefficients for wheat and sunflower in this context were established as 1.05 and 0.95, respectively. Nevertheless, these estimations may lack precision, since intercropping might alter the aerodynamic characteristics of the surface [36].

Over the course of two years, we used a three-point average sampling technique to quantify crop output for each treatment in the wheat–sunflower intercrop. Furthermore, we derived crop yield response coefficients, denoted as K_y, by considering theoretical yield, plant evapotranspiration, and soil evapotranspiration among plants. We performed trials on real fields to obtain precise data and confirm the accuracy of the generated crop coefficients (Table 3). The model of the wheat and sunflower intercrop yielded an overall response coefficient of 1.01 (Figure 5). The coefficient was calculated by considering the ratio of each crop seeded and their respective maximum yields.

Table 3. K_y calculated results and measured values.

$1-E/E_m$ (m/d)	Wheat Intercropping with Sunflowers	Wheat	Sunflowers	Measured Value
0.22	0.2222	0.231	0.2194	0.231
0.27	0.2727	0.2835	0.2574	0.271
0.31	0.3131	0.3255	0.3012	0.317
0.35	0.3535	0.3675	0.3249	0.342
0.37	0.3737	0.3885	0.3553	0.374
0.42	0.4242	0.441	0.3943	0.415
0.45	0.4545	0.4725	0.4361	0.459
0.51	0.5151	0.5355	0.4874	0.513
0.57	0.5757	0.5985	0.5330	0.561

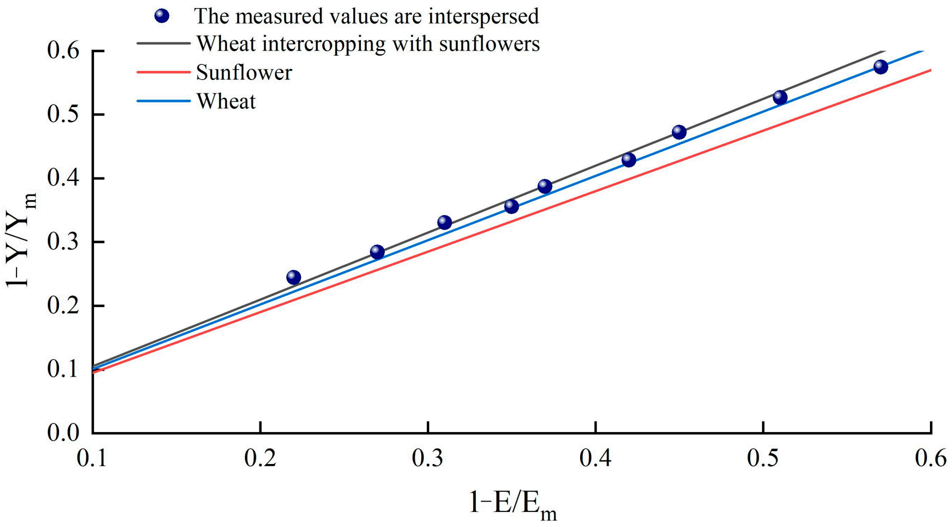

Figure 5. Calculation results of K_y.

2.5. Effective Water Availability Coefficient

The effective water availability coefficient (p), as defined by Zhang et al. [27] (2019), is the proportion of soil water that may be extracted from the root zone before moisture stress is experienced. It is expressed as a value between 0 and 1 and is influenced by the evaporation capacity of the atmosphere. Frequently, a fixed value is used for p throughout a certain period of growth instead of altering the value daily [31]. The numerical approximation for adjusting p is:

$$p = p_R + 0.04(5 - ET_c) \tag{2}$$

where p_R represents the effective water utilization coefficient recommended by FAO56, and ET_c represents the crop water requirement.

The p-values for wheat and sunflower varied throughout the various development phases and were computed in two separate procedures. Firstly, the FAO56 guidelines suggest dividing the calculation of the coefficient of the wheat and sunflower intercrop into six stages. A comprehensive effective water utilization coefficient (p) is then calculated for each stage using the weighted average method based on the coverage ratio of the two crops. Subsequently, a correction is applied. The statistical significance (p-value) of wheat intercropping with sunflowers at six stages is shown in Figure 6.

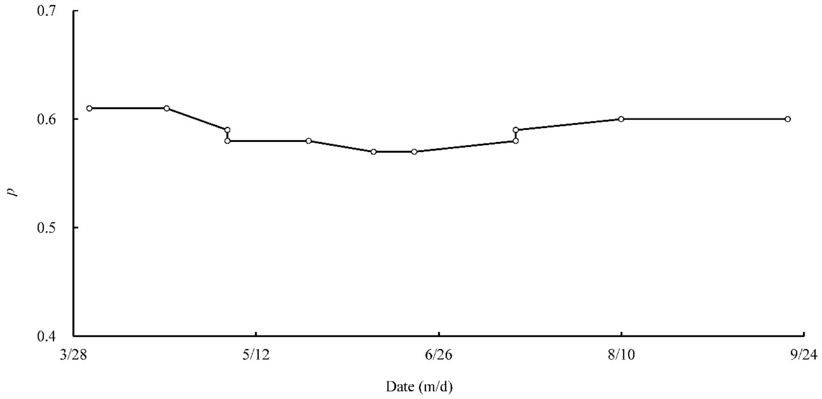

Figure 6. Calculation results of p.

2.6. ISAREG Model

The ISAREG model, as proposed by Zhang et al., was used in the present work to determine irrigation schedules [37]. The ISAREG model is a potent modeling tool that uses precise data inputs such as soil qualities, meteorological variables, and crop attributes. The treatment can simulate and assess real irrigation schedules for intercropping systems, producing several irrigation methods to identify the best option. The ISAREG model offers a diverse set of simulation options, enabling users to customize choices according to various requirements and circumstances. This enables the formulation and assessment of alternative irrigation schemes to efficiently address the issues posed by droughts and water shortages. J.L. Teixeira et al. highlighted that ISAREG models are often used in agricultural irrigation projects to optimize irrigation schedules, enhance irrigation water usage efficiency, minimize water waste, and increase crop yields [13]. The model has received acclaim for its coherent design, high simulation accuracy, intuitive interface, and extensive array of features. Our study aims to precisely replicate fluctuations in soil moisture levels on a farm. We used the model to assess the proposed irrigation schedules, conducted calculations to establish crop water needs, and determined the necessary irrigation water amount to reach the objective. The ISAREG model developed by J. L. Teixeira develops optimal irrigation strategies by analyzing and simulating different irrigation schedules [13]. This model considers the depth of water uptake by the crop root system, soil heterogeneity, varying water table depths, and the soil water supply capacity's impact on evapotranspiration during drought conditions. We used the ISAREG model with a cropping model to enhance the irrigation scheduling efficiency in a wheat–sunflower intercropping system. The intercrop irrigation model was simulated by generating and verifying essential parameters. We combined the ISAREG model with a cropping model by developing and validating key parameters for simulating intercrop irrigation patterns. The use of this improved model led to an increased irrigation water use efficiency, an optimized irrigation time, and increased crop yields compared to the traditional ISAREG model.

The ISAREG model is founded upon the fundamental idea of water balance, which is represented by the water balance equation [13]:

$$\theta_i = \theta_{i-1} + \frac{P_i + I_{ni} - ET_{ai} - DP_i + GW_i}{1000 z_{ri}} \tag{3}$$

where θ_i and θ_{i-1} are the soil moisture contents of the root layer on the I-th and i–1-th days, %; P_i is the effective rainfall on the I-th day, mm; I_{ni} is the net of irrigation water on the I-th day, mm; ET_{ai} is the actual evapotranspiration of the crop on the I-th day, mm; DP_i is the deep seepage quota on the I-th day, mm; GW_i is the groundwater recharge on the I-th day, mm; and z_{ri} is the depth of the root layer on the I-th day, mm.

2.7. Data Structure of the Model

The model's input data are categorized into seven primary categories: (1) Meteorological data, i.e., effective rainfall (PE), reference crop evapotranspiration (ET_0), and other general meteorological data. (2) Crop data, which consist of crop type, crop growth period, planned wet layer depth, water availability coefficient (p), crop coefficients (K_c), and yield response factor (K_y). (3) Soil data, which consist of information on soil types, the soil depth for each layer, the field capacity (θ_{FC}), and the wilting point moisture content (θ_{WP}). (4) Groundwater data, such as the groundwater supply quota (GW) and the deep percolation quota (DP). (5) Irrigation data, including the initial soil moisture content, the irrigation date, the total irrigation, the range of soil water contents, and any constraint conditions associated with different simulation types. (6) Each quantity of irrigation water data, which consist of information on irrigation intervals and the available water supply. (7) Verification data, consisting of the measured moisture content in the field.

The model's output data are influenced by the various input options used for simulation, such as total irrigating, irrigation times, deep seepage, water use efficiencies, maximum evapotranspiration, practical evapotranspiration, yield reduction rates during water stress, yield reduction rates during salt stress, and the comparison of simulated moisture content with field data. In this research, validation trials were performed to confirm the accuracy of the ISAREG model. We used three standard assessment measures to evaluate the model's simulation performance: mean square error (MSE), root mean square error (RMSE), and coefficient of determination (R^2). Our simulation model is more accurate and more practical compared to the old model, as proven by its lower error value. The model simulation results are very accurate and outperform the classic ISAREG irrigation regime model, with a significant relative error reduction of 0.06 [28]. This improvement is crucial for making informed decisions and using the model in real applications. The water resource utilization efficiency is an important comprehensive indicator reflecting the effective development, utilization, and management of water resources. The formula for calculating water resource utilization efficiency can be expressed as follows [15]:

$$R = \frac{RO}{EO - NO} \tag{4}$$

where R is the water use efficiency, RO is the consumption of water resources, EO is the value output of water resources, and NO is the negative value of water consumption.

2.8. Irrigation Schedule Design

Irrigation schedules for wheat intercropped with sunflower were developed based on the real-world situation and the evaluation results of actual irrigation schedules. Multiple combinations were studied and multiple simulations were conducted to determine the most suitable design, with a focus on minimizing yield decreases, which were generally below 10.0%. A total of nine treatments were analyzed (Table 4).

We conducted three repetitions of all experiments to guarantee the reliability and accuracy of the findings. The irrigation protocols for wheat intercropped with sunflower were formulated based on the border irrigation method. The minimum water supply for each irrigation was set at 50 mm, and irrigation was not allowed after 20 August. We conducted simulations on these nine strategies using an initial water content in the root layer soil that matched the ventral effective water content before sowing wheat. The original soil moisture content was around 34%. This area mostly accumulated water from fall precipitation the previous year.

Table 4. Irrigation scheme for each treatment.

Treatment	Irrigation Scheme
Treatment 1	The crop was watered when the average soil moisture content in the root layer reached the optimal level. The total irrigation was then applied to replenish the required soil moisture in the root layer of the field. This treatment resulted in the highest possible yield.
Treatment 2	The irrigation date was determined based on the soil moisture content. Crop irrigation is necessary when the soil moisture content in the root layer suitably declines. The allocation of irrigation water increased the moisture content in the top layer of soil to 90% of the necessary level. This software can decrease the frequency of irrigation and extend the time intervals between each irrigation, therefore maximizing the use of rainfall.
Treatment 3	The irrigation date was determined based on the soil moisture content. The crop was watered when the soil moisture content in the root layer reached 90% of the optimal level. The irrigation water required to reach field capacity was the necessary quantity of irrigating water. This software can decrease the frequency of irrigation and extend the time between each irrigation, hence reducing water loss.
Treatment 4	The irrigation date was determined based on the soil moisture content. Irrigation occurred when the soil moisture content in the root layer reached a minimum threshold of 80%. The irrigation water required to reach field capacity was the necessary total irrigation.
Treatment 5	Irrigation dates were selected based on the water influx from the Yellow River. There were four instances of irrigation. Local farmers conducted irrigation on the following dates: 10 May to 15 May, 12 June to 18 June, 3 July to 10 July, and 1 August to 7 August. The irrigation simulation used the median date from Treatment 5. Due to the limited availability of irrigation water, the total irrigation was reduced to the field capacity to mitigate the danger of agricultural drought.
Treatment 6	Treatment 6 used the same irrigation frequency and date as Treatment 5, but the amount of irrigation water used was reduced to 90% of the field capacity.
Treatment 7	Treatment 7 has the same watering frequency and date as Treatment 5. The irrigation allocation for the first irrigation (solely for wheat growth) and the fourth irrigation (solely for sunflower growth) was set at 90% of the field's maximum water-holding capacity.
Treatment 8	The irrigation depth was established at 72 mm, based on the wheat medium-term field capacity and the desired water content at the lower limit. The model determined the irrigation date for each instance, with the restriction that no irrigation occurred after August 20.
Treatment 9	Treatment 9 allocated 90% of the total irrigation from Treatment 7. The irrigation depth amount for each session was 65 mm. The model determined the dates for irrigation, and, due to restrictions, no irrigation occurred after August 20.

3. Results

3.1. Actual Irrigation Schedules

We conducted a field experiment where we introduced an intercropping system of wheat and sunflower and examined two distinct watering methods. The characteristics of these two irrigation systems were determined via field observations and model simulations. Treatment 1 had a percolation depth of 61.61 mm, suggesting that some of the irrigation water was not absorbed by the crop, but instead seeped into the lower soil layers (Table 5). This might potentially replenish groundwater, but it also involves the partial loss of irrigation water. Treatment 2 had no seepage, since all the irrigation water was either absorbed by the crop or evaporated, with no water penetrating deeper into the soil. In this scenario, the water efficiency is enhanced, but it might result in soil water depletion in cases of thin soil layers or low water tables. Treatment 1 led to a 9.14% decrease in production, perhaps due to water leaks that led to soil moisture supporting the crop during the drought. Treatment 2 led to a production decrease of 15.62%. Despite an excellent water use efficiency, the crop could have endured increased water stress during growth due to insufficient soil moisture reserves or poorly timed irrigation. Both treatments were watered four times throughout the reproductive phase. The first irrigation took place early in the wheat growth cycle, before planting sunflowers, to provide a strong foundation for wheat seedlings and supply moisture for their growth after sunflower planting. The second and third irrigation periods were conducted while wheat and sunflower were growing simultaneously to provide enough water supply for the development of both crops. The fourth irrigation, conducted post-wheat harvest, aims to enhance the subsequent development of sunflowers, perhaps leading to increased production and quality. The monthly average total precipitation of 18 mm may impact the development of wheat and sunflowers (Figure 7). Precipitation is the primary water supply for agricultural growth and significantly influences crop development and production. Wheat is a crop that requires a significant amount of water, particularly during crucial development phases like tasseling and grubbing. Insufficient water availability during these times may lead to reduced yields. Sunflowers are very resistant to drought, although insufficient water during early growth and bud formation may still impact their development and productivity. Thus, an effective irrigation plan is crucial to guarantee optimal crop development and productivity. Local farmers often use this intercropping and irrigation technique, drawing on their understanding of regional climate and soil characteristics together with conventional agricultural expertise. Intercropping may enhance land use efficiency, mitigate the spread of diseases and pests, and contribute to enhancing soil fertility and structure.

Table 5. Related parameters of actual irrigation plans in the intercropping mode.

Treatment	**1**	**2**
Irrigation depth (mm)	300	208
Deep percolation (mm)	61.61	0
Groundwater recharge (mm)	9.8	14
Irrigation efficiency (%)	79.46	100
E_{ta} (mm)	464.1	431.4
Yield loss (%)	9.14	15.62

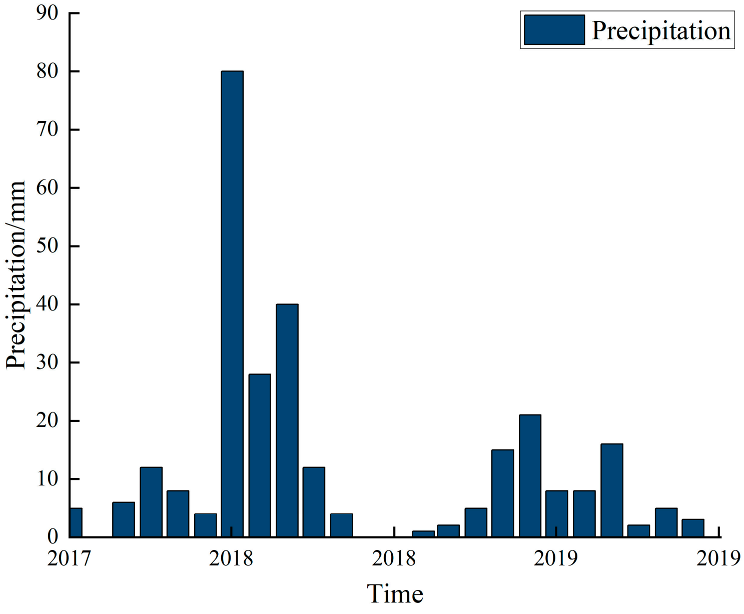

Figure 7. Total monthly precipitation from 2018 to 2019.

3.2. Results of Irrigation Scheme Design Simulations

When scheduling irrigation for wheat-intercropped sunflowers, it is crucial to modify the irrigation frequency and the amount of water used. This guarantees that the crop receives sufficient water during crucial development phases, thus enhancing the crop's output and quality. We suggest extending the irrigation duration throughout the growth season to ensure the crop's water requirements are met at this point. This suggestion is derived from the irrigation scheme previously discussed. This plan takes into account aspects like the crop development stage, soil type, and meteorological conditions to establish the optimal irrigation treatment (Table 6). We performed modeling trials to enhance our watering method. We examined nine distinct irrigation scenarios in these studies and simulated the essential parameters for each scenario. These parameters include the irrigation volume, irrigation frequency, irrigation depth, and so forth. Our simulation model is more accurate and practical compared to the old model, as highlighted by its decreased error. This model offers precise simulation results and outperforms the standard model in simulation performance, which is very significant for decision-making and practical applications. We evaluated the model's simulation performance using three metrics: MSE = 0.01, RMSE = 0.02, and R^2 = 0.94. Table 6 displays the simulation findings.

Table 6. The parameters related to the design of the irrigation scheme.

Designed Irrigation Schedules (Treatment)	Irrigation Water (mm)	Irrigation Frequency (times)	Leakage (mm)	Groundwater Recharge (mm)	Water Use Efficiency (%)	ETa (mm)	Yield Decline Rate (%)
1	410.4	6	7.84	0	98.09	510.3	0
2	349.65	6	7.84	0.23	97.76	509.51	0.16
3	340.87	5	0	2.03	100	501.13	1.81
4	294.92	4	0	4.75	100	492.25	3.57
5	309.7	4	0	5.24	100	494.81	3.07
6	283.43	4	0	10.85	100	467.38	8.49
7	292.16	4	0	7.27	100	493.65	3.3
8	360	5	23.94	0.31	93.35	508.84	0.29
9	325	5	12.38	3.98	96.19	494.43	3.14

4. Discussion

4.1. Model Applicability

Irrigation simulations were conducted based on the given parameters. Figure 4 shows a comparison of dynamic soil moisture model results with the actual measurements after several treatments for the wheat and sunflower intercrop. The findings indicate that the simulated soil moisture in both treatments had a relative error of less than 10%, with an average error of 3.5%. The accuracy of the measurements is deemed suitable. This demonstrates that the soil, meteorological, rainfall, and crop factors used are appropriate for simulating irrigation schedules, enabling the assessment of different irrigation designs via the utilization of diverse model parameters and the optimization of the irrigation schedule [36].

Figure 8a,b compares two real irrigation treatment plans for wheat intercropped with sunflower. Both treatments had identical watering schedules throughout the whole growth period, with watering conducted four times during each treatment. The timing of each irrigation was determined according to the widely adopted practice of local farmers. The first irrigation took place before planting sunflowers, specifically during the initial growth stage of the wheat. The second and third irrigations occurred during the typical growth stages of both wheat and sunflower. Following the wheat harvesting, the sunflower crop underwent a fourth irrigation. We observed that the water distribution was adequate throughout the growing phases of both crops.

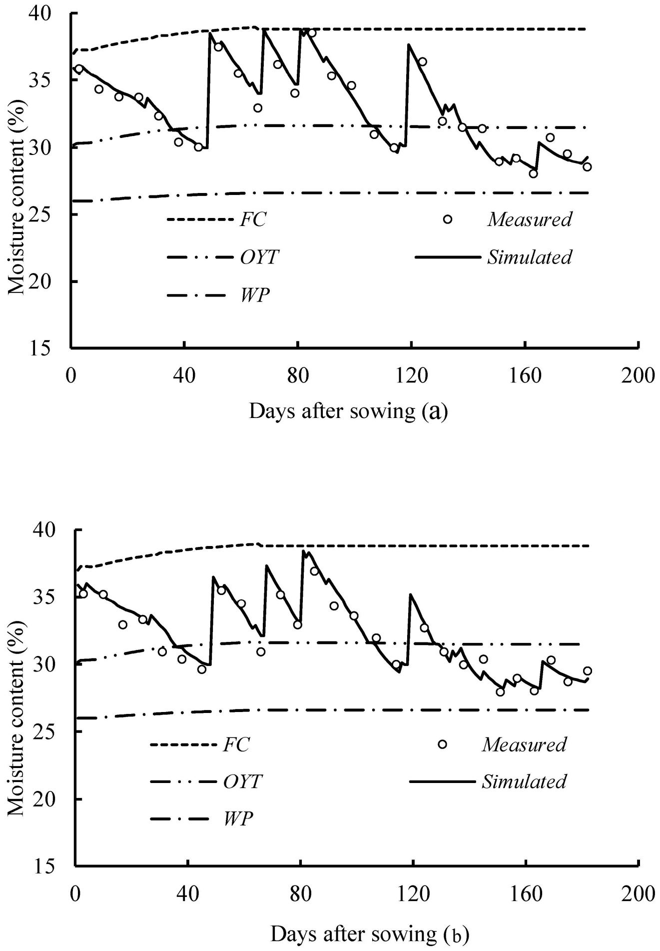

Figure 8. Comparisons of simulated and measured soil water content of wheat intercropped with sunflower for different treatments (**a**,**b**).

4.2. Evaluation of Actual Irrigation Schedule

The primary cause for the decreased water usage efficiency in Treatment 1 was the insufficient intervals between the first, second, and third irrigations. The second irrigation was mostly conducted in response to the soil's water content, and due to the comparatively high amount of water utilized for irrigation, this resulted in very deep seepage [37]. The decrease in yield for Treatment 1 may be attributed to the first watering, which resulted in the soil's moisture content dropping below the optimal threshold for around 10 days. During this stage, known as the wheat tiller and jointing stage, water shortages have a significant impact on subsequent wheat development [38]. During the wheat maturation stage, the soil moisture content dropped below the required threshold for around 10 days when the fourth irrigation occurred. While this was beneficial for wheat harvesting, the sunflower was at a critical stage regarding water demand; a lack of water would significantly impact its production [39]. The sunflowers were not irrigated after the fourth watering, resulting in a significant decrease in soil moisture content, which mostly ranged between the wilting point and the optimal moisture level. This led to a decrease in the sunflower's output [40]. It is reasonable to infer that the water distribution in Treatment 1 was illogical. The frequency of irrigation was insufficient, and the amounts of water allocated for the second and third irrigations were excessive. Consequently, the water use efficiency was poor and there was a decline in output [41].

Contrastingly, the irrigation allocation decreased in Treatment 2, resulting in four shallow irrigations that effectively used water. Although the soil moisture content at different stages remained lower compared to Treatment 1, Treatment 2 led to an increase in groundwater recharge and a drop in the ET value. Specifically, the ET value was 84.54% of the maximum ET value. The production decline rate was 15.62%. The irrigation dates in Treatment 2 were unsuitable, with an insufficient irrigation frequency and a modest single irrigation volume.

4.3. Improving the Efficiency of the Irrigation Schedule

Through an examination of the simulation outcomes shown in Table 4, the following observations were noted.

Treatment 1: Six irrigations were performed over the whole growth period, but the crops required a much greater amount of water. The attained ET value was the highest, with crops being unaffected by water stress and experiencing no growth reduction. This irrigation schedule proved to be more efficient under conditions of a sufficient water supply. The irrigation dates for Treatments 2~4 were determined based on the soil's moisture content.

Treatment 2: The plants were irrigated six times during their entire growth cycle. In comparison to Treatment 1, there was a reduction in both the amount of water utilized for each irrigation and the total irrigation water. However, the moisture content of the soil was still maintained at adequate levels. When the moisture level during the growth anaphase reached the lowest suitable level, greater amounts of rainwater were used in Treatment 2 compared to Treatment 1. The evapotranspiration (ET) value remained at its peak, with a small decrease in production. Overall, Treatment 2 conserved a greater amount of water compared to Treatment 1.

Treatment 3: In comparison to Treatment 1, not only did the total irrigation water decrease to 46.6 mm but irrigation was conducted five times. The reduction in water loss resulted in a 1.81% drop in yield. Treatment 3 used a greater amount of water for irrigation than Treatment 2. The decrease in crop output was less significant, and there was one less irrigation event. However, the two schemes exhibit similarities.

Treatment 4 had the lowest total irrigation relative to Treatments 1~3, with just four irrigation events. Irrigation commenced when the soil's moisture content dropped below 80% of the lower threshold for suitable moisture levels, resulting in an actual evapotranspiration (*ET*) value that was below the maximum. Consequently, there was a drop in yield, with a reduction rate of 3.57%. The irrigation dates for Treatments 5~7 were determined based on practices used by local farmers, which are widely adopted.

Treatment 5's simulation findings indicate that the overall amount of irrigation water used was much less compared to Treatments 2~4; however, it was comparable to Treatment 4. The occurrence of deep seepage decreased, with a groundwater recharge of 5.24 mm. The actual evapotranspiration (*ET*) value was 96.96% of the maximum, and the yield decreased at a rate of 3.07%. Therefore, this treatment may be considered appropriate.

Treatment 6 is a solution that builds upon Treatment 5, with the difference being that each quantity of irrigation water decreased. The overall irrigation water volume was reduced by 26 mm, but the individual output increased. The rate of decline was 8.49%. This treatment should not be considered.

Treatment 7 is a mix of the parameters of Treatments 5 and 6. Compared to Treatment 5, the water amount in the first and fourth irrigations was decreased, although there was an increase in groundwater recharge and the use of rainfall. Based on the production outcomes, it is evident that there was a decline in output. Treatment 7 outperformed Treatment 5 in terms of moisture production.

In Treatments 8 and 9, irrigation was consistently performed on five occasions, and the overall amount of irrigation was higher. The cumulative amount of irrigation water used in Treatment 8 was 360 mm. During the first and second irrigation cycles, both Treatments 8 and 9 led to significant deep seepage, with a total seepage quantity of 23.94 mm. Each quantity of irrigation water for the last two cycles was deemed appropriate. Despite achieving peak output, Treatment 7 led to higher levels of total irrigation water and deep leakage. Additionally, the water use efficiency was poor, and the implementation of additional irrigation led to an increase in water loss. Therefore, it is not recommended to utilize this treatment. Despite a reduction in overall irrigation water, Treatment 9 saw a drop in the production rate of 3.14%. Therefore, it is not advisable to use this treatment.

The above studies were used to determine the most efficient irrigation schedules, taking into account factors such as total irrigation, irrigation frequency, leakage, recharge, water usage efficiency, evaporation, and the reduction in the wheat production rate when intercropping with sunflowers [42]. Treatments 4 and 7 are shown in Table 7, demonstrating their similarities except for variations in irrigation dates and total irrigation. The optimal watering schedule should be determined by considering the attributes of each of these plans. The optimized irrigation schedule in Treatment 4 was not constrained by the irrigation date from the Yellow River. The intercrops were watered on four occasions, with the dates determined based on the calculations of the ISAREG model. Irrigation was scheduled when the soil water content dropped below 80% of the optimal moisture level [43]. The rate of output reduction was quite small, making this scheme appropriate. Treatment 7 was the optional optimized irrigation plan and was influenced by the specific date of irrigation from the Yellow River. Irrigation was conducted on four occasions. Each quantity of irrigation water differed, and the results were computed according to the water needs of the two crops. The allocation of irrigation resources was limited, and the decrease in output was quite insignificant [44]. In comparison to Treatment 1, the irrigation frequency and dates remained unchanged; however, the irrigation depth decreased by 7.84 mm. By optimizing each quantity of irrigation water, the output rate was substantially reduced.

Table 7. Optimization of irrigation time for sunflowers during wheat intercropping.

Irrigation Events (Times)	Treatment 4		
	Irrigation Date (m/d)	Irrigation Depth (mm)	Irrigation Water (mm)
1	5/4	56.53	294.92
2	6/8	75.91	
3	7/5	81.92	
4	8/9	80.56	
Irrigation Events (Times)	**Treatment 7**		
	Irrigation Date (m/d)	**Irrigation Depth (mm)**	**Irrigation Water (mm)**
1	5/12	59.28	292.16
2	6/15	73.53	
3	7/6	77.17	
4	8/4	82.18	

5. Conclusions

The ISAREG model can be used to preprocess and validate the parameters of irrigation, soils, and crops. This model can assess real-world irrigation schedules for intercrops by simulating multiple irrigation schedules and determining the optimal one. It has a high practicality and enables flexible comparisons through the study of different irrigation systems. The water consumption of intercrops is taken into consideration to design a multi-combination plan that includes both full irrigation and inadequate irrigation. Among the different irrigation schemes, Treatment 4 demonstrates the highest level of efficiency when the amount and duration of irrigation are consistent. This conclusion is reached by considering various factors, such as irrigation water use efficiency, evapotranspiration, and the rate at which yield decreases. It is important to note that this assessment takes into account the limitations imposed by the availability of water to tdentify the optimal irrigation plan for intercropping.

The ISAREG model presently depends partially on a substantial quantity of data support, including meteorological data and crop growth data, to guarantee the precision of input parameters, such as soil moisture content data, crop parameters, and irrigation parameters. The model's geographical applicability is limited by these constraints. Furthermore, the model may not possess the capability to completely include all pertinent variables, such as local pests and diseases, as well as the many kinds of fertilizers used. Consequently, the thorough monitoring of crop development remains rather distant.

Nevertheless, these constraints provide crucial perspectives for future investigations. Additional enhancements may be made by including a broader range of environmental and climate change variables in the ISAREG model. Through the use of innovative irrigation systems, we may enhance the efficiency and effectiveness of scientific equipment used in agricultural crop production. Implementing this solution would not only enhance the efficacy of agricultural output, but also enable places facing water supply limitations to effectively address the difficulties posed by climate change.

Author Contributions: Conceptualization, H.Z., H.H. and J.W.; methodology, H.Z.; software, D.T.; resources, J.W.; data curation, H.Z., H.H. and P.M.; writing—original draft preparation, H.Z.; writing—review and editing, H.Z. and J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the Research and Demonstration of Key Technologies for Efficient Water saving of the Forage Belt in the Yellow River Basin of Inner Mongolia (2023JBGS0014); the Key projects of "Rejuvenating Inner Mongolia Through Science and Technology" (Grant No. 2021EEDSCXSFQZD010) and Inner Mongolia Scientific and Technological Achievements Transformation Project (Grant No. 2021CG0003).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are not publicly available due to privacy.

Acknowledgments: All authors thank the academic editors and reviewers for their valuable comments.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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