Optimize the Irrigation and Fertilizer Schedules by Combining DSSAT and GA

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Abstract

As one of the main food crops in the world, the yield of maize directly affects the food security of the world. The optimization of irrigation and fertilizer schedules is also one of the hot issues in the world. In this paper, the genetic algorithm (GA) and DSSAT crop model were combined to provide theoretical basis for the optimization of irrigation and fertilizer schedules of maize in China. On the basis of field experimental data in previous references, the model was calibrated and verified, and get a well simulation result with RMSE ranged from 0.262 to 0.580 Mg/ha. After that, GA and DSSAT were run to obtain the optimized irrigation and fertilizer schedules. Compared with the results of previous references, the new optimization schedules can improve the yield (1.9~2.6%) and economic benefits (7.3~8.9%). It is proved that this method has a good optimization effect, and the method also has a wide range of research prospects.

1. Introduction

As one of the main food crops in the world, the yield of maize directly affects the food security of the world (Gao et al. 2019). As one of the main producing countries, China has a large area of maize planting, but the average yield of maize is far less than that of the United States (Zheng et al. 2020). The main reason is that there are many deficiencies in the cultivation mode and management system of maize (Hu et al. 2020). Among them, poor irrigation and fertilizer schedules can't fully play the potential of maize production, while the traditional excessive irrigation and fertilization schedules will cause waste of water quality and environmental pollution (Zhao et al. 2020; Zhou et al. 2019). So how to find the optimal irrigation and fertilizer schedules are the focus of attention now.

Sui et al. (2018) determined the optimum nitrogen (N) level under mulched drip irrigation in Northeast of China by two years field experiments. Wang et al. (2018) evaluated the optimal N rate for maize production based on the analysis of economic benefits through field experiments. Zhang et al. (2017) give the optimal drip irrigation schedule for maize with plastic film mulching systems in arid areas by taking into account grain yield, economic return, and ecological effects. The traditional solution of irrigation and fertilizer optimization schedules usually tends to use field experiment, but field experiment has been gradually replaced by field experiment combined with crop model due to the disadvantages of complex experiment, high cost and limited number of experimental groups (Li et al. 2019; Li et al. 2020). One of the most commonly used crop models to simulate maize growth is DSSAT crop model (Bannayan et al. 2003; Dai et al. 2009). Jiang et al. (2016) suggested the best planting dates and irrigation schedule in the Yingke Irrigation District based on DSSAT with climate data of field series. Chen et al. (2020) provided dynamic within-season irrigation scheduling for maize production in Northwest China based on Weather Data Fusion and yield prediction by DSSAT. Kaur et al. (2018) discussed the synergistic effects of irrigation and N on grain yield, water use and N uptake through DSSAT model. Amouzou et al. (2018) simulate the N and phosphorus (P) uptake, and soil moisture dynamics in the dry savanna of West Africa by DSSAT to give the best management schedules. Corbeels et al. (2016) give the performance and sensitivity of the DSSAT model in simulating maize yield under conservation agriculture.

DSSAT has become more and more popular in maize irrigation and fertilizer schedules optimization, and many scholars have proved that it has good simulation results (Jiang et al. 2016; Liu et al. 2011; Yakoub et al. 2017). However, the design of the experimental scheme is generally inclined to the orthogonal test method, whether it is field experiment or crop model simulation (Yakou et al. 2017; Wang et al. 2014; He et al. 2018). But the limited number of experimental groups will make the solution fall into local optimal. This can not only save water and save fertilizer, but also the yield of crops can't be guaranteed (Chen et al. 2019; Zou et al. 2019). Therefore, an optimal solution of irrigation and fertilizer schedules is needed to solve this kind of nonlinear problems. As an excellent global optimization algorithm, genetic algorithm (GA) can find the optimal solution of water and fertilizer system only with a given range of water and fertilizer amount, which is very suitable for solving this kind of problem (Ferreiro et al. 2016; Huo et al. 2020). In this paper, the DSSAT model is verified by the data of previous references. Under the condition of high simulation accuracy, the irrigation and fertilizer schedules are optimized by combining GA and DSSAT, and analysis the benefits of simulation results to determine the effect of the optimized model. This optimized model can provide theoretical reference for optimizing water and fertilizer system in maize production.

2. Data Sources And Analysis Methods

2.1 Data sources

The data for DSSAT model calibration and validation are taken from Zou et al. (2020) and Li et al. (2020). Zou used drip irrigation in Tengger Desert, China and Li used traditional irrigation in Shandong, China in Fig.1. The rainfall in Shandong is obviously higher than that in Tengger Desert. The total precipitation during growth season were 356mm in 2014 and 379mm in 2015 in Li's study. The total precipitation during growth season were 141mm in 2014 and 115 mm in 2015 in Zou's study. The soil conditions are shown in the table 1. The plant density is 67,500 plants/ha in Li's paper and 76,500 plants/ha in Zou's paper.

Table 1

The soil properties

Source	Soil type	pH	Soil field water holding capacity (%)	Bulk density (g/cm ³)	N (mg/kg)	P (mg/kg)	Organic matter (g/kg)
Zou	Clay	8.22	32.90%	1.52	50.3	3.82	8.9
Li	Brown loam	6.1	21.10%	1.51	124	45	11.3

The calibration and verification data are shown in the table 2 and 3. The naming method of processing group is the same as that in the previous references. Because both literatures have optimized water and fertilizer schedules, which can be used for us to compare the optimized results. In table 2 and 3, CI presents conventional irrigation and RI presents half-reduced conventional irrigation, CRN presents Controlled-release urea, N presents conventional urea. I presents irrigation amount and I60 presents 60% of the ETC, F presents N amount.

Table 2

The calibration and validation data from Zou et al. (2020)

2015 (Calibration)					2016 (Validation)				
Treatment	Irrigation (mm/ha)	N fertilizer (kg/ha)	P fertilizer (kg/ha)	K fertilizer (kg/ha)	Treatment	Irrigation (mm/ha)	N fertilizer (kg/ha)	P fertilizer (kg/ha)	K fertilizer (kg/ha)
I60F60	245	60	30	30	I60F60	290	60	30	30
I60F120	306	120	60	60	I60F120	370	120	60	60
I60F180	368	180	90	90	I60F180	450	180	90	90
I60F240	430	240	120	120	I60F240	530	240	120	120
I75F60	245	60	30	30	I80F60	290	60	30	30
I75F120	306	120	60	60	I80F120	370	120	60	60
I75F180	368	180	90	90	I80F180	450	180	90	90
I75F240	430	240	120	120	I80F240	530	240	120	120
I90F60	245	60	30	30	I100F60	290	60	30	30
I90F120	306	120	60	60	I100F120	370	120	60	60
I90F180	368	180	90	90	I100F180	450	180	90	90
I90F240	430	240	120	120	I100F240	530	240	120	120
I105F60	245	60	30	30	I120F60	290	60	30	30
I105F120	306	120	60	60	I120F120	370	120	60	60
I105F180	368	180	90	90	I120F180	450	180	90	90
I105F240	430	240	120	120	I120F240	530	240	120	120

Table 3

The calibration and validation data from Li et al. (2020)

2014 (Calibration)					2015 (Validation)				
Treatment	Irrigation (mm/ha)	N fertilizer (kg/ha)	P fertilizer (kg/ha)	K fertilizer (kg/ha)	Treatment	Irrigation (mm/ha)	N fertilizer (kg/ha)	P fertilizer (kg/ha)	K fertilizer (kg/ha)
RIN0	263	0	120	240	RIN0	263	0	120	240
RICN105	263	105	120	240	RICN105	263	105	120	240
RICN210	263	210	120	240	RICN210	263	210	120	240
RICN315	263	315	120	240	RICN315	263	315	120	240
RIN315	263	315	120	240	RIN315	263	315	120	240
CIN0	525	0	120	240	CIN0	525	0	120	240
CICN105	525	105	120	240	CICN105	525	105	120	240
CICN210	525	210	120	240	CICN210	525	210	120	240
CICN315	525	315	120	240	CICN315	525	315	120	240
CIN315	525	315	120	240	CIN315	525	315	120	240

Among them, irrigation is carried out when the soil moisture is suitable for the lower limit of soil moisture (70% of field capacity), irrigation amount design percentage of evapotranspiration. Phosphorus and potassium fertilizer are applied to the soil in the form of base fertilizer at one time before planting, and CRN was applied once as basal fertilizer before planting maize, and conventional urea was applied twice: once before planting the maize seeds (50% of the

total) and again at V12 (50% of the total) in Li's paper. Four fertilization levels of N-P₂O₅-K₂O (kg/ha) were applied as low, medium, medium high and normal high fertilization rates, 20 % of fertilizers at the seeding stage, 30 % at the six leaf collar stage, 30 % at the tasseling stage and 20 % at the grain filling stage in Zou's paper.

2.2 GA

GA is a global optimization algorithm based on the survival of the fittest. GA encodes the solution of the problem as chromosome, and then selects the individuals with high fitness value according to the probability distribution of fitness function value by creating fitness function, and then exchanges chromosome information in the population through selection, crossover and mutation, and finally produces the chromosome (optimal solution) that meets the optimization goal. The main steps of GA include:

(1) Generating initial population

In this study, the population number is 10. To identify the water and fertilizer regimes, the string length of fertilization and irrigation factor encoded by binary code is 6. The range of fertilizer and irrigation amount is shown in Table 4.

Table 4

Range of irrigation and fertilizer amount

	Irrigation (mm/ha)	N fertilizer (kg/ha)	P fertilizer (kg/ha)	K fertilizer (kg/ha)
Range	0-1000	0-500	0-500	0-500

(2) Calculating each fitness

The fitness function of GA used in this paper is mainly to maximize the benefit, and the formula is as follow:

$$f(x)=\frac{\sum_1^n(Y_r-F_r-W_r-C_r)}{n}\tag{1}$$

where Y_r denotes the profit from the yield; F_r is the cost of the amount of fertilizer; W_r is the cost of the amount of water, C_r is the other cost like seed, land use and machines.

(3) Selection

This paper uses roulette selection, which is a playback random sampling method.

(4) Crossover;

In this paper, single-point crossover is used, and the crossover probability is 0.9 in this paper.

(5) Mutation;

In this paper, we use gene mutation, and the mutation coefficient is 0.1 in this paper.

(6) Termination conditions

Reach genetic algebra which is 1000, output the result.

2.3 DSSAT

DSSAT model is a crop model system developed by many universities under the support of the U.S. Department of agriculture. It can solve some problems in crop cultivation and management, and provide scientific basis for crop growth management decisions. It has been used in many crop experiments in China. DSSAT version 4.5 is an application software including 28 crop simulation models. DSSAT v4.5 is a functional software based on Soil and meteorological database management, crop management and experimental data, supported by practical programs and application programs. Crop models simulate the effects of soil plant atmosphere functions on crop growth and yield. Its main input data include: (1) meteorological data: daily maximum temperature, daily minimum temperature and daily rainfall (meteorological data from the website of China Meteorological Administration); (2) Soil data: Soil texture, bulk

density, soil N, soil organic carbon and water capacity for each soil layer (soil data from table 1); (3) Management data: Irrigation schedule, planting method, fertilizer schedule, planting and harvest date (section 2.1).

2.4 The combination of GA and DSSAT

The advantage of GA is that the initial irrigation and fertilization schedules can be generated randomly, and then it can be substituted into DSSAT to solve the yield. After DSSAT obtains the accurate yield, it can be substituted into equation (1) to calculate the fitness, repeatedly calculate the fitness, selection, crossover and mutation until the genetic algebra is reached, then output result is obtained. The flowchart of GA and DSSAT is shown in Fig.2.

2.5 Data analysis

To verify whether the model results perform well, the root mean square error (*RMSE*), mean absolute error (*MAE*), average root mean square error (*nRMSE*), and Nash-Sutcliffe efficiency coefficient (*NSE*) are adopted. Error analysis is conducted to determine the differences between the assessed and measured data. The *RMSE*, *MAE*, *nRMSE* and *NSE* are calculated as follows:

$$MAE = \frac{1}{N} \sum_{i=1}^N |X_i - Y_i|, \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (X_i - Y_i)^2}{N}}, \quad (3)$$

$$nRMSE = \frac{RMSE}{\bar{Y}} \times 100, \quad (4)$$

$$NSE = 1 - \frac{\sum_{i=1}^N (Y_i - X_i)^2}{\sum_{i=1}^N (Y_i - \bar{Y})^2}, \quad (5)$$

where *N* denotes the number of lateral measuring points and *X* and *Y* represent the calculated and measured values, respectively.

3. Results

3.1 Calibration and validation of the model

The climatic conditions, soil conditions and management conditions for DSSAT are the same as those described in section 2.1 and 2.2. Firstly, we need to solve the six parameters of maize in DSSAT model according to the calibration data. The solution method is solved by applying GLUE, and the results are shown in the table 5 (Liu et al. 2013). The GLUE Coefficient Estimator combining with trial-and-error method was used to estimate the genetic parameters.

Table 5
Genetic parameters of maize for Zou and Li.

	P1	P2	P5	G2	G3	PHINT
Zou	319.8	1.12	629	329.3	17.2	39.7
Li	240.1	1.23	677.4	462.4	15.6	40.9
Notes: P1: Degree days (base 8 °C) from emergence to end of juvenile phase. P2: Photoperiod sensitivity coefficient (0–1.0). P5: Degree days (base 8 °C) from silking to physiological maturity. G2: Potential kernel number. G3: Potential kernel growth rate mg/ (kernel d). PHINT: Degree days required for a leaf tip to emerge (phyllochron interval) (°C d).						

The calibration and validation results of DSSAT for Zou and Li are shown in the table 6. For the calibration and validation datasets, the *RMSE*, *nRMSE*, *MAE* and *NSE* values for yield ranged from 0.262 to 0.580 Mg/ha, 2.404 to 3.441, 0.206 to 0.522 Mg/ha and 0.944 to 0.961, respectively, indicating good agreement between the simulated and measured yield.

Table 6
Comparison of the measured and simulated maize yield with the calibrated and validated data

2015			2016			2014			2015		
Treatment	Measured	Simulated	Treatment	Measured	Simulated	Treatment	Measured	Simulated	Treatment	Measured	Simulat
I60F60	11.6	11.7	I60F60	12.6	12.2	RIN0	8.83	8.95	RIN0	8.97	8.96
I60F120	13.2	13.8	I60F120	14.4	14.6	RICN105	10.88	10.74	RICN105	10.47	10.46
I60F180	13.1	13.4	I60F180	14.3	14.7	RICN210	10.93	10.62	RICN210	10.54	10.21
I60F240	11.7	12.1	I60F240	13	13.1	RICN315	12.08	12.59	RICN315	11.33	11.00
I75F60	12.9	13.3	I80F60	14.5	15.1	RIN315	11.79	11.28	RIN315	10.97	10.81
I75F120	14.7	15.1	I80F120	16.5	17.1	CIN0	10.49	10.20	CIN0	9.87	9.99
I75F180	15.9	16.0	I80F180	17.8	17.0	CICN105	11.95	11.97	CICN105	11.23	10.88
I75F240	15.2	15.9	I80F240	17.2	16.4	CICN210	13.61	13.70	CICN210	12.98	12.94
I90F60	14.7	14.1	I100F60	17.4	17.3	CICN315	13.28	13.35	CICN315	12.34	12.52
I90F120	16.8	16.1	I100F120	18.2	19.0	CIN315	12.46	12.70	CIN315	11.73	11.22
I90F180	18.3	18.3	I100F180	20.5	21.0						
I90F240	17.5	17.5	I100F240	19.6	19.9						
I105F60	15.7	16.0	I120F60	15.9	15.4						
I105F120	17.5	16.8	I120F120	17.8	18.7						
I105F180	18.8	19.0	I120F180	18.8	19.7						
I105F240	18	18.7	I120F240	17.8	18.4						
RMSE	0.461		RMSE	0.580		RMSE	0.282		RMSE	0.262	
nRMSE	2.976		nRMSE	3.441		nRMSE	2.426		nRMSE	2.404	
MAE	0.388		MAE	0.522		MAE	0.228		MAE	0.206	
NSE	0.956		NSE	0.944		NSE	0.961		NSE	0.944	

3.2 Optimal model application

On the basis of proving the accuracy of the model, we use our combined model to solve the optimal water and fertilizer regime. In order to make a better comparison with the previous literatures, the frequency, time and proportion of irrigation and fertilization remain unchanged, we only change the total amount. The other conditions are the same as those described in the literatures. The initial set of total population number is 10, population code length is 6, genetic algebra is 200, selection method roulette, crossover method is single-point with 0.9 of crossover probability, mutation method is gene mutation with 0.1 of mutation coefficient. The initial range of irrigation and fertilization is shown in the table 4. The results of optimization are shown in the figures 3 and 4. The simulation results are completed in the 76th and 74th generations respectively, and the results are the best and keep stable. The optimal economic benefits are 19533 and 11794 CNY respectively. The corresponding optimization results are shown in the table 7. It can be found that our optimization results are higher than the original optimization results in previous literatures.

Table 7

Compared with the results of the previous optimization method

Methods	Irrigation (mm/ha)	N fertilizer (kg/ha)	P fertilizer (kg/ha)	K fertilizer (kg/ha)	Yield (Mg/ha)	Economic benefits (CNY/ha)
Zou's optimal result	478	173	86	86	19.15	17935
Optimal result of this paper	501	182	91	91	19.52	19533
Li's optimal result	525	210	120	240	13.61	10986
Optimal result of this paper	497	193	112	207	13.97	11794

4. Discussion

In accordance with previous studies, adjusting the water and fertilizer schedules can greatly improve the yield of maize (Djaman et al. 2013; Xu et al. 2014; Kresović et al. 2016). We get higher maize yield by adjusting different water and fertilizer systems. In Zou's paper, the experimental data are used to fit the three-dimensional surface between irrigation amount, fertilizer amount and economic benefit. Then the formula of the surface is obtained by the three-

dimensional surface, and finally the optimal yield is obtained through solution of equation. However, we know that the coupling problem of irrigation and fertilizer schedules is usually not a linear optimization problem, and the surface of irrigation amount, fertilizer amount and economic benefits is usually not smooth, but there are many peaks and valleys (Gheysari et al. 2009; Li et al. 2010). Therefore, if the smooth surface is used to solve this kind of problem, it is not accurate enough to solve this kind of problem by combining the optimization algorithm and crop model (Islam et al. 2012; Biau et al. 2012). So the global solution method in this paper can obtain better results. At the same time, Zou uses fixed proportion compound fertilizer, so the ratio of N, P and K is not changed. In order to compare with the previous results, the ratio of N, P, K used by Zou is also unchanged. However, the total amount of P and K also has interaction with water and fertilizer, and the change of the ratio of N, P and potassium (K) may increase the yield of maize (Xin et al. 2017; Martineau et al. 2017).

Li's paper showed that under the condition of sufficient irrigation, the appropriate amount of N fertilizer was 210 kg/ha, and K and N fertilizer were applied to the field at one time. The optimal conditions given by us are that the irrigation water is less than the sufficient irrigation water, and the fertilizer amount of N, P and K is also lower than that of Li as sometimes full irrigation doesn't make the most use rate of the fertilizer (Singandhupe et al., 2003; Tian et al., 2017). The main reasons why the yield of Li is lower than that of Zou may be caused by the planting density and irrigation methods, the density of Li is 67500 plants/ha, which is much less than 76500 plants/ha of Zou. On the other hand, Zou adopted drip irrigation and many researches provided that drip irrigation can significantly increase the yield of maize (Kang et al. 2010; El-Hendawy et al. 2010; Martins et al. 2013). Close planting has higher requirements for seeds, it may cause soil degradation. Therefore, further research is needed in the selection of dense planting.

The results of optimization are mainly reflected in the yield and benefit. Compared with Zou's scheme, our output increased by 1.9%, and the benefit increased by 8.9%. Compared with Li's scheme, our output increased by 2.6% and the benefit increased by 7.3%. According to the proportion of benefit increase, our optimization method has high application value. The optimization method in this paper is not only suitable for conventional irrigation, but also suitable for drip irrigation. But the research foundation of this paper is the verified crop model, and more field experiments should be carried out in the future. At the same time, there are many emerging technologies in modern agriculture, such as the combination of remote sensing technology and crop model (Guo et al., 2018; Leroux et al., 2019), weather prediction technology and crop model (Chen et al. 2017, 2020). How to combine these excellent technologies with the research results of this paper is also our main research direction in the future.

5. Conclusions

In this paper, on the basis of previous experimental data validation, optimal irrigation and fertilizer schedules are obtained by combining GA and DSSAT. The main research results are as follows:

- (1) The combination of the GA and crop model can obtain the optimal irrigation and fertilizer schedules of maize both in traditional irrigation and drip irrigation, and the yield and economic benefits are improved 1.9~2.6%, 7.3~8.9% respectively compared with the original optimization scheme.
- (2) The optimization method in this paper is not only suitable for conventional irrigation, but also suitable for drip irrigation. At the same time, this method is easier to popularize, which can provide theoretical reference for the decision of water and fertilizer optimization strategy of maize in the world.

Declarations

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Ethical Approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Authors Contributions

Yu Bai analyzed and interpreted the soil loss data and was a major contributor in writing the manuscript. Wenjun Yue and Chunmei Ding performed the calculation of the model. All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests

Availability of data and materials

All data generated or analysed during this study are included in this published article [and its supplementary information files].

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Figures

Figure 1

The study area of this paper

Figure 2

The flowchart of DSSAT and the GA

Figure 3

The optimized results of Zou

Figure 4

The optimized results of Li