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Applications of land surface model to economic and environmental-friendly optimization of nitrogen fertilization and irrigation

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ABSTRACT

Land surface models (LSMs) have prominent advantages for exploring the best agricultural practices in terms of both economic and environmental benefits with regard to different climate scenarios. However, their applications to optimizing fertilization and irrigation have not been well discussed because of their relatively underdeveloped crop modules. We used a CLM5-Crop LSM to optimize fertilization and irrigation schedules that follow actual agricultural practices for the cultivation of maize and wheat, as well as to explore the most economic and environmental-friendly inputs of nitrogen fertilizer and irrigation (FI), in the North China Plain (NCP), which is a typical intensive farming area. The model used the indicators of crop yield, farm gross margin (FGM), nitrogen use efficiency (NUE), water use efficiency (WUE), and soil nitrogen leaching. The results showed that the total optimal FI inputs of FGM were the highest (230 $\pm$ 75.8 kg N ha^{-1} and 20 $\pm$ 44.7 mm for maize; 137.5 $\pm$ 25 kg N ha^{-1} and 362.5 $\pm$ 47.9 mm for wheat), followed by the FIs of yield, NUE, WUE, and soil nitrogen leaching. After multi-objective optimization, the optimal FIs were 230 $\pm$ 75.8 kg N ha^{-1} and 20 $\pm$ 44.7 mm for maize, and 137.5 $\pm$ 25 kg N ha^{-1} and 387.5 $\pm$ 85.4 mm for wheat. By comparing our model-based diagnostic results with the actual inputs of FIs in the NCP, we found excessive usage of nitrogen fertilizer and irrigation during the current cultivation period of maize and wheat. The scientific collocation of fertilizer and water resources should be seriously considered for economic and environmental benefits. Overall, the optimized inputs of the FIs were in reasonable ranges, as postulated by previous studies. This result hints at the potential applications of LSMs for guiding sustainable agricultural development.

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1. Introduction

Climate change and its manifestations, especially extreme weather events such as heat waves and drought, pose great threats to agriculture [1,2]. To mitigate the adverse effects of these events, fertilization and irrigation (FI) are now the two prevailing ways to preserve agricultural development. Irrigated cropland accounts for about 25% of global cropland [3], but its yield contribution rate can be up to 40% of global total production [3,4]. Nitrogen fertilizer accounts for 40%–60% of global yield increases [5]. However, the relentless pursuit of high yields and high economic income has led to frequent abuses of FI at the expense of the environment, resulting in multiple problems, such as high emissions of greenhouse gases [6], soil salinization, and groundwater overexploitation and pollution [7,8].

Today, agricultural development requires not only high crop productivity but also a healthy environment that can support agriculture sustainability [9]. Hence, both economic and environmental benefits should be considered in agricultural practices. The North China Plain (NCP) is one of the most populated and intensively farmed areas in China. Agriculture in the NCP has remarkable impacts on national food security and the economy. Many studies on fertilization and irrigation optimization have been conducted in this region to boost crop yields in order to meet rising demands for food and increase economic incomes [10–13]. Some studies have also focused on minimizing environmental costs by reducing N_2O emissions and nitrogen leaching [14–16] or improving the use efficiencies of nitrogen and water [17–19]. Although various individual indicators have shown promising results for economic and environmental objectives [19–22], attempts at synthetic optimization integrating the primary indicators of economic and environmental benefits have been insufficient [23–27]. Unlike optimizations with individual indicators, multi-objective optimizations are more complicated because making trade-offs between indicators is difficult if there are many indicators or indicators that have contradictory effects [28].

Recently, model-based analysis has been proven to be more efficient for studying the optimization of fertilization and irrigation management [29–32]. Such analysis can break through the limitations of large manpower inputs and long data acquisition cycles in traditional field experiments. Using crop models, various economic and environmental indicators with different fertilizer and irrigation treatments can be easily obtained and simultaneously assessed, thus facilitating optimizations with single or multiple objectives.

Generally, the optimal management of fertilization and irrigation is strongly associated with climate, which influences the status of crop growth, and consequently, the values of the economic and environmental indicators related to crops. Exploring reasonable inputs of fertilizers and irrigation under future climate scenarios and making timely adjustments to current fertilization and irrigation management may be critical to protecting crop yields, economic incomes, and agro-environments from the negative impacts of climate change [33]. However, the models most used in optimization studies are agricultural crop models, such as DASST [34], WOFOST [35], and APSIM [36], or agro-ecosystem models, such as DNDC [37] and WNMM [38]. Land surface models (LSMs) are rarely used because of their relatively underdeveloped crop modules. LSM can be easily embedded in an earth system model that includes atmospheric models to deliver the predicted climate directly and provides a prominent advantage in exploring the best management practices of fertilization and irrigation in future scenarios. However, the prospects of LSMs for optimizing fertilization and irrigation practices under current climate conditions have not been well discussed. Additionally, the fertilization and irrigation schedules in LSMs are simple and show wide discrepancies with actual practices [39,40], thus producing uncertainties in optimizing fertilizer and irrigation inputs while providing poor agricultural guidance.

The Community Land Model version 5 crop model (CLM5-Crop) is a state-of-the-art, open-source LSM that includes a newly developed crop model for simulating dynamic vegetation growth, soil hydrothermal processes, carbon and nitrogen cycling, and interactions between the land surface and atmosphere in different climate scenarios [39,41]. CLM5-Crop has more crop types and comprehensive crop-related processes, such as dynamic planting, fertilization, irrigation, nitrogen reabsorption, harvest stubble, and yield prediction [42,43], than do other LSMs and has proven effective in simulating crop yields, cropland GPP, and evapotranspiration [44–46]. However, the current fertilization and irrigation schedules in the CLM5-Crop model are different from the actual practices in the NCP. In particular, the irrigation amounts are calculated according to simulated soil moisture rather than external input data [47]. The irrigation amounts must be accurately manipulated for optimization, but the current irrigation schedule in CLM5-Crop cannot meet this requirement.

The overall goal of this study was to investigate the performance of CLM5-Crop for supporting the best fertilization and irrigation management practices under current climate conditions for different objectives. First, new fertilization and irrigation schedules that accord with the actual practices in the NCP and can be easily manipulated were designed and incorporated into CLM5-Crop. Second, this model was calibrated to ensure that the simulations of the variables used in this study were accurate. Third, the optimizations of fertilizer rates and irrigation amounts were conducted at three cropland sites in the NCP and with five individual indicators of economic and environmental benefits, as well as with the synthesis of these indicators. We intended to (a) provide appropriate inputs of fertilizer and irrigation for both economic and environmental benefits or achieve a trade-off between the two benefits for crop planting in the NCP, (b) compare the optimal results with actual FI inputs, and (c) assess and provide references about the capabilities of an LSM for guiding current and future agricultural practices.

2. Material and methods

2.1. Study area and observation data

The study was conducted at three cropland sites within the Chinese Ecological Research Network in the NCP (Fig. 1): Yucheng (YCA, 36.93°N, 116.56°E), Luancheng (LCA, 37.88°N, 114.68°E), and Shangqiu (SQA, 34.52°N, 115.58°E). They have temperate monsoon climates with perennial average temperatures/annual precipitations of 13.1 °C/582 mm, 12.2 °C/530 mm, and 13.9 °C/708 mm, respectively. The precipitations mainly occur in summer. Their soil types are saline moisture soil, meadow cinnamon soil, and moisture soil, respectively. The three sites include typical intensive and productive agro-ecosystems with mainly winter-wheat––summer-maize crop rotation. This study determined separate optimizations for the two crops.

At the three sites, meteorological data including air temperature, solar radiation, relative humidity, pressure, wind speed, and precipitation with a temporal resolution of 0.5–1 h were collected in 2006–2010 at Yucheng, 2006–2010 at Luancheng, and 2012–2017 at Shangqiu. An eddy covariance system with a fast response open-path CO_2/H_2O infrared gas analyzer (LI-Cor Inc., USA) was used to measure the flux data, including net ecosystem exchange (NEE), ecosystem respiration (Re), latent heat (LE), and sensible heat (H) at Yucheng in 2006–2010 and Luancheng in 2007–2013. The gross primary production (GPP) was postprocessed as the difference between Re and NEE at Yucheng, whereas the GPP data were not released at Luancheng. Moreover, the LE flux data at Luancheng were also absent in the current release [48]. The phenological development dates, crop yields, fertilization, and irrigation records including application time, frequency, and amount were documented in 2006–2010 at Yucheng, 2006–2010 at Luancheng, and 2006–2017 at Shangqiu. All the mentioned data can be obtained from the Chinese Ecological Research Network (http://www.cnern.org.cn).

2.2. Indicator selections and calculations

Five indicators for economic and environmental benefits were selected for optimization. Crop yield refers to the effects of irrigation and fertilizer on crop growth and is directly related to agricultural income. Farm gross margin (FGM) is the surplus income to sustain agricultural development and farmers' livelihoods [49]. These two indicators represent the economic benefits. Water use efficiency (WUE) and nitrogen use efficiency (NUE) reflect the conversion efficiency from water and nitrogen consumption, respectively, for crop yields. Nitrogen leaching reflects the soil quality related to water and fertilizer application rates [50]. These three indicators represent the environmental benefits.

Of the five indicators, crop yield and nitrogen leaching were directly simulated by the CLM5-Crop model. NUE is the ratio of crop yield to the nitrogen fertilizer rate. WUE is the ratio of gross primary production (GPP) to evapotranspiration (ET), which was also simulated. As expressed in Eq. (1), FGM is the difference between crop income and planting costs [51]:

$$\mathrm{FGM} = \sum_{S=1}^{S} \sum_{y=1}^{y} \frac{1}{(1+r)_y} A_s \left(p_s Y_{s,y} - p_n N_{s,y} - p_w W_{s,y} - C_s + S_s\right), \tag{Eq. 1}$$

where FGM is the farm gross margin in CNY ha^{-1}, r is the annual discount rate in percentage, s is the number of crop types, and y is years of crop growth. The FGM for summer maize and winter wheat were calculated separately, so for each crop, $s = 1$, $y = 1$, and r was ignored ($r = 0$). A_s is a planting area of 1 ha^{-1} in this study, p_s is the price of grain in CNY kg^{-1}, $Y_{s,y}$ is the yield in kg ha^{-1}, p_n is the price of fertilizer in CNY kg^{-1}, $N_{s,y}$ is the fertilizer rate in kg ha^{-1}, p_w is the price of water in CNY m^{-3}, $W_{s,y}$ is the irrigation amount in m^3

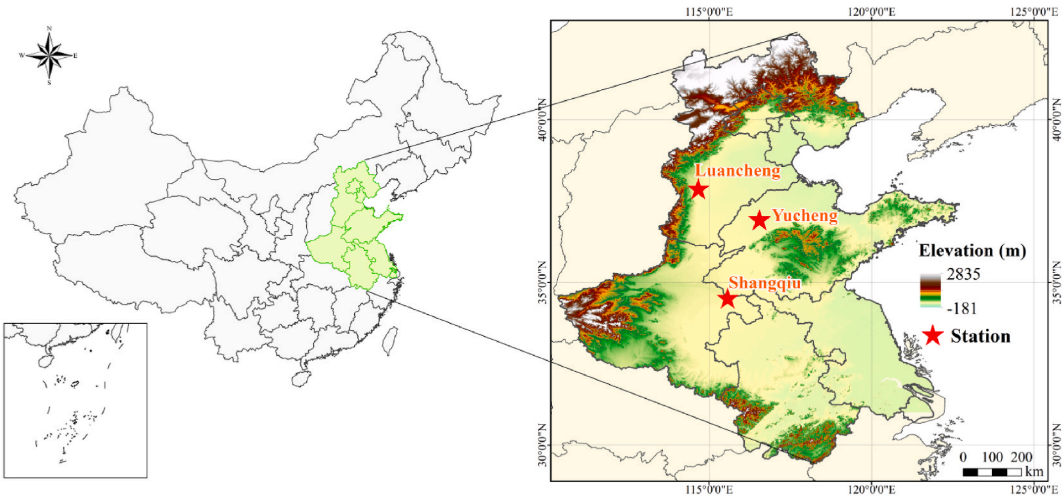

Fig. 1. Spatial locations of the study area and the cropland sites.

ha^{-1}, C_s represents other planting costs in CNY ha^{-1}, such as seed fees, pesticide fees, lease operation fees, and labor costs, and S_s is the planting subsidy in CNY ha^{-1}.

The grain prices, which were the average prices over the last five years, were obtained from a database of the Food and Agriculture Organization (http://www.fao.org/statistics/databases/). The price of nitrogen fertilizer, which was also the average over the last five years, was obtained from the China fertilizer network. The price of irrigated water was taken from Tang et al. [52]. Cost data were obtained from the yearbooks of National Agricultural Product Cost and Income (https://data.cnki.net/Trade/yearbook/). Information on planting subsidies was acquired from the National Ministry of Agriculture (http://www.moa.gov.cn/). The incomes and costs are listed in Table 1.

2.3. Model and introduction of new schedules

The CLM5-Crop model originated from the Agro-IBIS model [53] and gradually developed to supplement crop types, phenology, carbon–nitrogen allocation, and interactive crop management. The model can simulate the growth processes of maize (temperate and tropical), wheat (spring and winter plantings), soybean (temperate and tropical), rice, cotton, sugarcane, and other common rainfall and irrigated crop types [41,42].

Fertilization and irrigation processes are all included in the model. Nitrogen fertilizer is applied at the leaf emergence phase and continues over 20 days. The fertilizer rate is extracted from a global fertilizer map based on FAO statistics [42]. Irrigation occurs from 06:00 to 10:00 h, when the crop leaf area >0 and the simulated soil water content is below a specific threshold. The irrigation amount is the gap between the current and target soil water content [47]. The amounts, frequencies, and times to irrigate over a full growing season are uncertain. Descriptions of fertilization and irrigation algorithms can be found in the CLM5 technical manual [54].

The default fertilization and irrigation schedules of the CLM5-Crop model did not match actual practices in the NCP and thus hindered FI optimization. Hence, new schedules of fertilization and irrigation were proposed in this study. All the fertilization and irrigation records in 2006–2010 at Yucheng, 2006–2010 at Luancheng, and 2006–2017 at Shangqiu (http://www.cnern.org.cn), along with other related literature [20,55–60], were collected to extract the general rules of crop nitrogen and water requirements, as well as the amounts, frequencies, and times to fertilize and irrigate, in the NCP. In the new fertilization schedule, nitrogen fertilizer was applied twice during the sowing and jointing stages while the fertilizer proportions between the two applications were 3:7 for summer maize and 3:2 for winter wheat. The formulas are as follows.

First fertilization during the sowing stage:

$$fert = (manutro * 1000 + fertnitro * fertfrac)/fert\_counter \tag{Eq. 2}$$

Second fertilization during the jointing stage:

$$fert = (manutro * 1000 + fertnitro * (1 - fertfrac))/fert\_counter \tag{Eq. 3}$$

where *fert* is the fertilizer rate in g N $\mathrm{m}^{-2}\,\mathrm{s}^{-1}$, *manutro* is the manure constant of 0.002 kg N $\mathrm{m}^{-2}\,\mathrm{yr}^{-1}$, *fertnitro* is the industrial nitrogen fertilizer rate in g N $\mathrm{m}^{-2}\,\mathrm{yr}^{-1}$, and *fert_counter* is the total fertilization time in seconds. In the new schedule, *fert_counter* is 1 day multiplied by 86,400 s d^{-1} (1 d = 86,400 s) because 1 day is the common fertilization duration in practice, whereas *fert_counter* in the original schedule is 20 days multiplied by 86,400 s d^{-1} *fertfrac* is the allocated fertilizer proportions for the first application, which are 33% for summer maize and 60% for winter wheat.

Irrigation frequency and time depend on soil moisture before sowing, as shown in Fig. S1. If soil moisture is greater than 65% of the field capacity (FC) for summer maize [61], which will be irrigated once during the jointing to tasseling stages; if soil moisture is less than 65% of the FC, the maize will be irrigated twice during the pre-emergence and jointing to tasseling stages. For winter wheat, if soil moisture is greater than 60% of the FC [62], the wheat will be irrigated twice during the regreening and late jointing stages; if soil

Table 1
Statistics on the costs and incomes for wheat and maize planting.

Item	Crop type	Fee	Value	Unit
Cost	Wheat	Seeds	997.82	CNY ha^{-1}
		Pesticides	302.30	
		Lease operations	2460.6	
		Labor	5391.4	
		Total	**9152**	
	Maize	Seeds	837.05	CNY ha^{-1}
		Pesticides	244.98	
		Lease operations	2016.2	
		Labor	6829	
		Total	**9927**	
		Nitrogen fertilizers	3.90	CNY kg^{-1}
		Water	0.11	CNY m^{-3}
Income	Wheat	Grain prices	2.44	CNY kg^{-1}
		Subsidies	1650	CNY ha^{-1}
	Maize	Grain prices	2.02	CNY kg^{-1}
		Subsidies	1575	CNY ha^{-1}

moisture is less than 60% of the FC, the wheat will be irrigated twice during the wintering and early jointing stages. The watering proportions when irrigating twice are 1:1 for summer maize and 3:2 for winter wheat. The irrigation amounts were obtained from the external input data, which were easily changed to fit the requirements of the experiments.

2.4. Model experiment and execution

To obtain optimal usage, multiple sets of model experiments with different fertilizer and watering amounts were designed. The highest irrigation amount for a hectare is typically 337–675 mm. The average nitrogen fertilizer rate in the double-crop system of the NCP is 600 kg N ha^{-1} [63], and according to the collected data, fertilizer rates at the three sites can be up to 400 kg N ha^{-1} for one crop in a year. Therefore, we used the approximate mean values, 500 kg N ha^{-1} and 500 mm, as the highest fertilizer and irrigation amounts, respectively. The inputs started at zero and increased by increments of 50 kg N ha^{-1} and 50 mm, respectively. Irrigation amounts were numbered as I_0, I_{50}, …, I_{500}, and the fertilizer rates were numbered as F_0, F_{50}, …, F_{500}.

To run the CLM5-Crop model, meteorological data from the Yucheng, Luancheng, and Shangqiu sites, as mentioned in Section 2.1 were used as atmospheric forcing. Soil property information (Table S1) was collected from the China Soil Science Database (http://vdb3.soil.csdb.cn/) to substitute the default soil data of clay and sand percentages in the model because the accuracy of soil characteristics significantly affects simulations of soil-related processes. Crop phenological dates at the crucial stages, such as sowing, germination, jointing, heading for wheat, tasseling for maize, and harvesting, were used to regulate the model parameters related to the growing season and eliminate the disagreements between the simulated and actual crop growth periods.

Firstly, the model was spun up to reach equilibrium status and obtain the initial file. Secondly, the model was supposed to be calibrated before the model experiment to guarantee the simulation accuracies of related variables (GPP, ET, yield, and soil nitrogen leaching amount) used in the indicator calculations. However, there was no soil nitrogen leaching observed at the three sites (Table S2). As a result, this calibration was neglected. Observations of ET were also absent; therefore, the calibration of ET was substituted with latent heat flux (LE) in this study because LE is the energy required for the evapotranspiration process [54]. Because of the low-quality and absence of some meteorological data at the Luancheng and Shangqiu sites, the data from 2006 to 2010 at Yucheng, 2007–2008 at Luancheng, and 2014–2017 at Shangqiu were used in the FI optimization study. Only the Yucheng site had the flux observations of GPP and LE (the time scale was 0.5 h), so the calibrations were conducted with the data of Yucheng for 2008–2010. The calibration of crop yield was also conducted using the data of Yucheng for 2008–2010, Luancheng for 2007, and Shangqiu for 2014 (Table S2).

The calibrated parameters include the maximum LAI constraint ($L_{\max}$) to prevent an exaggerated overestimation of LAI and control the onset of the grain filling stage, the initial allocation coefficient of leaf (a^i_{leaf}), which affects the carbon allocation ratio of leaves, and the reduced coefficient of stem allocation (d^{stem}_{alloc}), which influences the carbon allocation of stems and fruit in the grain filling stage [54]. The three parameters are used to optimize the simulation of LAI and yield because LAI is a key parameter influencing the carbon cycle, as well as the energy and water balance processes, thereby also influencing the accuracies of simulations of GPP and energy fluxes [64]. However, the observed LAI and yield values are discrete and the observation amounts are limited; therefore, the GPP observations were used in the calibration, since GPP is directly related to LAI formation and is the foundation of yield. $L_{\max}$ was adjusted to field observations of the three sites while the other two parameters were calibrated simultaneously by a simulated annealing algorithm [65] targeting GPP and LE. The coefficient of determination (R^2) and root mean square error (RMSE) were used to evaluate the accuracies of the calibrations of GPP and LE. Calibrations were conducted separately at each site but averaged from all sites to produce the final calibrated values, which are listed in Table S3. Afterward, the remaining data were used for the optimization experiment (Table S2). Notably, the atmospheric data of Luancheng for 2009–2010 led to huge simulation biases in GPP and LE, as described in the literature [66], and were therefore excluded.

2.5. Determinations of optimal fertilizer and irrigation inputs

Two methods were used to determine the optimal fertilizer and irrigation inputs separately with individual and multiple indicators. For individual indicators, the marginal effect method was adopted [67]. It uses the first derivative (denoted as y') and second derivative (denoted as y'') of the indicator values to identify the inflection points and find the corresponding fertilizer and irrigation amounts. The four possible cases are listed below.

1) $y' < 0$: indicator values keep decreasing. In this case, the initial fertilizer or irrigation amount is the optimal one that can assure the highest indicator value.
2) $y' > 0$: indicator values keep increasing. In this case, y'' is needed. The appropriate fertilizer or irrigation amount is when y'' is minimized.
3) From $y' < 0$ to $y' > 0$: indicator values decrease, then increase. In this case, y'' is needed. The appropriate fertilizer or irrigation amount is when y'' is minimized at $y' > 0$.
4) From $y' > 0$ to $y' < 0$: indicator values increase, then decrease. In this case, the optimal fertilizer or irrigation amount is when y' turns from positive to negative.

The best inputs of fertilizer and irrigation for the indicator of soil nitrogen leaching should be the ones that produce the lowest leached amounts.

For the synthesis of multiple indicators, a comprehensive scoring method was adopted. As shown in Fig. 2, indicator values with different fertilizer and irrigation combinations have been normalized to obtain new values, which have been used as the scores for different combinations. Then, the combination with the maximum normalized value is considered the optimal case. Because there are five indicators, there are five corresponding optimal cases. The scores from all the indicators corresponding to one optimal case have been added together and used as the comprehensive score. According to Wei et al. [49], the economic and environmental components are equally important. Thus, the five indicators are given the same weight. Finally, the combination with the highest comprehensive score is identified as the optimal fertilizer and irrigation inputs for a crop.

After the optimization with the individual and multiple indicators, the actual fertilizer, and irrigation amounts at the three sites were used to make the comparisons.

3. Results

3.1. The results of model calibration

The model calibration results of GPP and LE for summer maize and winter wheat are exhibited in Figs. S2 and S3. Overall, the calibration effects are satisfactory. R^2 of GPP for maize and LE for wheat are close to or above 0.9, which implies accurate estimations. The determination coefficients of the other calibration results are also high with values above 0.8, except for the calibrated LE for maize in 2010. Although the calibrated R^2 of GPP for winter wheat is high, there are still some simulated outliers when the observed GPP is below 1.5E-4 gC m^{-2} s^{-1}, which suggests that the model may have poor capability for estimating GPP during the early or late growing stage when the photosynthesis of winter wheat is weak. Overall, the adjusted CLM5-Crop model has been able to simulate GPP and LE with relatively high accuracy, as well as provide reasonable indicator values for the optimization of the fertilizer and irrigation inputs.

The calibration results for yield given in Table S4 show that, in most cases, the biases between the simulated and observed yields of summer maize and winter wheat vary within the range of 100–300 kg ha^{-1}. The smallest bias is 50 kg ha^{-1}, which had been obtained in the calibration for summer maize in Luancheng. The biggest bias is 1167 kg ha^{-1}, which is 10.5% of the actual maize yield in Shangqiu. Despite one significant error, the overall simulated yields in the calibrations are close to the observed values. Hence, the adjusted CLM5-Crop model has been able to provide credible results related to crop yield in the optimizing process.

3.2. Optimal fertilizer and irrigation inputs of individual indicators

3.2.1. Optimal FI inputs of yield

The relationships of the simulated yields with the different inputs of fertilizer and irrigation are shown in Fig. 3. The yields are positively related and increase with the fertilizer rates. In the CLM5-Crop model, nitrogen is an important factor controlling plant photosynthesis rates and the assimilated carbon amounts [54]. During photosynthesis, the maximum rate of carboxylation (V_{cmax}) determines the maximum amount of fixed CO_2 by leaves per unit area and per unit time. Also, V_{cmax} is positively related to leaf

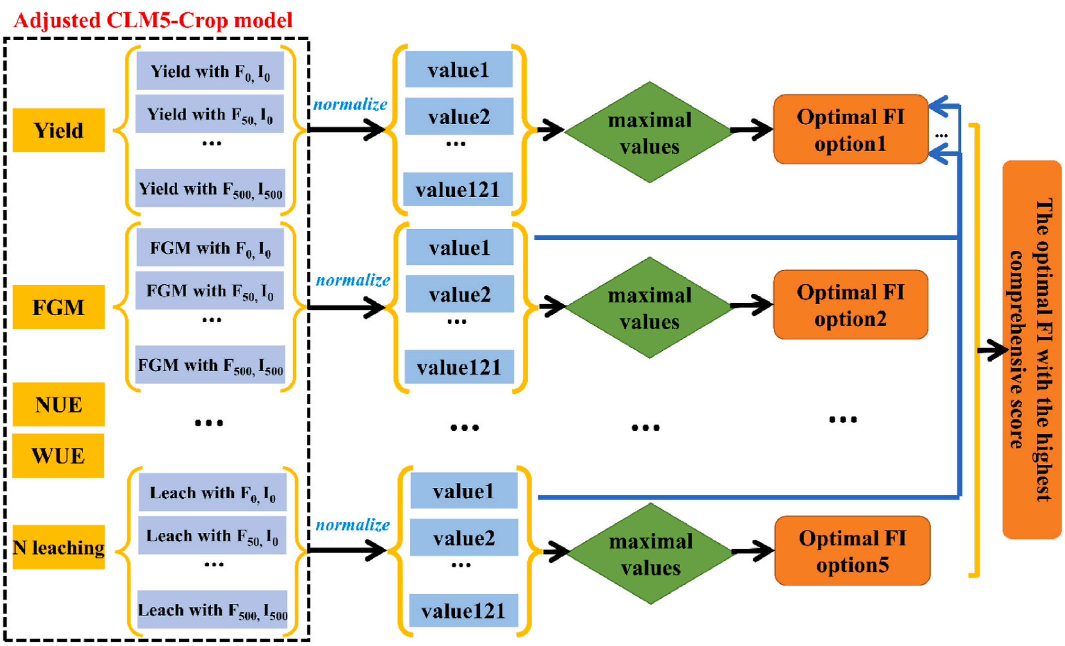

Fig. 2. The flowchart of comprehensive scoring method.

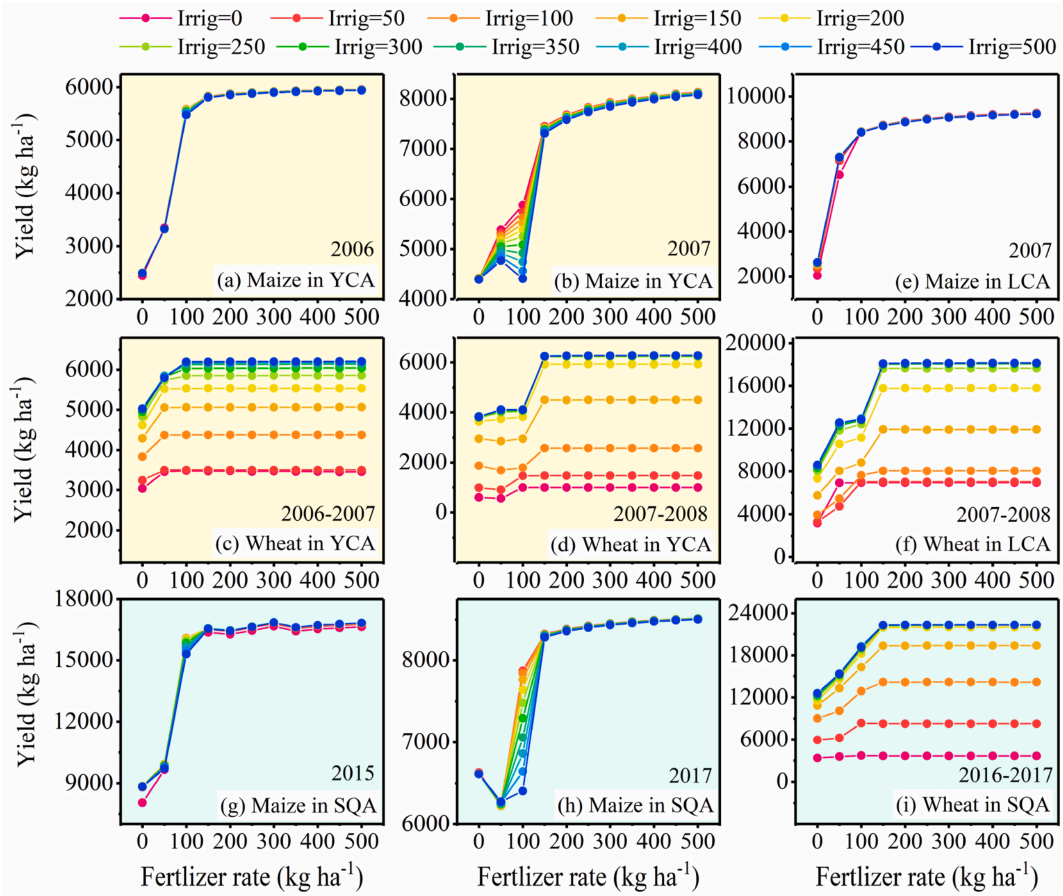

Fig. 3. The relationships of the simulated yields with different fertilizer and irrigation inputs in Yucheng for maize during (a) 2006 and (b) 2007, and for wheat during (c) 2006–2007 and (d) 2007–2008; in Luancheng for maize during (e) 2008 and wheat during (f) 2007–2008; in Shangqiu for maize during (g) 2015 and (h) 2017, and for wheat during (i) 2016–2017.

nitrogen content [66,68]. High nitrogen inputs can promote the carbon assimilation capacities of plants, produce more photosynthates, and finally improve yields [42,44]. However, the influence of nitrogen on V_{cmax} does not increase linearly but gradually levels off [69,70]. This result is in accordance with previous studies that have indicated two distinct stages, yield increase and yield stabilization or reduction, when correlating nitrogen inputs and crop yields [11,71,72]. Yield increases rapidly when the fertilizer rate increases from F_0 to F_{100} (or F_{150}), after which the margins are small.

The relationships between yield and irrigation are crop-specific. On the one hand, irrigation barely affects the yields of summer maize. On the other hand, it improves the yields of wheat. Particularly, when the watering amount increases from I_0 to I_{200}, the increase in the wheat yield is large, then the increase becomes insignificant. It can be deduced that the irrigation requirements of winter

Table 2
The optimal FI inputs of each indicator for maize and wheat at the three sites.

Input	Site	Summer maize						Winter wheat					
		Year	Yield	FGM	NUE	WUE	Leaching	Year	Yield	FGM	NUE	WUE	Leaching
Fertilizer	YCA	2006	F_{150}	F_{150}	F_{50}	F_{100}	F_0	2006–2007	F_{350}	F_{100}	F_{50}	F_{200}	F_0
		2007	F_{200}	F_{300}	F_{50}	F_{100}	F_0	2007–2008	F_{200}	F_{150}	F_{50}	F_{50}	F_0
	LCA	2008	F_{150}	F_{250}	F_{50}	F_{100}	–	2007–2008	F_{200}	F_{150}	F_{50}	F_{50}	–
	SQA	2015	F_{150}	F_{300}	F_{50}	F_0	F_0	2016–2017	F_{200}	F_{150}	F_{50}	F_{150}	F_0
		2017	F_{150}	F_{150}	F_{50}	F_{100}	F_0						
Irrigation	YCA	2006	I_0	I_0	I_{450}	I_0	I_0	2006–2007	I_{200}	I_{400}	I_{450}	I_0	I_0
		2007	I_0	I_0	I_{50}	I_0	I_0	2007–2008	I_{250}	I_{400}	I_{250}	I_{200}	I_0
	LCA	2008	I_0	I_0	I_{200}	I_0	–	2007–2008	I_{250}	I_{350}	I_{250}	I_{150}	–
	SQA	2015	I_{150}	I_{100}	I_{100}	I_0	I_0	2016–2017	I_{250}	I_{300}	I_{150}	I_{200}	I_0
		2017	I_0	I_0	I_0	I_0	I_0						

Note: " - " means data not available. "Leaching" represents soil nitrogen leaching.

wheat were higher than that of summer maize. This result may be ascribed to precipitation supply and crop type. About 70% of the precipitation in the NCP occurs from July to September [11], so many researchers have suggested that the soil water supply was already sufficient for plant growth and that there had been no need to irrigate during the maize growing season [25,73,74]. However, precipitation during the growing seasons of winter wheat is scarce and can barely meet the crop water requirements. Therefore, extra irrigation is needed. Furthermore, wheat is a C3 plant, whereas maize is a C4 plant. C4 plant has a stronger growth capacity, a higher carbon dioxide assimilation rate, and lower water requirements [75]. Consequently, the required irrigation amounts for summer maize are lower than those for winter wheat.

According to the derivatives of the yield results for maize, F_{150} was the optimal fertilizer rate at the three sites, except that F_{200} was the optimum during 2007 in Yucheng while the optimal irrigation amounts were I_0 in most cases, except that I_{150} was the optimum during 2015 in Shangqiu. For wheat, the optimal fertilizer rate and irrigation amount were F_{200} and I_{250}, respectively, except that F_{350} and I_{200} were the optimums during 2006–2007 in Yucheng (Table 2).

3.2.2. Optimal FI inputs of FGM

Fig. 4 shows that the relationship between FGM and the fertilizer rates is first positive, then negative after FGM reaches the maximums of 2836.9 and 6496.4 CNY ha^{-1} in Yucheng, 8883.1 CNY ha^{-1} in Luancheng, 24396.7 and 7869 CNY ha^{-1} in Shangqiu for maize while they are 6714.7 and 6838.5 CNY ha^{-1} in Yucheng, 35569.9 CNY ha^{-1} in Luancheng, and 45899.7 CNY ha^{-1} in Shangqiu for wheat. There are rapid increases in FGM when the fertilizer rates increase from F_0 to F_{100} (or F_{150}), after which they decrease slowly. The relationship between FGM and irrigation is crop-specific. FGM is negatively related to the watering amounts for maize and the differences between each FGM are small. However, FGM is positively related to irrigation for wheat. The differences are large when irrigation is below I_{250} but insignificant above I_{250}.

Although FGM is highly associated with yield, the optimal FIs of FGM show some differences with the results of yield. Higher yields can be obtained with higher FI inputs, as shown in Fig. 4. However, high crop yields do not necessarily mean high profits, since economic performance depends on the balance between incomes and costs [76]. The excess inputs of FI greatly increase the planting

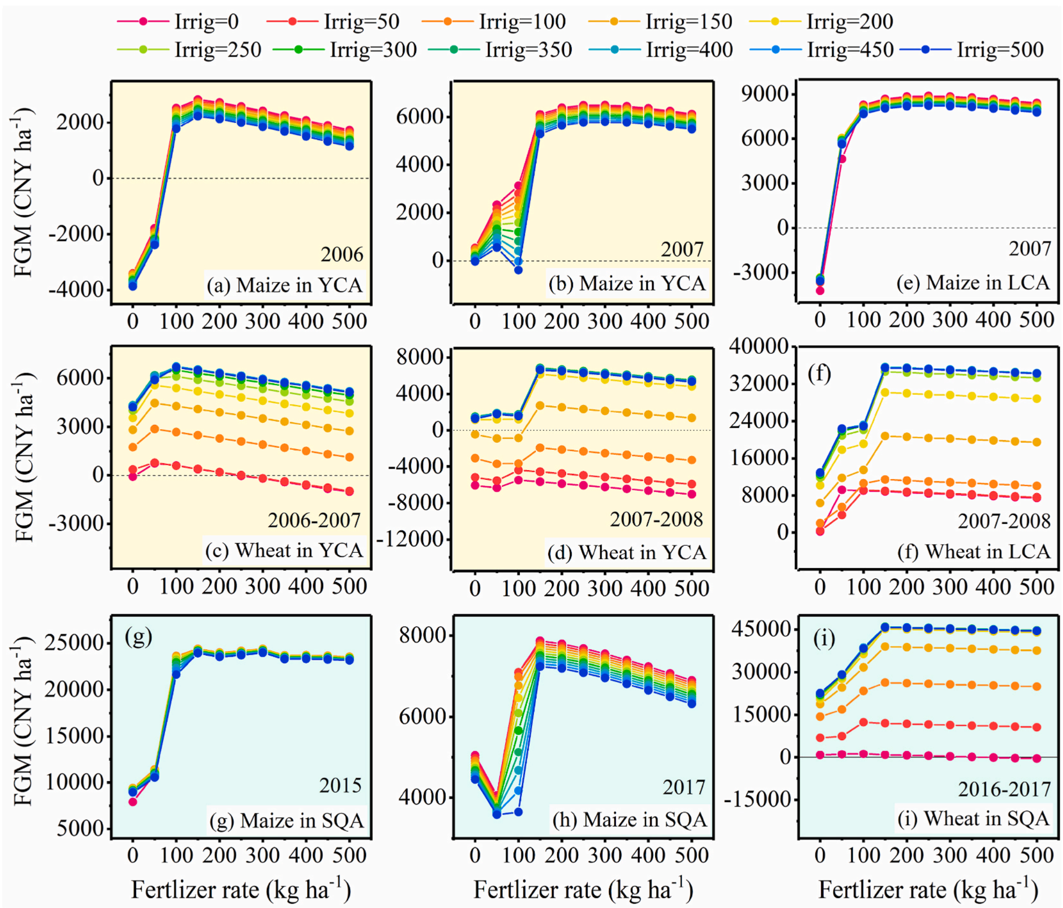

Fig. 4. The relationships of the simulated farm gross margin (FGM) with different fertilizer and irrigation inputs during (a) 2006 and (b) 2007, and for wheat during (c) 2006–2007 and (d) 2007–2008; in Luancheng for maize during (e) 2008 and wheat during (f) 2007–2008; in Shangqiu for maize during (g) 2015 and (h) 2017, and for wheat during (i) 2016–2017.

costs. Because the margin of yield gradually decreases, the margin of income becomes less than that of cost. Consequently, FGM constantly decreases.

According to the derivatives of the FGM results for maize, the optimal fertilizer rates were F_{150} in Shangqiu and Yucheng during 2006 but F_{250} in Luancheng and F_{300} in Yucheng during 2007. The optimal irrigation amounts were I_0 in most cases, except for I_{100} in Shangqiu during 2015. For wheat, the optimal fertilizer rate was F_{150}, except for F_{100} in Yucheng during 2006–2007 while the optimal irrigation amounts were I_{400}, I_{350}, and I_{300} in Yucheng, Luancheng, and Shangqiu, respectively (Table 2).

3.2.3. Optimal FI inputs of NUE

The simulated results show that NUE has negative relationships with fertilizer rates for both maize and wheat at the three sites (Fig. 5). The optimal fertilizer rate is F_{50} and NUE varies from about 176 in Shangqiu during 2015 to about 66 in Yucheng during 2006 for maize but varies from about 250 in Shangqiu to 11.1 (the lowest of all) in Yucheng during 2007–2008 for wheat. These results may be attributed to the disproportionate increase between fertilizer rate and yield. In the experiment, the fertilizer rate uniformly increases with the interval of 50 kg N ha^{-1} while the margin of yield declines. Therefore, the input (fertilizer) - output (yield) ratio is more likely to be high with low fertilizer rates. This finding accords with some results of other FI experiments, such as those of Xin and Tao [25], Zhu et al. [77], Dai et al. [78], and Si et al. [79].

The influences of irrigation on NUE are quite different for the two crops. On the one hand, irrigation barely affects NUE for summer maize. However, when it does so, it is negative, as can be seen in the result for Yucheng during 2007 with the fertilizer rates of F_{100} and F_{150}. On the other hand, irrigation positively improves NUE for winter wheat but is apparent only when the watering amount is below I_{250}. Unlike the relatively identical optimal irrigation of yield and FGM, the optimum irrigation amounts of NUE are more diverse across sites. According to the derivatives of the NUE results, the optimized irrigation amounts for maize are: I_{450} and I_{50} during 2006 and 2007, respectively, in Yucheng; I_{200} during 2008 in Luancheng; I_{150} and I_0 during 2015 and 2017, respectively, in Shangqiu. For

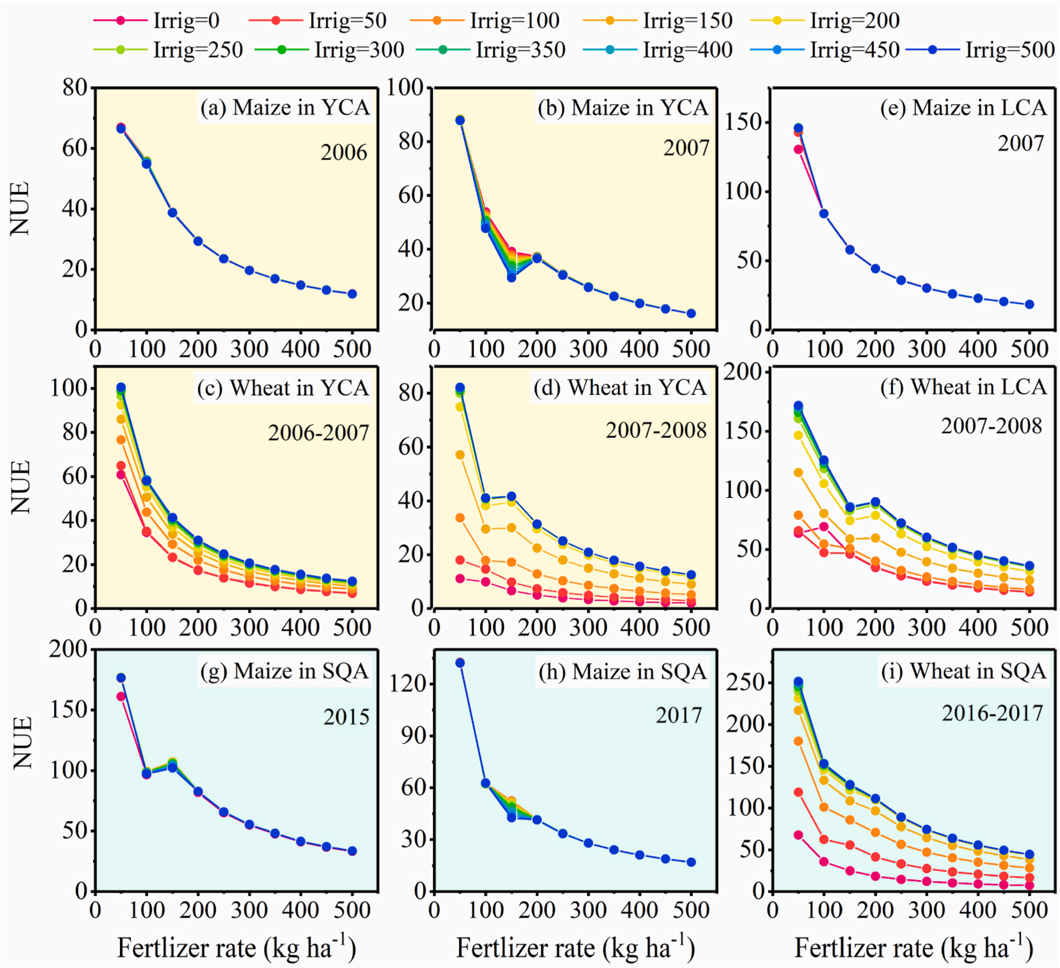

Fig. 5. The relationships of the simulated nitrogen use efficiency (NUE) with different fertilizer and irrigation inputs in Yucheng for maize during (a) 2006 and (b) 2007, and for wheat during (c) 2006–2007 and (d) 2007–2008; in Luancheng for maize during (e) 2008 and wheat during (f) 2007–2008; in Shangqiu for maize during (g) 2015 and (h) 2017, and for wheat during (i) 2016–2017.

wheat, the optimized irrigation amounts are: I_{450} and I_{250} during 2006–2007 and 2007–2008, respectively, in Yucheng; I_{250} during 2007–2008 in Luancheng; I_{150} during 2016–2017 in Shangqiu.

It is worth noting that the average optimal irrigation requirement of NUE is higher than the optimal yield (Table 2), which may be due to low fertilizer inputs inducing nitrogen stress in plants and causing yield reductions. To compensate for the negative effects of insufficient nitrogen fertilizer on plant growth, more irrigation is required to improve yield for a higher NUE.

3.2.4. Optimal FI inputs of WUE

The simulated WUE results (Fig. 6) show that for maize, the relationship between WUE and fertilizer inputs exhibits two patterns. High fertilizer rates, such as F_0–F_{200}, improve WUE, but under some conditions, actually reduce it. For example, when the watering amount is I_0, WUE decreases from 2.723 to 2.699 with the increased fertilizer input during 2015 in Shangqiu (Fig. 6(g)). For wheat, WUE is positively associated with fertilizer input. However, the increases in WUE are most apparent when the fertilizer rate ranges from F_0 to F_{50} (F_{100} in Shangqiu), after which more fertilizer cannot enhance WUE but even lowers it. WUE during 2006–2007 in Yucheng (Fig. 6(c)) is exceptional, as the changing trend is uncertain and the differences between the WUEs with different fertilizer rates are very small.

The relationships between WUE and irrigation are complicated. First, watering first decreases WUE, then slightly increases it, as seen in Yucheng and Shangqiu for maize, as well as in Yucheng for wheat during 2006–2007. However, in this case, the characteristics of the decreases in WUE vary from site to site. For example, in Yucheng during 2007 for maize, the decreases after irrigation exceeding I_0 could barely be distinguished from 3.243 with F_0I_{50} to 3.236 with F_0I_{500} while in Shangqiu and Yucheng for wheat, the decreases are distinct when irrigation ranges from I_0 to I_{150}. Second, irrigation first enhances WUE significantly, especially when it increases from I_0 to I_{200}, after which additional irrigation slightly decreases WUE, as seen in Luancheng, Shangqiu, and Yucheng during 2007–2008. Third, WUE decreases continuously as irrigation increases, as seen in Luancheng for maize.

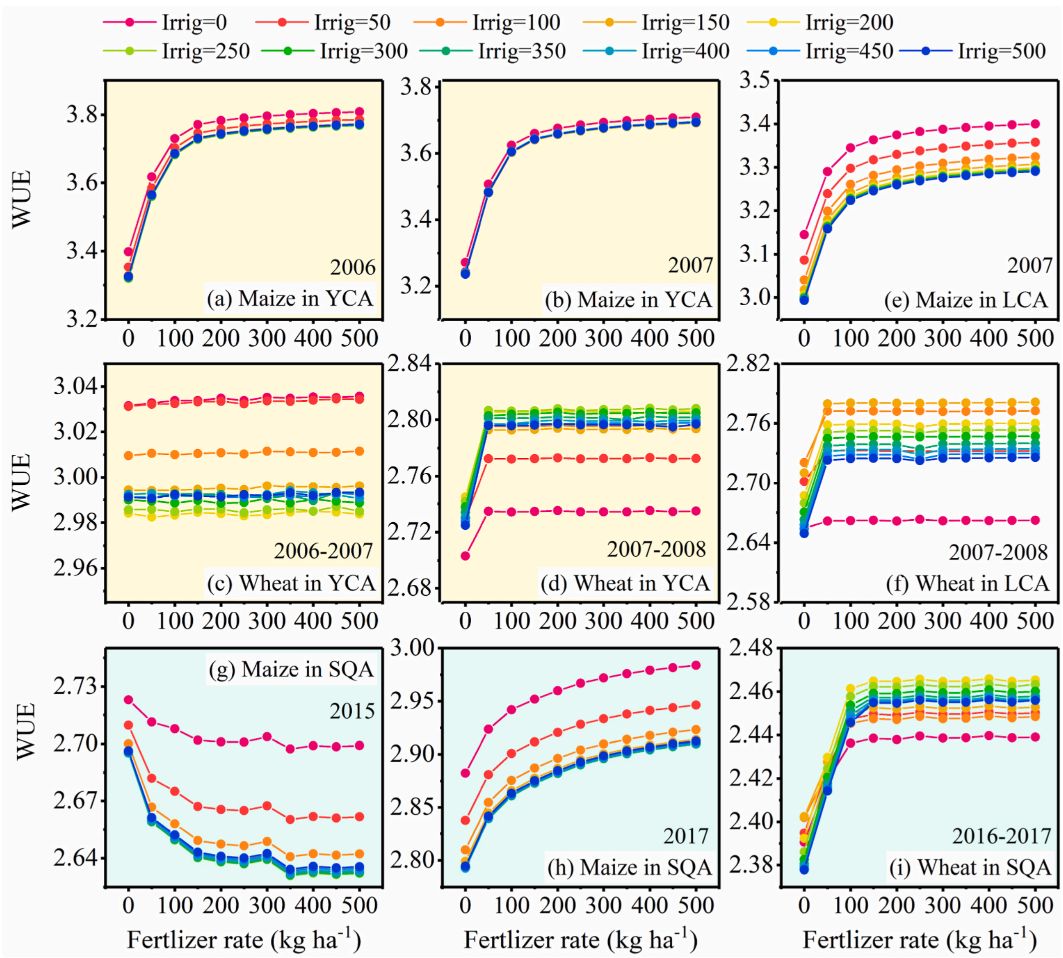

Fig. 6. Simulated water use efficiency (WUE) with different fertilizer and irrigation inputs in Yucheng for maize during (a) 2006 and (b) 2007, and for wheat during (c) 2006–2007 and (d) 2007–2008; in Luancheng for maize during (e) 2008 and wheat during (f) 2007–2008; in Shangqiu for maize during (g) 2015 and (h) 2017, and for wheat during (i) 2016–2017.

According to the derivatives of the results for WUE, the optimal fertilizer rate for maize is F_{100}, except for the optimum, which is F_0 in Shangqiu during 2015. The optimal irrigation amount is I_0. For wheat, the optimal fertilizer rates are F_{200} in Yucheng during 2006–2007, F_{50} in Yucheng and Luancheng during 2007–2008, and F_{150} in Shangqiu. The optimal irrigation amounts are I_{200} in Yucheng and Shangqiu during 2007–2008, I_0 in Yucheng during 2006–2007, and I_{150} in Luancheng (Table 2).

Compared with the optimal FIs of the previous indicators, the requirements of WUE to irrigate are the lowest and the fertilizer rates are also much lower than those of yield and FGM. In this study, WUE is the ratio of GPP to ET. ET mainly consists of ground evaporation and plant transpiration. Irrigation can enhance ground evaporation, especially when the water content in the soil is more than the field capacity and plant uptake. Irrigation can also mitigate water stress in plants by facilitating transpiration and promoting GPP, of which higher values further contribute to larger leaf areas, thus improving total transpiration. Therefore, the optimized irrigation amount of WUE should not be too high in case the denominator, namely ET, is large because such a high amount would result in low WUE even while meeting the water requirements of the crops. The optimal fertilizer rates of WUE should be determined by the trade-off between a high GPP as the numerator and low plant transpiration caused by large leaf areas as the denominator.

3.2.5. Optimal FI inputs of soil nitrogen leaching

As shown in Fig. 7, the annual leached amount of soil nitrogen is positively related to fertilizer input. When the fertilizer rate exceeds F_{200}, the leached nitrogen rapidly increases to about 420–450 kg ha^{-1} in Yucheng and about 270–350 kg ha^{-1} in Shangqiu for maize, and about 100–350 kg ha^{-1} in Yucheng and about 390 kg ha^{-1} in Shangqiu for wheat.

Increased irrigation also enhances nitrogen leaching but to different degrees. For maize, the margins of the leached amounts are relatively steady (Fig. 7(a), (b), (e), and (f)). For the winter wheat in Yucheng (Fig. 7(c) and (d)), the margins are obvious only when irrigation is above I_{200} (the differences between each leached nitrogen line are large). The result for wheat in Shangqiu is distinctive (Fig. 7(g)). When the fertilizer rate is smaller than F_{300}, it seems that higher irrigation would weaken nitrogen leaching. When the fertilizer rate exceeds F_{300}, the increased irrigation varying from I_0 to I_{200} would first reduce the leached nitrogen, then increase it.

Generally, crops cannot uptake nitrogen after reaching nitrogen saturation [80]. The excess nitrogen is lost through leakage and runoff [63,81]. Therefore, the amount of soil nitrogen leaching can also be seen as a symbol of crop nitrogen uptake efficiency. Lower

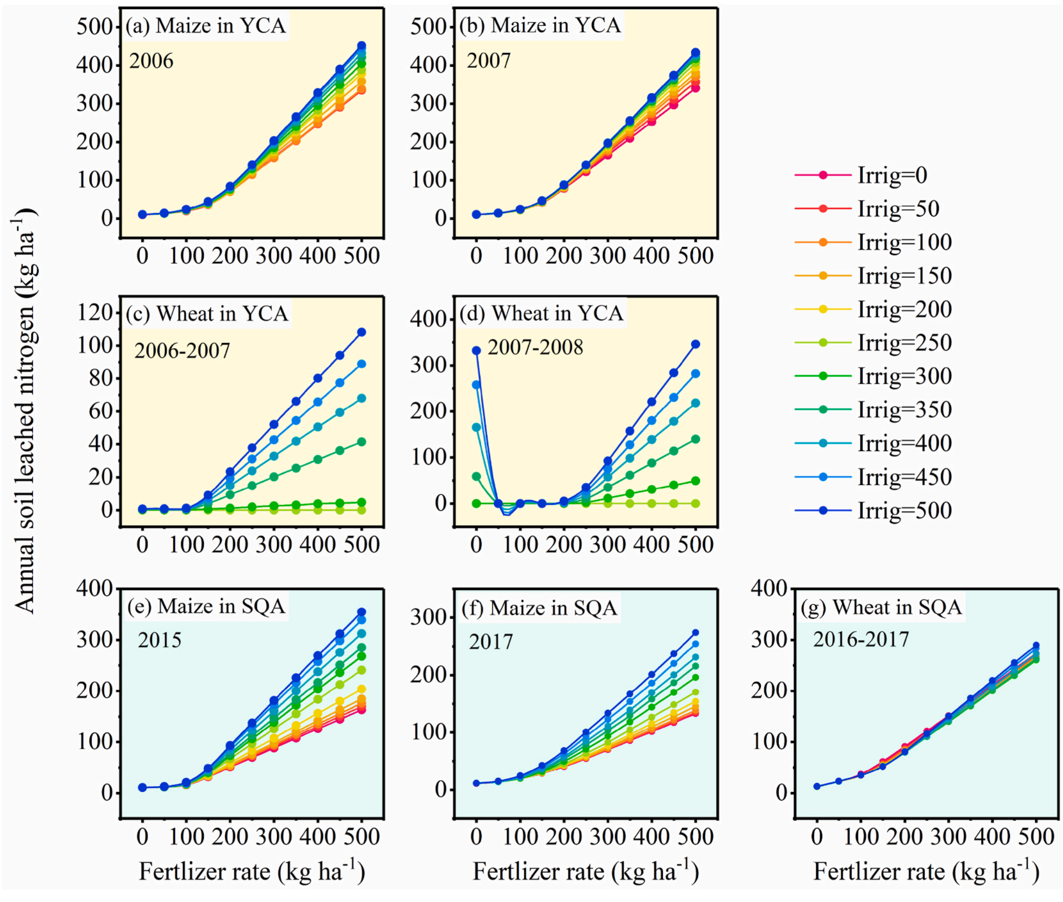

Fig. 7. The relationships of the simulated amounts of soil nitrogen leaching with different fertilizer and irrigation inputs in Yucheng for maize during (a) 2006 and (b) 2007, and for wheat during (c) 2006–2007 and (d) 2007–2008; in Shangqiu for maize during (e) 2015 and (f) 2017, and for wheat during (g) 2016–2017. The results for LCA were omitted because of no soil nitrogen leaching in our experiments.

amounts of leached nitrogen result in higher NUE. In the model's algorithm, the amount of soil nitrogen leaching in CLM5 is associated with the inorganic nitrogen concentration in the soil solution and soil runoff rate [50]. The nitrogen content in the soil solution increases with fertilizer input. The soil runoff increases with irrigation. When the soil water content after irrigation exceeds the field capacity, the excess water and the nitrogen contained will move downward by the force of gravity. If the soil solution flows out of the crop root zone, then nitrogen cannot be absorbed by the crops and leaching occurs. Hence, the optimal fertilizer and irrigation inputs should be zero to minimize soil nitrogen leaching, which is also the result obtained by this study (Table 2).

3.3. Optimal fertilizer and irrigation inputs with multiple indicators

The comprehensive scoring results for maize (Table 3) show that the best fertilizer and irrigation combinations are all obtained when the FGM is well guaranteed (the score is 1). However, appropriate amounts vary from site to site. The optimal FIs are F_{150} with I_0 in Yucheng during 2006 and Shangqiu during 2017, F_{300} with I_0 in Yucheng during 2007, F_{250} with I_0 in Luancheng, and F_{300} with I_{100} in Shangqiu during 2015. With such combinations of the maximal FGM, the goals of high yield and WUE are warranted (the scores of the yields are all above 0.9 or equal to 1 and the scores of WUE in Yucheng and Luancheng exceed 0.9) and the degrees of soil nitrogen leaching are acceptable (the scores range from 0.493 to 0.922). In contrast, NUE has less satisfactory results, such as in Yucheng during 2007, and in Luancheng and Shangqiu during 2015, of which the scores are 0.138, 0.157, and 0.153, respectively.

The second-best FI combinations are obtained with different maximal indicators. For example, in Yucheng, the combinations when the score of NUE is 1 are superior, of which the total scores are 3.044 and 3.046. At the other two sites, the combinations in which the score of yield equals 1 are better. Interestingly, the FI combination (F_{500}, I_0) with maximal yield and WUE is the same at all three sites, except in Shangqiu during 2015, because the effects of FI on the changing characteristics of both yield and WUE of maize are similar (Figs. 3 and 6). This combination is only good at assuring yield, FGM, and WUE but jeopardizes NUE and increases nitrogen leaching because of the highest fertilizer rate (F_{500}).

The comprehensive scoring results for wheat (Table 4) suggest that the superior fertilizer and irrigation combinations are also obtained when the score of FGM is 1, such as in Yucheng during 2007–2008 and at the other two sites. The appropriate fertilizer rate is F_{150} with varying irrigation amounts from I_{300} to I_{400}. The scores of WUE are about 0.4, but those of the other indicators can be greater than 0.8 or up to 0.9, which implies that the FI inputs with the optimal FGM are effective for balancing economic and environmental benefits. However, the comprehensive scoring result in Yucheng during 2006–2007 is exceptional. The superior FI combination (fertilizer rate of F_{100} and irrigation amount of I_{500}) is obtained when the score of yield is 1. In this case, the scores of FGM and soil nitrogen leaching are also equal or close to 1, whereas the scores of NUE and WUE are insufficient at 0.517 and 0.63, respectively. The second-best FI combinations for wheat are mostly obtained when WUE is the highest, except in Yucheng during 2006–2007. The corresponding total scores are 3.87, 2.905, and 3.265. With the second-best combinations, good yield, FGM, WUE, and sometimes, nitrogen leaching can be achieved, but NUE is low because of the high fertilizer rates above F_{400}.

Table 3

The comprehensive scores of different FI combinations for maize at the three sites in different years.

Site	Combination	Yield	FGM	NUE	WUE	Leaching	Total
YCA	2006						
	F_{500}, I_{0} (Yield & WUE)	1.000	0.822	0.000	1.000	0.000	2.822
	F_{150}, I_{0} (FGM)	**0.965**	**1.000**	**0.490**	**0.908**	**0.922**	**4.285**
	F_{50}, I_{0} (NUE)	0.258	0.261	1.000	0.533	0.992	3.044
	F_{0}, I_{0} (Leach)	0.000	0.000	–	0.000	1.000	1.000
	2007						
	F_{500}, I_{0} (Yield & WUE)	1.000	0.937	0.000	1.000	0.000	2.937
	F_{300}, I_{0} (FGM)	**0.946**	**1.000**	**0.138**	**0.963**	**0.529**	**3.576**
	F_{50}, I_{50} (NUE)	0.244	0.276	1.000	0.536	0.990	3.046
	F_{0}, I_{0} (Leach)	0.000	0.000	–	0.000	1.000	1.000
LCA	2008						
	F_{500}, I_{0} (Yield & WUE)	1.000	0.964	0.000	1.000	–	2.964
	F_{250}, I_{0} (FGM)	**0.966**	**1.000**	**0.157**	**0.929**	**-**	**3.052**
	F_{50}, I_{0} (NUE)	0.620	0.675	1.000	0.569	–	2.864
SQA	2015						
	F_{300}, I_{200} (Yield)	1.000	1.000	0.153	0.129	0.497	2.779
	F_{300}, I_{100} (FGM)	**1.000**	**1.000**	**0.153**	**0.133**	**0.493**	**2.779**
	F_{50}, I_{100} (NUE)	0.136	0.133	1.000	0.439	0.991	2.699
	F_{0}, I_{0} (WUE & Leach)	0.000	0.000	–	1.000	1.000	2.000
	2017						
	F_{500}, I_{0} (Yield & WUE)	1.000	0.745	0.000	1.000	0.000	2.745
	F_{150}, I_{0} (FGM)	**0.915**	**1.000**	**0.305**	**0.684**	**0.858**	**3.762**
	F_{50}, I_{0} (NUE)	0.000	0.000	1.000	0.405	0.977	2.382
	F_{0}, I_{0} (Leach)	0.172	0.258	–	0.000	1.000	1.430

Note: the subscript of each FI combination indicates the most obvious benefit. " - " means data not available. "Leaching" represents soil nitrogen leaching.

Table 4
Comprehensive scores of different FI combinations for wheat at the three sites in different years.

Site	Combination	Yield	FGM	NUE	WUE	Leaching	Total
YCA	2006–2007						
	F_{100}, I_{500} (Yield)	**1.000**	**1.000**	**0.517**	**0.630**	**0.996**	**4.143**
	F_{50}, I_{350} (FGM)	0.744	1.000	1.000	0.371	0.999	4.114
	F_{50}, I_{450} (NUE)	0.679	0.715	1.000	0.050	1.000	3.444
	F_{500}, I_0 (WUE)	0.933	0.000	0.000	1.000	1.000	2.933
	F_0, I_0 (Leach)	0.000	0.533	–	0.000	1.000	1.533
	2007–2008						
	F_{500}, I_0 (Yield)	1.000	0.000	0.000	0.991	1.000	2.991
	F_{150}, I_{400} (FGM)	**0.991**	**1.000**	**0.420**	**0.986**	**1.000**	**4.397**
	F_{50}, I_{500} (NUE)	0.116	0.090	1.000	0.985	1.000	3.191
	F_{400}, I_{250} (WUE)	0.999	0.825	0.046	1.000	1.000	3.870
	F_0, I_0 (Leach)	0.101	0.637	–	0.000	1.000	1.738
LCA	2007–2008						
	F_{500}, I_{500} (Yield)	1.000	0.809	0.000	1.000	–	2.809
	F_{150}, I_{350} (FGM)	**0.995**	**1.000**	**0.376**	**0.990**	**-**	**3.361**
	F_{50}, I_{500} (NUE)	0.417	0.422	1.000	0.962	–	2.801
	F_{500}, I_{150} (WUE)	0.999	0.906	0.000	1.000	–	2.905
SQA	2016–2017						
	F_{500}, I_{450} (Yield)	1.000	0.946	0.000	0.995	0.000	2.941
	F_{150}, I_{300} (FGM)	**0.996**	**1.000**	**0.411**	**0.981**	**0.838**	**4.226**
	F_{50}, I_{500} (NUE)	0.281	0.281	1.000	0.464	0.963	2.989
	F_{400}, I_{200} (WUE)	1.000	0.964	0.060	1.000	0.241	3.265
	F_0, I_0 (Leach)	0.000	0.740	–	0.000	1.000	1.740

Note: the subscript of each FI combination indicates the most obvious benefit. " - " means data not available. "Leaching" represents soil nitrogen leaching.

3.4. Comparison between the optimized results and actual FI inputs

The comparisons between the FIs of each indicator (Table 2) show that the optimized fertilizer rates of FGM for maize at the three sites are the highest, followed by the application rates of yield, WUE, NUE, and nitrogen leaching. The situation for wheat is different only in the rank between the fertilizer rates of yield and FGM. For irrigation, the water requirement of NUE during the planting of maize is the highest, whereas the appropriate irrigation amounts of the other four indicators are I_0 in most cases. The highest irrigation input for wheat is obtained with the FGM indicator. The application amount of NUE is the second-highest, followed by the watering amounts of NUE, yield, WUE, and soil nitrogen leaching.

It is interesting to note that most of the best fertilizer rates and irrigation amounts of multiple indicators are identical to the optimal results of the single FGM indicator, as explained in Section 3.3. During the optimization of the individual indicators, the optimized FIs of FGM, NUE, and nitrogen leaching are explicitly obtained when the three indicators reach their maximal values (minimal values for nitrogen leaching), whereas the optimized FIs of yield and WUE are obtained when the indicator values reach the inflection point (as mentioned in Section 2.5). Therefore, only the FIs of FGM, NUE, and nitrogen leaching can be treated as the optimal cases during the multi-objective optimization because of the calculation method (as mentioned in Section 2.5). The FIs of FGM are moderate, whereas the FIs of NUE and nitrogen leaching are very low (Table 2) and cannot meet the demands for high yield and net profit. Undoubtedly, the optimal case of FGM is superior during the comprehensive optimization. Maize had higher fertilizer requirements while wheat had higher water demand, as revealed by the optimized results of FGM. This phenomenon may point out the different primary factors

Table 5
The actual fertilizer and irrigation inputs with the statistics on the optimized results for maize and wheat at the three sites.

Sites	Summer maize			Winter wheat		
	Year	Fertilizer	Irrigation	Year	Fertilizer	Irrigation
YCA	2006	192	150	2006–2007	207	385
	2007	300	115	2007–2008	421	233
LCA	2008	276	60	2007–2008	286	67
SQA	2015	157	60	2016–2017	263	50
	2017	174	50			
Mean (SD)	Actual input	**219.8 (64)**	**87 (43.5)**	Actual input	**294.25 (90.8)**	**183.75 (157.5)**
	Multiple objectives	**230 (75.8)**	**20 (44.7)**	Multiple objectives	**137.5 (25)**	**387.5 (85.4)**
	Yield	**160 (22.4)**	**30 (67.1)**	Yield	**237.5 (75)**	**237.5 (25)**
	FGM	**230 (75.8)**	**20 (44.7)**	FGM	**137.5 (25)**	**362.5 (47.9)**
	NUE	**50 (0)**	**160 (178.2)**	NUE	**50 (0)**	**275 (125.8)**
	WUE	**80 (44.7)**	**0 (0)**	WUE	**112.5 (75)**	**137.5 (94.6)**
	Leaching	**0 (0)**	**0 (0)**	Leaching	**0 (0)**	**0 (0)**

Note: the units of the fertilizer rate and irrigation amount are kg N ha^{-1} and mm, respectively. "Leaching" represents soil nitrogen leaching.

influencing the yields of the two crops. To be specific, fertilizer input is the primary factor that promotes maize yield, and consequently, income. To reduce the planting expenditures, irrigation can be reduced because it has less effect on maize yield. In contrast, irrigation is the primary factor that generates high yield and income for wheat while fertilizer input can be reduced, i.e., the nitrogen and water amounts used to maximize FGM are not redundant but tightly controlled. Therefore, FGM can be a good indicator for balancing economic and environmental benefits. However, the optimum FI (F_{100}, I_{500}) in Yucheng during 2006–2007 obtained with maximum yield during the comprehensive scoring process is different from the optimal FI (F_{350}, I_{200}) obtained with the single yield indicator because the appropriate FIs probably do not have to generate the highest yield during the optimization by targeting only one objective but have to generate the highest yields during the multi-objective optimizing process.

As shown in Table 5, the actual fertilizer and irrigation inputs used at each site and during each year vary significantly, the standard deviations (SDs) of fertilizer and irrigation are 64 kg N ha^{-1} and 43.5 mm, respectively, for maize and 90.8 kg N ha^{-1} and 157.5 mm, respectively, for wheat. To be specific, the fertilizer rates for maize in Shangqiu are 157 and 174 kg N ha^{-1} during 2015 and 2017, respectively. In contrast, the fertilizer rates used at the other two sites are higher, especially in Yucheng during 2007, the value is 300 kg N ha^{-1}. The irrigation amounts in Yucheng for maize are 150 and 115 mm during 2006 and 2007, respectively, which are 2–3 times greater than the amounts at the other two sites. The fertilizer rates for winter wheat are all above 200 kg N ha^{-1} and the value in Yucheng during 2007–2008 is 421 kg N ha^{-1}. The irrigation amounts in Yucheng during the two years for wheat are also higher at 385 and 233 mm, respectively. Although the actual FI inputs are various, the average fertilizer rate and especially the irrigation amount for winter wheat are greater than for summer maize.

Compared with the optimized FIs of individual indicators, the actual FIs at the three sites are generally higher. For example, the fertilizer rates for FGM are the highest for maize. The actual fertilizer rate in Yucheng during 2007 equals this optimal value of 300 kg N ha^{-1}. Other actual fertilizer rates are 7–42 kg N ha^{-1} greater than the optimal values. The irrigation of FGM for maize is lower than the actual watering amounts because the optimal values are zero. However, the result in Shangqiu during 2015 is distinctive because the optimal irrigation amount exceeds the actual one. Interestingly, the optimized fertilizer rates are much lower than the actual inputs, but the watering amounts sometimes surpass the actual irrigation amounts, as in Yucheng during 2006, and in Luancheng and Shangqiu during 2015.

As for wheat, the fertilizer rates of the yield indicator are the highest but still below the real fertilizer inputs, except for the optimized value of 143 kg N ha^{-1} being more than the actual input in Yucheng during 2006–2007. However, the corresponding optimal irrigation inputs are above the actual watering amounts in most situations. For other single indicators, the differences between the actual FIs and the optimized results are even more significant.

The actual inputs for maize at the three sites are higher than the optimized FIs integrating all indicators, with the differences varying from 24 to 42 kg N ha^{-1} and 50–150 mm. However, there are two special cases. First, the actual fertilizer rate in Yucheng during 2007 equals the optimal value. Second, the actual FI inputs in Shangqiu during 2015 are lower than the optimized values. For wheat, the actual fertilizer rates at all three sites surpass the optimal results with the apparent differences varying from 107 to 271 kg N ha^{-1} while the actual irrigation amounts are all lower than the optimal results with the significant differences varying from 115 to 283 mm.

A comparison of the averages between the actual FIs and the optimized results of both single and multiple indicators at the three sites show that the average fertilizer rates used in real practice for maize are greater than the optimized amounts of most single indicators but lower than the optimized results of FGM and multiple objectives, with the differences being 10.2 kg N ha^{-1}. The average actual irrigation amount also surpasses the optimal values in most cases, except that the average appropriate watering amount of NUE is 73 mm more than the real amount. For wheat, the average actual fertilizer input is much higher. The smallest gap is 56.75 kg N ha^{-1} between the fertilizer rates of the yield indicator and actual practice. However, unlike maize, the average actual irrigation amount is significantly smaller than the optimized values of either the single or multiple indicators, except for WUE. The biggest difference was observed between the actual and comprehensive optimal irrigation amounts in YCA during 2006–2007, of which the averages were 183.75 and 387.5 mm, respectively. Overall, the fertilizer used in practice may be excessive while the actual irrigation amounts for summer maize can be reduced.

4. Discussion

4.1. Optimal FI inputs of individual and multiple indicators

Sustainable intensification of agricultural systems for enhancing productivity and environmental benefits simultaneously is of great importance to coping with the growing demand for food in the future [82]. When identifying the appropriate inputs of nitrogen fertilizer and irrigation, economic and environmental factors should be considered [83,84]. Generally, farmers are more concerned about the net profit they can earn, which is the main reason for the excessive inputs of FIs [28]. In the NCP, the overuse of fertilizer and irrigation has been a long-standing problem. The average nitrogen input is as high as 600 kg N ha^{-1} yr^{-1} [63], exceeding the crop nitrogen requirement of 200–300 kg N ha^{-1} [23]. The approximated watering amount is 400–450 mm annually in the wheat–maize double-crop system [85]. Studies that focused on optimizing FIs to maximize yield and net profit were most abundant [11,86–88]. Xin and Tao [25] as well as Cui et al. [89] suggested the appropriate fertilizer rate be 180 kg N ha^{-1} for maize in the NCP. The recommended nitrogen application rate for wheat in the NCP ranged from 106 to 141 kg N ha^{-1} for yields less than 5.6 Mg ha^{-1} (the lowest yield category) recommended by the Ministry of Agriculture of the People's Republic of China. Cui et al. [90] considered the total nitrogen requirement of winter wheat to be about 160 kg N ha^{-1} while Li et al. [91] found the appropriate fertilizer input to be 216 kg N ha^{-1} in the NCP. In our study, the appropriate fertilizer rate of the yield indicator was 160 $\pm$ 22.4 kg N ha^{-1} for maize and 237.5 $\pm$

75 kg N ha^{-1} for wheat. Our optimized fertilizer rate for summer maize is in accordance with the results of other studies while our application rate for wheat (200 kg N ha^{-1} in most cases) was a little higher.

It is generally accepted that irrigation is inessential for summer maize but necessary for winter wheat because of the precipitation characteristics in the NCP (as mentioned in Section 3.2.1). Zhang et al. [92] proposed that two irrigation events of 60 mm each could maintain high yields of winter wheat (7.5–9.2 Mg ha^{-1}) during a four-year experiment in Luancheng. Sun et al. [93] considered 300 mm to be the optimal amount. Our experiment showed the optimal irrigation amounts to be 30 ± 67.1 and 237.5 ± 25 mm for maize and wheat, respectively. Our results also fell within the same range mentioned in other studies. With our optimized FIs, approximately 94–99% of the highest yield was ensured in the model experiments.

The determination of the optimal FIs with FGM was comparatively complicated and involved a trade-off between income and cost. As shown in Table 5, the appropriate fertilizer rates for maize and wheat are 230 ± 75.8 kg N ha^{-1} and 137.5 ± 25 kg N ha^{-1}, respectively, and the appropriate irrigation amounts are 20 ± 44.7 mm and 362.5 ± 47.9 mm, respectively. The optimal FIs of FGM in this study are close to the findings of other studies. For example, Khoshnevisan et al. [28] suggested that 150–188 kg N ha^{-1} could bring the highest net profit for maize and 200–250 kg N ha^{-1} for wheat. Wang et al. [94] found that the appropriate application rate was 237 kg N ha^{-1} for maize while Zhang et al. [11] recommended lower fertilizer inputs of 220 kg N ha^{-1} for maize and 213 kg N ha^{-1} for winter wheat to achieve the highest economic incomes.

The notable environmental problems introduced by the overuse of FIs have motivated farmers to find new ways to fertilize and irrigate. The easiest way has been to simply consider environmental friendliness. NUE, WUE, water drainage, nitrogen leaching, and N_2O emissions are the most common indicators of environmental benefits in FI optimization. According to Zhang et al. [95], the proportion of nitrogen fertilizer used by crops is lower than 30%. Most of the nitrogen is lost through runoff, leaching, or gas emissions. NUE is an important index in this context, since it shows how much excess nitrogen has been added to the soil and can offer appropriate nitrogen rates [96,97]. Liu et al. [98] conducted a meta-analysis with 79 related publications and found that a nitrogen application of 150–180 kg N ha^{-1} in the NCP could enhance the NUE of winter wheat. Zhang et al. [11] suggested that the optimal application rates were 142 kg N ha^{-1} for maize and 131 kg N ha^{-1} for wheat. However, lower fertilizer rates led to higher NUE, as found by Cui et al. [99], Dai et al. [78], Xin and Tao [25], and Dai et al. [26]. Our best application rate is 50 kg N ha^{-1}, which agreed with this rule. In contrast, the optimized irrigation amounts of NUE in our study show large variations for each crop. Specifically, the value is 160 ± 178.2 mm for maize and 275 ± 125.8 mm for wheat. Huanyuan et al. [100] suggested three irrigation events of 50, 50, and 20 mm, respectively, could contribute to high nitrogen use efficiency for summer maize. Xin and Tao [25] suggested that irrigation amounts of 80–180 mm were optimal for winter wheat. The optimized irrigation amounts for wheat in this study (Tables 2 and 5) are higher than those of previous studies because the magnitude of NUE in this study (Fig. 5) is larger. Liu et al. [98] suggested that higher NUE may lead to higher water consumption because moist soil can accelerate the dissolution of fertilizers and the mineralization process, thus enhancing nutrient availability by diluting the concentrations and decreasing the loss of soil nutrients [101,102].

Prior studies have advised 180 kg N ha^{-1} and 80 mm [25], 180 kg N ha^{-1} and moderate drought or limited irrigation for summer maize but 100 kg N ha^{-1} and 120 mm [103], 195 kg N ha^{-1} and 120 mm for winter wheat [104] to produce high WUE. Our optimal FIs of WUE (Table 5) are close to their optimized cases for wheat but lower than the optimized nitrogen inputs suggested by previous studies for maize. There are different methods of calculating WUE, which may contribute to the different optimal FIs. This study used the ratio of GPP to ET, whereas other studies have used the ratio of yield to the sum of ET and the irrigation amount [25,33], the ratio of yield to ET [105], or the ratio of yield to the irrigation amount [106]. The WUE in our study is more of an ecological indicator because the numerator, GPP, is related to photosynthesis.

The optimization to reduce nitrogen leaching is uniform at the three sites for the two crops. Lower inputs of fertilizer and irrigation result in less nitrogen leaching [11,49,52].

A complicated way of fertilizing and irrigating is to consider both environmental friendliness and economic benefits. In this study, the environmental aspect was more emphasized, so three indicators were used, whereas, for the economic aspect, two indicators were used. The suggested optimal fertilizer inputs are 230 ± 75.8 kg N ha^{-1} and 137.5 ± 25 kg N ha^{-1} for maize and wheat, respectively. The corresponding irrigation amounts are 20 ± 44.7 and 387.5 ± 85.4 mm. According to Dai et al. [26], 150–300 kg N ha^{-1} can balance the economic and environmental benefits. Xin and Tao [33] verified that 180 kg N ha^{-1} and no irrigation for maize while 180 kg N ha^{-1} and 240 mm for wheat resulted in higher yields, WUE, NUE, ET, soil carbon content, and groundwater recharge but lower nitrogen losses and carbon footprints. Bai et al. [23] suggested that 106–291 kg N ha^{-1} and 0–223 mm were beneficial for the high efficiency of WUE and NUE required to produce a wheat yield that was 80% of on-farm yield in the NCP. Our comparison found that the optimal nitrogen inputs of the two crops, as well as the optimal irrigation for maize, were within the recommendations of the previous studies, but our required amount of water for winter wheat was a little higher. Unlike the individual indicators, the combinations of multiple indicators were manifold. Different studies used different combinations. It must be admitted that the indicators and the indicator numbers used in multi-objective optimization have influenced the results. However, there has been scarce research on the effects of indicator selection on optimal fertilizer and irrigation inputs. The indicators used in this study were typical and our results were reasonable. Because different models have different structures, algorithms, and parameterizations, the simulated results of one variable may also vary. Consequently, different models can generate distinctive optimal FIs even with the same indicator selection.

4.2. Site-specifical optimized FI inputs

The large standard deviations of the optimal FIs shown in Table 5 imply spatial variations among the three sites. Soil properties, such as the physical characteristics of soil texture, bulk density (BD), and water holding capacity, as well as the chemical characteristics of soil organic matter (SOM) and total nitrogen, can significantly affect plant nitrogen and water absorption from soil [58,107]. As shown in Table S1, the soil textures in YCA and SQA are all clay loam while their bulk density values (1.37 and 1.36 g cm^{-3}) are close to each other. The soil texture in LCA is sandy loam, of which the sand percentage accounts for 53.12%, and the bulk density is the highest (1.53 g cm^{-3}). The SOM and total nitrogen are also the highest (15.14 g kg^{-1} and 1.03 g kg^{-1}, respectively) in LCA, followed by SQA and YCA. Bulk density is the comprehensive representation of soil texture, structure, porosity, SOM, and other physical characteristics. Small BD refers to more pore numbers, looser structures (poor water holding capacity), and good transmission conditions for soil water, air, and heat, which are beneficial for crop growth. SOM is one of the major sources of soil nutrients provided to plants and can help improve the venting ability, water permeability, and nutrient-preserving capability of soil. From this prior knowledge, it can be deduced that the nitrogen requirements in Luancheng may be lower than those at the other two sites, but the water demand may be higher. However, in this study, only the optimized fertilizer rates for maize partially fitted the rules. For example, the optimal fertilizer rates of FGM and the multiple objectives in LCA (F_{250}) are smaller than the application rates (F_{300}) in Yucheng during 2007 and in Shangqiu during 2015. These results accord with Dai et al. [26], who found that the required nitrogen in Shangqiu (170 kg N ha^{-1}) was higher than in Luancheng (150 kg N ha^{-1}) on account of both the economy and environment. Soil property is an important factor influencing crop growth, as well as the subsequent nitrogen and water demands, but it is not the determinant factor because climate also matters.

Fig. S4 shows that Shangqiu had the most abundant annual precipitation during the three years (734, 768, and 670 mm, respectively). Especially in July 2016, the rainfall amount approached 200 mm, accounting for about 25% of the total amount. The precipitation in Luancheng during 2007 is quite scarce. The annual amount is 190 mm and the maximal precipitation of 43.4 mm occurs in March. The annual precipitation in Yucheng during 2006 (380 mm) is also at a low level. Even with the limited precipitation in LCA, there is still no need to irrigate maize at any of the sites. However, there is an exception, which is the optimal irrigation in Shangqiu during 2015 being not I_0 but I_{100} or I_{150}. Theoretically, the precipitation in the NCP is sufficient to meet the water requirements of maize. This abnormal phenomenon may be due to the abnormal initial value of the model's soil water content, which implies that the poor soil water status could not support the water supply to the crops. This phenomenon reminds us that the initial soil water content strongly influences the irrigation amount, to which we should attach great importance.

The precipitations during the growing season (November to June) of winter wheat are generally small but also vary from site to site. The stages of large water requirements for winter wheat are the jointing–heading or heading−milking stages [108], which usually occur from March to mid-April. The irrigation in these stages is necessary to ensure vegetative growth and grain filling. As illustrated in Fig. S1, the precipitation during the growing season is highest in Yucheng during 2007, followed by YCA in 2008, LCA in 2008, and SQA in 2017. It stands to reason that the sequence of required water amounts should be SQA > LCA > YCA, but the optimized results exhibit the opposite trend. This outcome may have been due to the abundant precipitations during summer and autumn in Shangqiu, which provided a resulting better foundation of soil moisture for the growth of winter wheat.

Some researchers have also suggested that the irrigation amount should be adjusted according to the type of precipitation year [109–111]. According to Hao and Li-ping [112], a precipitation year is a dry year when the annual total precipitation in the NCP is below 551 mm, a normal year when it falls in the range of 551–763 mm, and a wet year when it is above 763 mm. The precipitation data in this paper show that 2016 in SQA is a wet year, 2015 and 2017 in SQA, as well as 2008 in LCA, are normal years, and the remaining years are dry years. The optimized irrigation in this study reflects the precipitation year to some extent. For example, the appropriate watering magnitude of winter wheat is ranked as SQA, LCA, and YCA (Table 4). The optimal irrigation amount for wheat is more related to the precipitation year than to the precipitation amount during the growing season.

Temperature affects photosynthesis, transpiration rates, and ground evaporation rates, which influence the magnitudes of crop yield, GPP, and ET. Generally, the relationship between temperature and photosynthesis or transpiration rates is nonlinear [113,114]. The rates usually keep rising in the range of 10–35 °C in C4 plants and 10–25 °C in C3 plants, after which the rates decline [115]. The highest temperatures are: 26.77 °C (in Jul. 2006), 25.94 °C (in Jul. 2007), and 25.97 °C (in Jul. 2008) in Yucheng; 26.23 °C (in Jul. 2007) and 26.08 °C (in Jul. 2008) in Luancheng; 30.4 °C (in Jul. 2015), 31.6 °C (in Jul. 2016), and 31.83 °C (in Jul. 2017) in Shangqiu. Except for −15.52 °C in December 2008 in LCA, the coldest temperatures are above −2 °C at all three sites. Overall, the hydrothermal conditions in Shangqiu are the best and provide good crop growth conditions, thus resulting in superior crop yields and FGM (Figs. 3 and 4), higher nitrogen uptake status (Fig. 5), and less nitrogen leaching (Fig. 7). Our results verify that low amounts of water and nitrogen are required to stimulate crop growth in Shangqiu. However, high temperatures also enhance ground evaporation and magnify the denominator of WUE, thus lowering WUE in SQA (Fig. 6).

4.3. Uncertainties

From comparisons with the optimal FIs in other studies, it can be assumed that the optimized FIs in this paper for different purposes were rational. However, there are still some uncertainties about the optimizations. Firstly, the incorrect atmospheric data for Luancheng during 2009–2010 were not included in our experiment, but there were still some missing values in other atmospheric data. To run the model, the missing data were filled by the REddyProcWeb online tool [116]. Because the CLM5-Crop model uses the meteorological elements to drive the simulations of plant photosynthesis, transpiration, growth process, and fruit formation, the less accurate atmospheric inputs would have led to biases in estimating GPP, ET, and yield. Secondly, the model calibration was conducted with limited data (Table S3). GPP was calibrated with only the flux data in Yucheng, the calibration of ET was substituted with the calibration of LE, and the calibrated and experimental data sets in LCA were the same. Although good calibrations were achieved (Figs. S2 and S3, Table S4), more available data would have generated more accurate simulated results.

The amount of soil nitrogen leaching was not calibrated in this study. The simulation results for the absence of nitrogen leaching in LCA were confusing because the soil texture in Luancheng was sandy loam, which was apt to leach [117] and the total soil nitrogen was the highest (1.03 g kg^{-1}). The applied fertilizer rates and irrigation amounts in the model experiment were identical at the three sites. The precipitation during 2008 was 552 mm, which was higher than the amounts in Yucheng, thus implying soil nitrogen leaching in LCA. Even though, no soil nitrogen leaching is allowed without deep infiltration of soil water when adequate fertilizer and irrigation are being applied [118]. In addition, the simulated amounts in Yucheng and Shangqiu were in reasonable ranges as compared to the field experiments in the NCP [118–121]. Generally, lower FIs result in lower levels of leached nitrogen, as mentioned in Section 4.1. Therefore, the optimized results were not influenced even without the calibration of soil nitrogen leaching.

The limited data also hampered the robustness of the optimized results. The recommended FI inputs were usually obtained with long historical data [117,122,123]. The irrigation optimization based on the type of precipitation year mentioned above also could not be performed. More credible results would have been obtained with more long-term and high-quality data. Thirdly, despite the well-developed crop module in the CLM5 model, the presentations of some crop growth stages and management practices were still absent. For example, the critical stage, flowering, was not included [124]. Field management practices, such as plant density, row spacing, and crop diseases, were also not included. Although we had modified the irrigation schedules, methods of irrigation, such as trickle irrigation and spray irrigation, had not been presented in the model. Irrigation methods have different water use efficiencies, which mainly influence the magnitudes of ground evaporation [125,126]. Overall, CLM5 is a land surface model, so the presentations of crop-related processes are inferior to those in specialized agricultural models such as WOFOST, DSSAT, and EPIC. However, according to our optimized results, the adjusted CLM5-Crop model is qualified to generate reasonable FI recommendations for agriculture practices and has proven the feasibility of adapting LSM to exploring the best management practices of fertilization and irrigation in current or various future climate scenarios, thus helping to ensure food security while protecting the environment.

5. Conclusion

This study investigated the capability of the CLM5-Crop land surface model (LSM) with the new fertilization and irrigation schedules to obtain the best economic and environmental-friendly inputs of nitrogen fertilizer and irrigation (FI) in the North China Plain (NCP). Five indicators, which are crop yield, farm gross margin, nitrogen use efficiency, water use efficiency, and soil nitrogen leaching were selected. The optimized results of individual indicators, multiple indicators, and the actual FI inputs in the study areas were compared and recommendations for sustainable agriculture development in the NCP were formulated.

The main findings are the following.

(1) The optimization results of the individual indicators indicate that the FI requirements of the FGM indicator were found to be the highest (230 ± 75.8 kg N ha^{-1} and 20 ± 44.7 mm for maize, and 137.5 ± 25 kg N ha^{-1} and 362.5 ± 47.9 mm for wheat), followed by the FIs of yield, NUE, WUE, and soil nitrogen leaching.
(2) The optimization results of the multiple indicators indicate that the optimal fertilizer rates were 230 ± 75.8 and 137.5 ± 25 kg N ha^{-1} for maize and wheat, respectively, while the irrigation amounts were 20 ± 44.7 mm and 387.5 ± 85.4 mm, respectively. These results are the same as those of FGM, which can be used as a simplified indicator to substitute multiple objectives while balancing economic and environmental benefits.
(3) The contrast between the optimized and actual FIs indicates that the actual irrigation amounts for winter wheat were appropriate, but the watering amounts for maize could be reduced because the summer precipitation in the NCP was able to meet the maize water demand. Fertilizer was mainly overused during the growing seasons of winter wheat. Certain adjustments should be made to mitigate the overuse of FI.

Our optimized values of the FI inputs fell within the reasonable ranges implied by the optimized results of previous studies. The adjusted CLM5-Crop model can be used in agricultural management studies. The potential of LSM in serving sustainable agriculture should be further explored and evaluated.

Data availability statement

Data will be made available on request.

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CRediT authorship contribution statement

Fei Wang: Writing – original draft, Funding acquisition, Conceptualization. **Jingchun Fang:** Writing – original draft, Validation, Methodology, Formal analysis. **Lei Yao:** Writing – review & editing, Formal analysis. **Dongrui Han:** Writing – review & editing, Funding acquisition. **Zihan Zhou:** Data curation. **Baozhang Chen:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e27549.

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