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Developing a real-time self-organizing algorithm for irrigation planning of rapeseed cultivation

Yunzhong Dai[a,b,c] and Kuan-yu Chen[d,*]

[a] Intelligent Manufacturing Institute, Yibin Vocational and Technical College, Yibin, Sichuan 644003, China
[b] Sichuan Dawn precision Technology Co., Ltd, Meishan, Sichuan 620460, China
[c] School of Aeronautics and Astronautics, University of Electronic Science and Technology of China, Chengdu, Sichuan 611731, China
[d] School of Political Science and Law, Yulin Normal University, Yulin, Guangxi 537000, China
*Corresponding author. E-mail: cgy2023888@163.com

ABSTRACT

Sustainable planning of water allocation in the agricultural sector requires attention to soil, plant, climate and their limitations. This study was conducted in order to develop a real-time framework for simulating soil–water balance in the root zone, crop growth curve and irrigation planning of rapeseed cultivation in Henan Province, China during a cropping season from March to October 2022. Simulation of production functions with field information calibration at daily time step was developed to accurately estimate the simulation of crop growth and soil water balance. Particle swarm optimization (PSO) algorithm is incorporated as an efficient tool to evaluate the water productivity as objective function in a self-organizing framework. Choosing the appropriate planting date for rapeseed cultivation at the beginning of the growing season was evaluated to increase the use of precipitation for canopy cover growth and thus reduce irrigation water consumption. The results showed that the proposed model increased water productivity by 23% as the objective function, and evaporation from the soil surface decreased by 16%. The maximum difference between the irrigation depth in the optimal and existing strategies was 41 mm in the germination stages until the seed-filling stage, which caused a decrease in final biomass and plant transpiration.

Key words: canopy cover, objective functions, particle swarm optimization, water use efficiency

HIGHLIGHTS

- An optimization framework was used to find the sustainable strategy of water distribution in rapeseed cultivation.
- A daily time step modeling was developed to estimate the crop growth process.
- Improving the planting date increased water productivity and effective use of rainfall.

1. INTRODUCTION

Rapeseed (*Brassica napus* L.) is one of the main priorities in the cropping pattern under different climate conditions (Enjalbert *et al.* 2013). The cultivation area of rapeseed in China is estimated at 258,000 ha, which is equivalent to 3.88% of the total area under cultivation of agricultural products and 38.6% of the total area of cultivation of industrial products (Li & Wang 2022). Rapeseed is the largest oilseed crop in China and accounts for about 20% of world production. For the last 10 years, the production, planting area, and yield of rapeseed have been stable, with improvement of seed quality and especially seed oil content (Hu *et al.* 2017). The mean yield production values of rapeseed are estimated at 2,100 and 1,700 kg/ha in irrigated and rainfed lands, respectively. One of the distinguishing features of rapeseed among oil-seeds is the ability to be cultivated as a winter crop for rainfed cultivation. Therefore, the cultivation of strategic plants such as rapeseed is one of the main polices to achieve the sustainable development. The effect of drought stress on the yield is a function of genotype, intensity and duration of stress, climatic conditions, and growth stages (Andarziana *et al.* 2011; Majidi *et al.* 2015). Adequate fresh-water supply has become an issue of increasing local and international concern (Sedghamiz *et al.* 2018; Varzi *et al.* 2019).

In addition to the effect on society, politics, urban planning (Huang *et al.* 2021), environment (Zhao *et al.* 2022; Zhang *et al.* 2023), geology (Liu *et al.* 2023) and economy, water resources are also known as the most important factor in agriculture. Emphasizing the importance of water management in dry areas, researchers used it as a decision variable in planning systems. Lalehzari *et al.* (2020) proposed an artificial intelligence-based framework with two economic and productivity

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objectives to reduce groundwater withdrawal in southern Iran. The pattern of cultivation of different crops was developed using the simulation of production functions and optimization by genetic algorithm. Changing the duration and depth of irrigation was one of the important results to increase productivity. Tian *et al.* (2021) investigated the potentials of growing rapeseed across the Yangtze River Basin to serve the goal of boosting bioenergy production and improving edible oil security in winter fallow fields. The assessments take into consideration of climate change adaptations on sowing dates and on the choice of varieties with suitable growth cycle length. Results showed that a 60% realization of the production potential would increase total rapeseed supply by 9.1 million tons.

The challenges evaluated in different researches indicate the existence of three main components in the development of agricultural water management decision systems, including the required information, the simulation process, and the efficiency of the optimization model. The selection of each of these components is based on the needs of the plant, climate, soil and decision variables (Nyakundi *et al.* 2022). The innovation of this research compared to previous researches was in the assessment of drought stress. Deficit irrigation scenarios were programmed to evaluate the role of each irrigation on biomass production in two stages for each experiment. The previous research works have applied deficit irrigation to all irrigation events based on a specific level (Safavi & Falsafioun 2017; Sun *et al.* 2017; Li *et al.* 2018). In simulation process, the yield production and soil moisture balance were developed for rapeseed cultivation based on daily information of growth, temperature, rainfall, moisture and stresses. Lalehzari *et al.* (2016) and Sedghamiz *et al.* (2018) used seasonal or multi-day time steps. Moreover, the simulation model follows an unchanged computational process during the optimization process (Varade & Patel 2018; Lalehzari & Kerachian 2021). But in the present study, the time and amount of complementary irrigation is reorganized to improve biomass in each iteration according to the output of the PSO model. Crop growth modeling and soil moisture balance were provided using real-time programming in MATLAB 2019b software. Furthermore, due the lack of systematic programs for irrigation scheduling in most of agricultural activities, many beneficial opportunities may stay unknown during the growing season.

2. MATERIALS AND METHODS

2.1. Study area

Henan Province is one of the major production sources of rapeseed in China. Henan is located in the east-central of China with the geographical coordinates of 34.76N and 113.75E and borders with Anhui and Shandong to the east, Shanxi and Hebei to the north, Shaanxi to the west, and Hubei to the south (Figure 1). The study area has a temperate climate that is

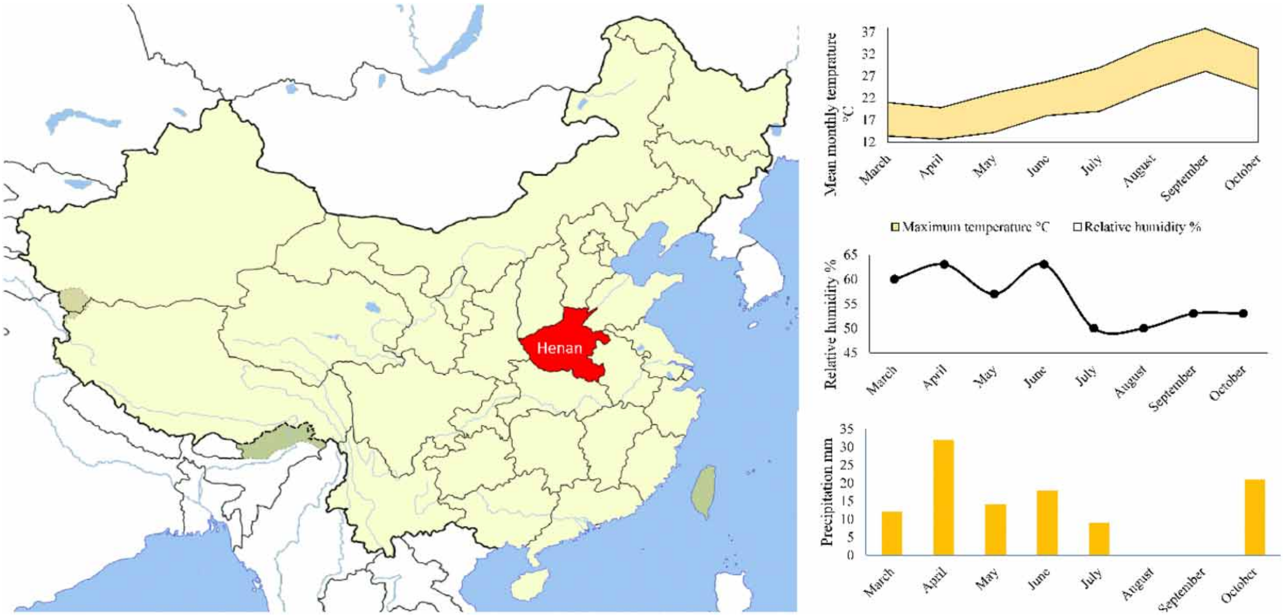

Figure 1 | Henan province in China and monthly climatic parameters.

humid subtropical to the south of the Yellow River and bordering on humid continental to the north. It has distinct seasonal climate characterized by hot, humid summer and cool to cold, windy, dry winters. The study was conducted between March and October 2022 by measuring the biomass of three rapeseed fields and recording the irrigation schedule.

The most important climatic information used as input data is the maximum and minimum daily temperature, potential evapotranspiration, CO_2 concentration, and rainfall (Raes *et al.* 2009). For each study area, a rapeseed field was selected and soil information, irrigation, canopy cover (CC) data, and cultivating dates were collected. Climatic information of the cropping season is summarized in Figure 1.

2.2. Self-organizing optimization

Figure 2 shows the process of achieving the optimal irrigation schedule based on agricultural and climatic information. The proposed algorithm is a self-organizing structure based on real time. Real time in irrigation modeling refers to the choice of

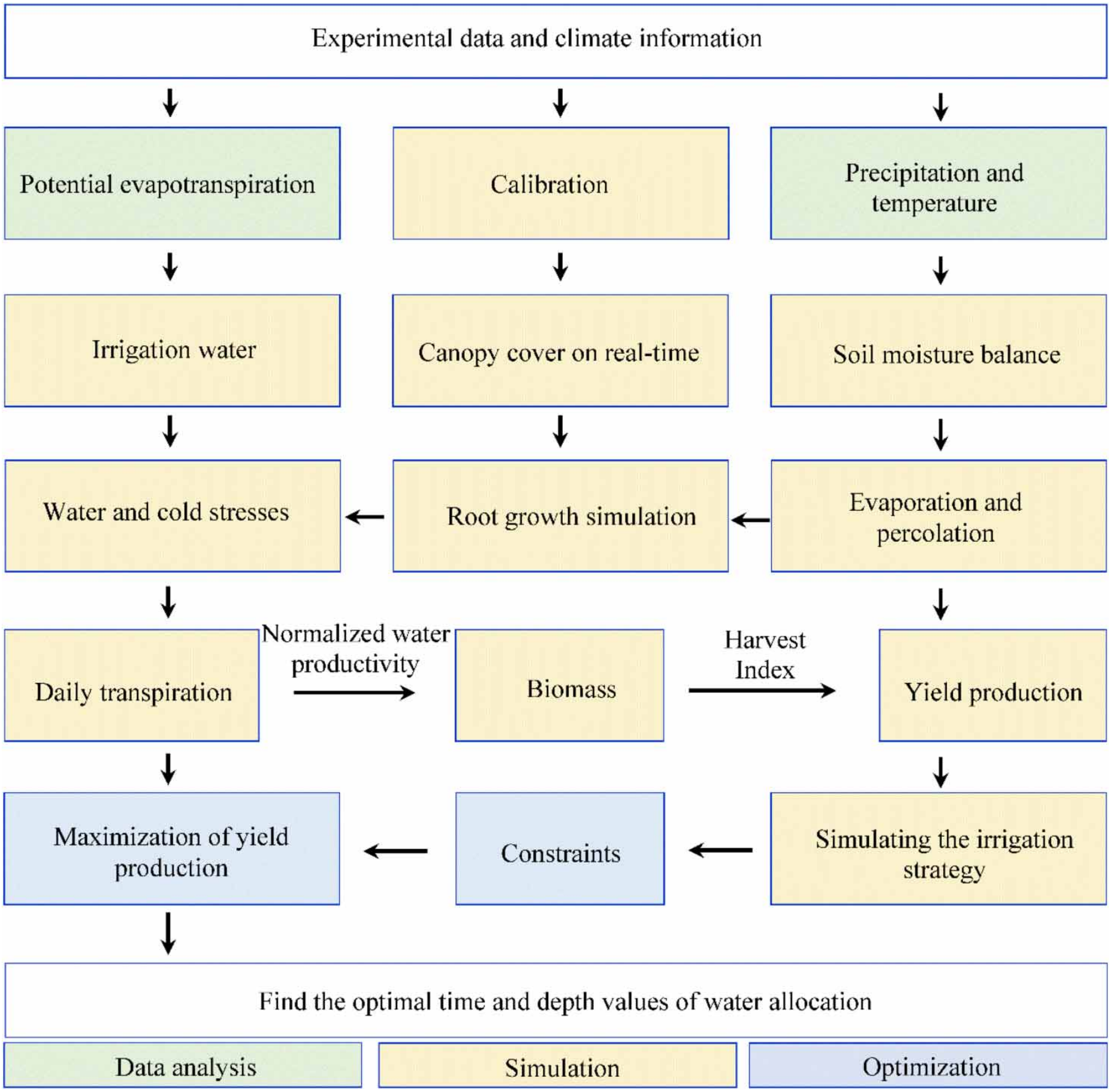

Figure 2 | Mechanism of self-organizing real-time optimization for rapeseed irrigation.

daily time step as described in the researches of Lalehzari & Kerachian (2021) and Wang *et al.* (2021). The organization of solutions in this research is based on the definition of a new feasible space in each iteration according to the responses calculated in the previous step (Wang *et al.* 2023). In this structure, the extreme points that complicate the search of the problem and disperse the solutions are removed and the speed of convergence increases (Cao *et al.* 2021a). The optimization algorithm used in this research is particle swarm optimization, whose efficiency has been confirmed in various studies (Cao *et al.* 2021b; Liu *et al.* 2021).

The relationship between water, soil, and crop has expanded significantly since the introduction of Doorenbos & Kassam (1979). The need to increase water productivity as an index of controlling the deficit irrigation has forced the Food and Agriculture Organization (FAO) to reformulate the previous equations for leading to simulate the reaction of crops to water. Therefore, water productivity was considered as the objective function, which increases production for reducing water consumption (Jabal *et al.* 2022). Water productivity is defined as the following relationship.

$$\max \mathrm{WP} = \frac{Y}{W} \tag{1}$$

where WP is the water productivity (kg/m^3), Y is the yield production (kg/ha), and W is the allocated irrigation water (m^3/ha). We try to develop the mathematical structure for real-time modeling of rapeseed growth process using the FAO formulations and papers (Allen *et al.* 1998; Reddy & Reddi 2003; Heng *et al.* 2009; Hsiao *et al.* 2009; Raes *et al.* 2009, 2012; Steduto 2009; Steduto *et al.* 2009; FAO 2012, 2015; Achieng 2020; Lalehzari *et al.* 2020).

2.3. Real-time simulation

Developing the growth simulation model in a real-time framework is essential to ensure the sustainability of the water management in agriculture. Hence, the difference between the simulated and observed yield production values should be considered in the calibration process (Lalehzari *et al.* 2020; Lalehzari & Kerachian 2021). Based on the explained concept, the calibration function was to minimize the following equation.

$$\mathrm{CF} = \sum_{i=1}^{n_i}\sum_{t=1}^{n_t}\left(\frac{T_\mathrm{r}}{\mathrm{ET}_o}\right)_t \times \mathrm{WP}^* \times A \times \mathrm{HI} - \mathrm{YP}_\mathrm{o} \tag{2}$$

where CF refers to the calibration function; T_r refers to the transpiration rate (mm/day); $\mathrm{ET_o}$ refers to the potential evapotranspiration (mm/day); WP* refers to the normalized biomass water productivity (kg/m^3); A refers to the cultivated area (ha); HI refers to the harvest index; $\mathrm{YP_o}$ refers to the observed yield production (kg); n_t refers to the days of the growing season, n_i refers to the number of experimental farms. The model constraints are defined to generate a feasible domain for each daily time step. T_r is calculated by the following equation:

$$T_\mathrm{r} = K_\mathrm{c} \times K_\mathrm{sw} \times K_\mathrm{cs} \times ET_\mathrm{o} \tag{3}$$

where the crop transpiration coefficient K_c is proportional to the green CC. K_sw is the soil water stress coefficient which becomes smaller than 1, and as such reduces crop transpiration when insufficient water is available to respond to the evaporative demand of the atmosphere, and K_cs is the cold stress coefficient which becomes smaller than 1 when there are not enough growing degrees in the day.

The modified form of K_c was suggested for considering the reduction in transpiration after the maximum CC and before senescence.

$$K_{\mathrm{c}_\mathrm{adj}} = K_\mathrm{c} - \mathrm{CC}_\mathrm{Max} \times F_\mathrm{Age} \times (t-3) \tag{4}$$

where $K_{\mathrm{c}_\mathrm{adj}}$ refers to the modified transpiration coefficient with an assumed lag phase of 3 days, F_Age refers to the reduction coefficient expressed as a fraction of the maximum canopy cover ($\mathrm{CC_{Max}}$). When senescence is triggered, the transpiration drops more markedly with time (Raes *et al.* 2012). This is simulated by multiplying $K_{\mathrm{c}_\mathrm{adj}}$with another adjustment factor, F_sen, which declines from 1 at the start of senescence to 0 when no green CC remains:

$$K_{\mathrm{c}_\mathrm{sen}} = F_\mathrm{sen} \times K_\mathrm{cadj} \tag{5}$$

Crop canopy cover at real-time t (CC_t) for $CC_t \leq CC_{Max}/2$ and $CC_t > CC_{Max}/2$ could be estimated by Equations (6) and (7), respectively:

$$CC_t = CC_{Min} \times \exp(t \times CGC) \tag{6}$$

$$CC_t = \frac{CC_{Max} - CC^2_{Max}}{CC_{Min}\exp(-t \times CGC)} \tag{7}$$

where CC_t is the canopy cover as a fraction ground cover at time t; CC_{Min} is the initial canopy size at $t = 0$; CC_{Max} is the maximum canopy cover; CGC is the canopy growth coefficient, and t is time (day). The decline in green crop canopy is described by (Steduto *et al.* 2009):

$$CC_t = CC_{Max} \times \left(1 - 0.05 \times \left(\frac{\exp(3.33t \times CDC)}{(CC_{Max} + 2.29)}\right) - 1\right) \tag{8}$$

where CDC is the canopy decline coefficient. The calibration process was carried out based on the observed fractions of the CC in the four times of emergence, maximum, senescence, and maturity measured in the fields. The required information to calibrate the daily biomass for the study area is summarized in Table 1. The rapeseed used in this study was Holya 401. Other information needed to perform the simulation includes four main dates of plant growth, including emergence, maximum canopy, senescence, and maturity, which were measured based on field observations. From the information presented in the table, the percentage of initial and maximum CC values are obtained through field measurements. The calibration of input parameters was carried out to achieve the final yield production.

3. RESULTS AND DISCUSSION

3.1. Simulated parameters in real-time

The evaluation of the calibrated model is shown in Figure 3. The results presented in the scatter diagram and the coefficient of determination values close to one showed that the simulation model can be used to estimate the yield production in different studied climate conditions.

The first step in the simulation model is to estimate the CC at different times of the growing season. This parameter is the main factor in calculating the transpiration and the separation of the transpiration values from the evapotranspiration. Table 2 shows the average CC level in different months of the growing season from March to October. The development

Table 1 | Calibrated parameters to predict the rapeseed biomass

Categories	Parameters	Unit	Value
Canopy cover	Initial canopy cover	%	3
	Maximum canopy cover	%	86
	Canopy growth coefficient	–	0.074
	Canopy decline coefficient	–	0.05
Crop characteristics	Normalized water productivity (WP*)	g/m^2	15.7
	Harvest index	%	53
Growth times	Emergence	day	16
	Maximum canopy	day	134
	Maximum root	day	124
	Flowering	day	132
	Senescence	day	161
	Maturity	day	183
Soil characteristics	Soil texture	–	Silt loam
	Field capacity	%	24.2
	Permanent wilting point	%	10.1
	Bulk density	gr/cm^3	1.42

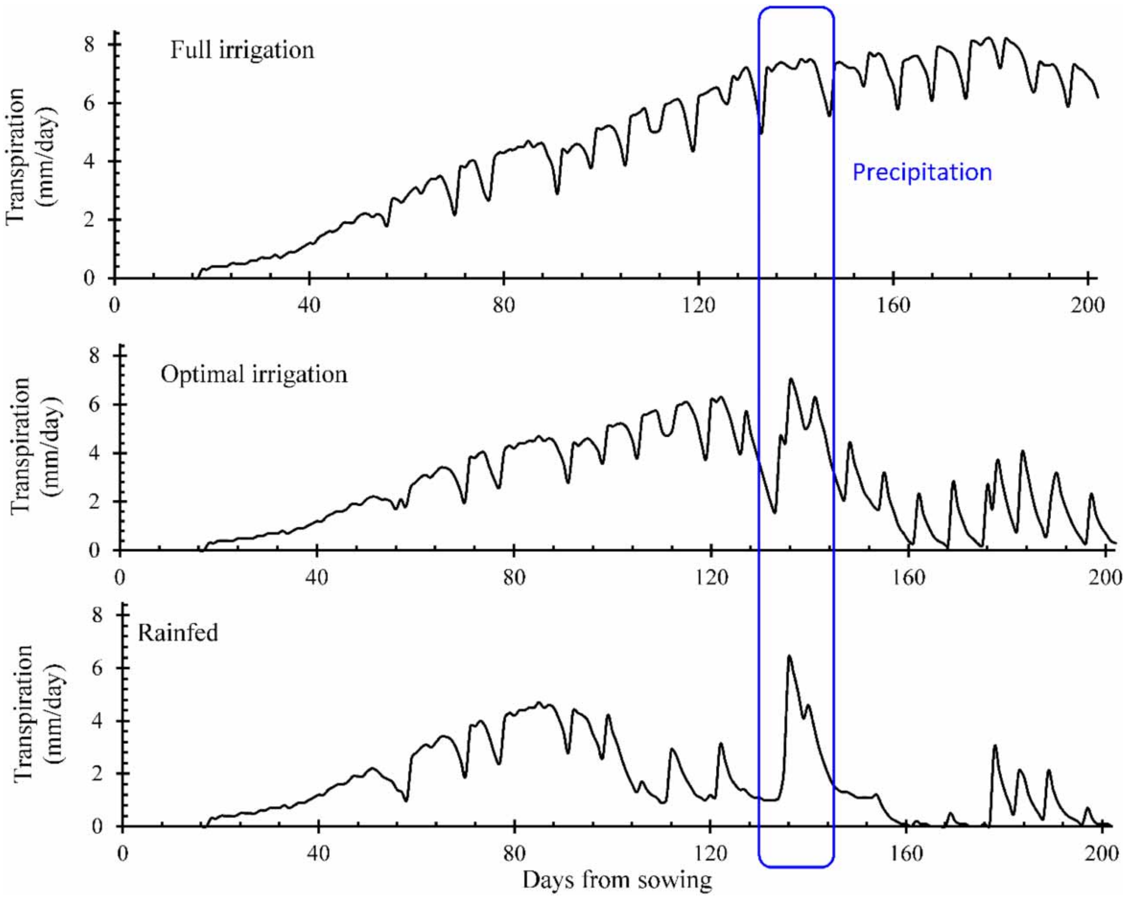

Figure 3 | Impact of irigation plans on the transpiration values.

Table 2 | The mean monthly canopy cover values in the study year

Month	**March** **%**	**April** **%**	**May** **%**	**June** **%**	**July** **%**	**August** **%**	**September** **%**	**October** **%**
Value	5	9	43	83	85	85	85	79

of vegetative growth of the plant will increase the transpiration of the plant compared to evaporation and increase the final biomass. In the research of Lalehzari *et al.* (2016) in Baghmalek Plain in Iran, the CC level reached 72% in June, which reduced the yield of rapeseed by 6% compared to optimal conditions. Tavakoli *et al.* (2014) showed that a longer vegetative growth period before the onset of the cold season increases the CC area. Therefore, in a region with a severe cold season where the temperature is less than 0 °C in a 3-month period, the suitable planting time has caused sufficient growth of the rapeseed plant and reduced vulnerability in winter.

Three patterns of transpiration are compared in Figure 4 according to the existing conditions, the optimal plan and rainfed cultivation. In rainfed cultivation, only the effect of rainfall on plant growth is considered. In the study year, rainfall during the seed-filling stage protected the plant from moisture stress. In rainfed conditions, the biomass produced is estimated to be less than 1 ton/ha. In the study area, rapeseed transpiration changes during the growing season without sudden changes and based on a predictable pattern. The air temperature changes in a short period fluctuate the transpiration on a daily and weekly scale.

The daily evapotranspiration during the growing season at the field level is illustrated in Figure 5. According to the growth pattern of plant cover, in the first 2 months, evaporation plays an essential role in the water balance, and gradually with the

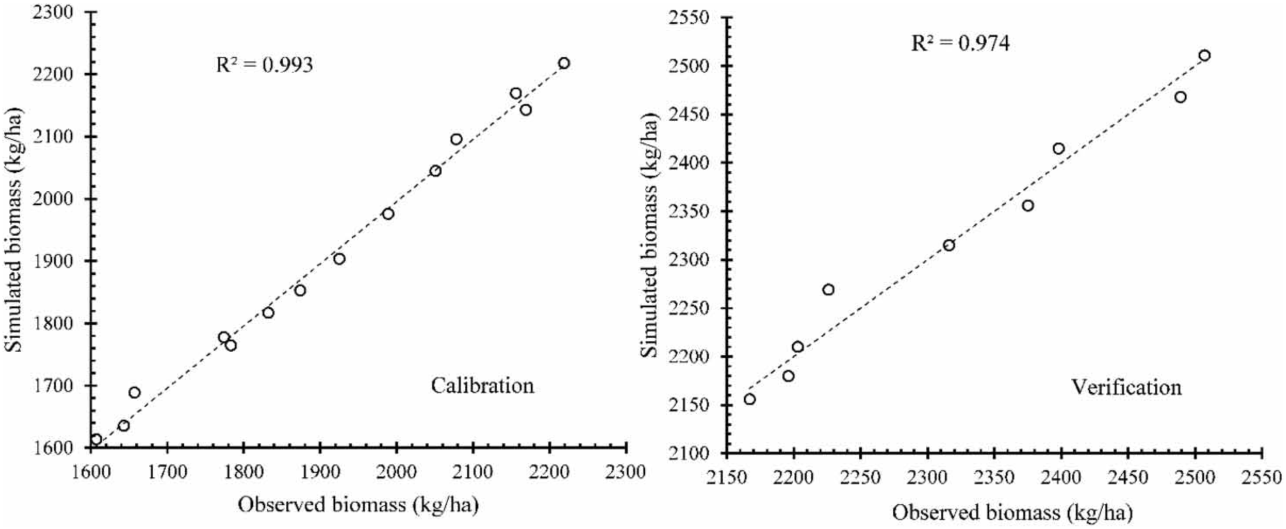

Figure 4 | Simulated and observed biomass in calibration and verification.

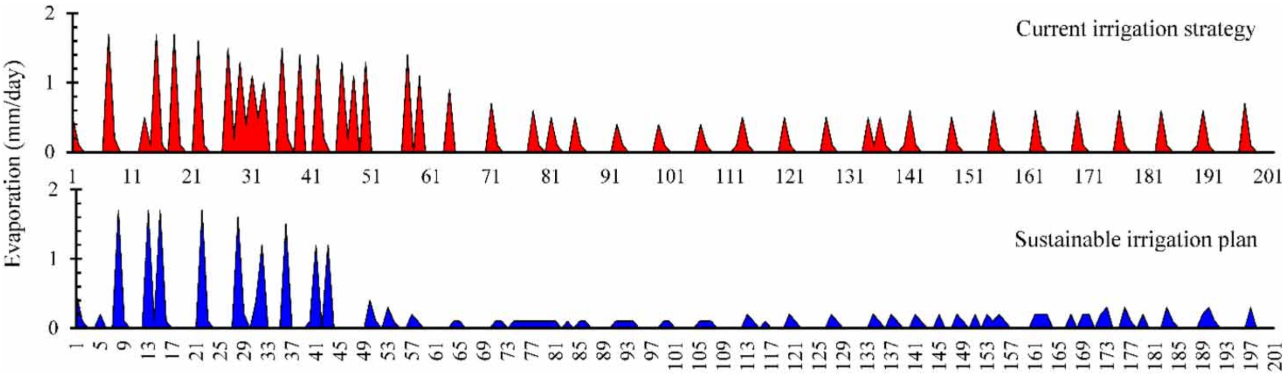

Figure 5 | Evaporation changed in the study period.

completion of the CC, transpiration becomes the most important factor of water absorption. Comparison of evaporation patterns in current and optimal conditions showed that optimal irrigation can reduce evaporation by 13%, which does not interfere with production.

Changes in soil moisture in the surface layer that is exposed to evaporation can be a suitable indicator of the available water to the plant. The amount of moisture content should be at a level that reduces evaporation while meeting the water needs of the roots (Li *et al.* 2021, 2023). Increasing the number of irrigations is one of the ways to maintain the surface moisture of the soil, but this method increases the cost of irrigation. Therefore, the number of irrigations in this research is considered the same as the number of irrigations in the current conditions. As shown in Figure 6, in the current irrigation program, about 33% of irrigation water penetrates into the deep layer, which has decreased to 17% in optimal conditions. Most of the water loss was in the emergence stage.

3.2. Optimal irrigation program

Figure 7 compares the optimal irrigation planning of rapeseed based on the recommended concepts with the existing conditions. The gross volume of irrigation water in the current conditions is estimated to be 8,560 m^3/ha, which has decreased to 6,280 m^3/ha in optimal conditions. The production biomass curve compared to time, which was simulated on a daily basis, showed that the crop production increased from 1,210 to 1,575 kg/ha with the application of the optimal

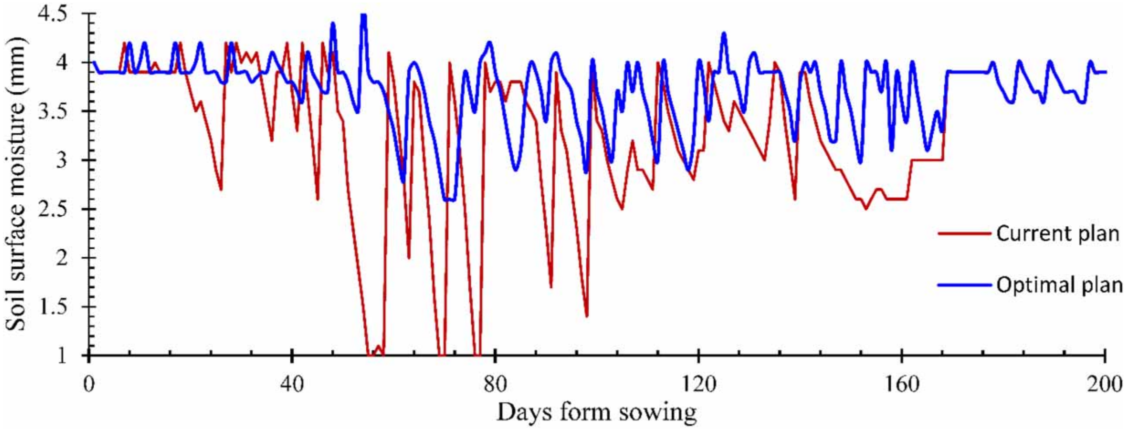

Figure 6 | Fluctuations of soil surface moisture.

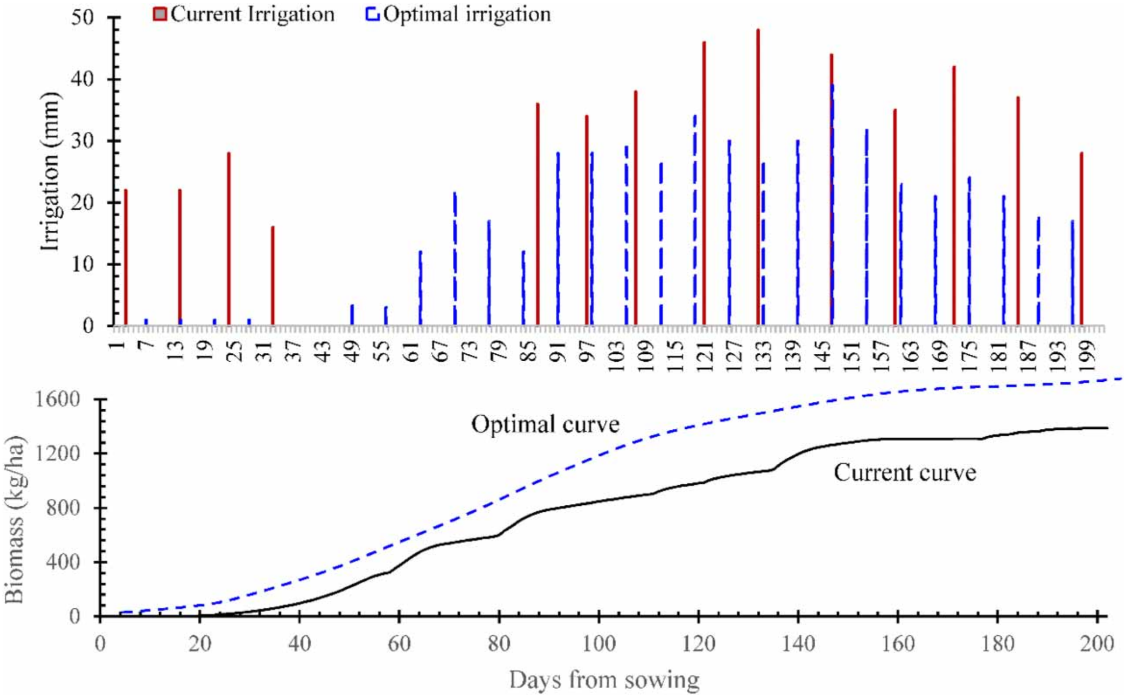

Figure 7 | Irrigation strategies and produced biomass.

strategy. The most important stage in irrigation planning, which has resulted in the difference in production, is the time when the canopy reaches maturity.

3.3. Planting date

The best planting date is the factor in crop water management that affects plant growth and yield. For this purpose, using the growth pattern prepared for the four study areas, three planting dates including (1) existing planting date based on which modeling has been done; (2) decrease the planting date by 10 days compared to the current situation; and (3) increase the planting date by 10 days. The first parameter evaluated in this regard is the effect of changing the date of cultivation on the volume of water consumed by the plant, which is shown in Figure 8. The results showed that the volume of required water for rapeseed production is the highest amount that the main reason being the difference in effective rainfall used by the plant. On the other hand, in all study farms, the 10-day decrease in planting date has reduced water consumption.

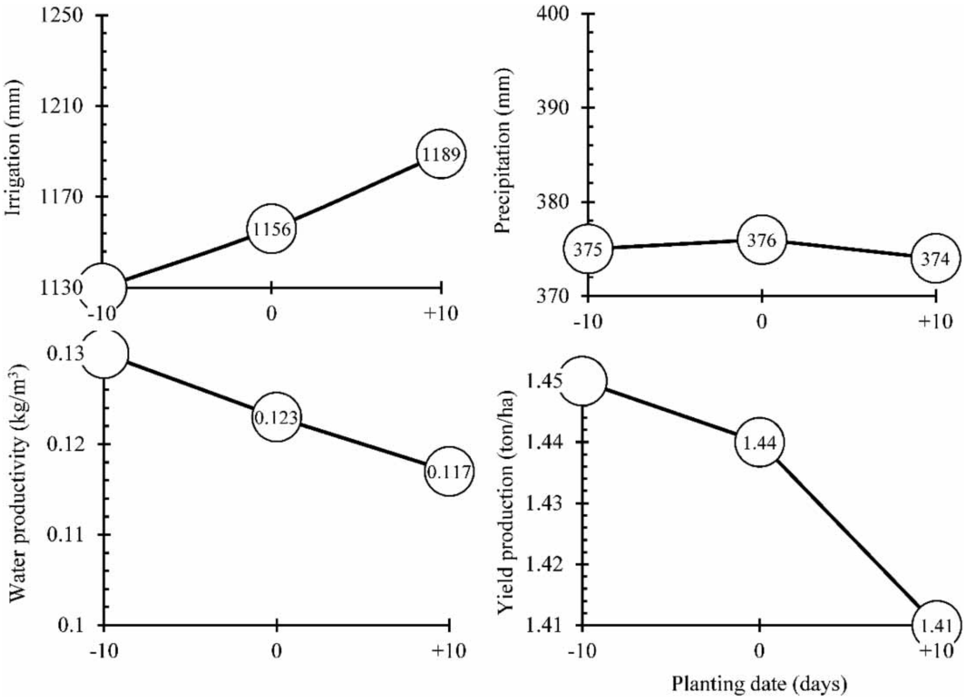

Figure 8 | Changes in water allocation and yield production based on planting date.

Delaying the cultivation of the plant will increase the harvest date and the greatest water requirement of the plant is in the stages of maturation and reproductive growth of the plant, so this issue transfers the highest level of CC from the winter season to summer and the plant has used more water to produce seeds. According to Figure 8, at the end of the growing season, the intensity of rainfall has decreased compared to autumn and winter, and therefore the volume of water received from rainfall has decreased during the planting date.

Yield production and water productivity are two other criteria for assessing the impact of changing the date of cultivation on final biomass, as shown in the figure. Under irrigated cultivation conditions, it cannot be expected that crop yields will change significantly due to changes in planting dates because only the effect of air temperature in this regard can be investigated. The difference in temperature due to the delay in planting dates has led to a slight reduction in crop yields at 32 kg/ha, respectively. In the study area, the reduction in planting date has resulted in a 12 kg increase in yield per hectare.

The previous studies have shown that delays in rapeseed cultivation reduce the growth of vegetative growth plants, reduce yields of biomass plants, and reduce yields due to increased temperatures during the reproductive stage (Javidfar *et al.* 2001; Faraji *et al.* 2009; Honar *et al.* 2012). Selecting the planting period earlier increases water and nutrient uptake during the fall season, resulting in increased plant growth. Danaie *et al.* (2014) showed that planting date is one of the most important components of climate diversity in rapeseed cultivation, which has the greatest impact on yield production compared to other managerial scenarios. As a result, by choosing the optimum planting date, the most adaptation can be made between the growth process of the plant and the climatic conditions (Javidfar *et al.* 2001; Ozer 2003; Sinaki *et al.* 2007; Faraji *et al.* 2009; He *et al.* 2017; Chen *et al.* 2019).

Water productivity as an indicator of performance interference and water consumption can show an acceptable assessment of the impact of changing planting dates. According to this index, the 10-day decrease in planting date due to the decrease in the volume of water used and the optimal use of precipitation to complete the vegetative growth period has increased production per unit of allocated water. Furthermore, the increase in planting date has reduced water productivity. Tayyab *et al.* (2022) considered that increasing water productivity requires a paradigm shift in water policy and management. Therefore, two technical and political approaches should be considered simultaneously for sustainable development. Each of these approaches separately cannot provide the needs of farmers and consumers in optimal conditions.

4. CONCLUSIONS

Using optimization methods to develop a sustainable strategy of water distribution during the growing season is necessary for achieving the best performance in reducing water consumption. The results of optimal irrigation planning showed that the growth of rapeseed in the climatic zone of Henan province without water stress requires 9,390 m^3/ha of irrigation water, which with sustainable planning leads to the production of 1,408 kg/ha and water productivity of 0.15 kg/m^3. Planting date is one of the effective management parameters for increasing water productivity and effective use of rainfall. Therefore, the results of modeling estimate an average decrease of about 10% in the crop water requirement and an increase of 1% in water productivity due to a 10-day decrease in planting date compared to experiments. Rapeseed was usually incorporated in rotation with crops such as rice and cereals. Therefore, attention to the crop rotation and the possibility of changing and managing the time of planting and harvesting the first crop should be considered. Effective use of rainfall and deficit irrigation can be considered in daily planning to increase water productivity.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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