The effect of the rainfall on the nitrogen fertilizer schedule of maize in Jilin, China

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ABSTRACT

The traditional optimization maize nitrogen fertilizer schedule tends to be fixed, even in different meteorological years. Because different meteorological conditions will affect the use efficiency of nitrogen fertilizer, this method of fertilization will limit the yield of maize. Based on the DSSAT crop model, this paper simulated the optimized nitrogen fertilizer schedule of maize in Central Jilin Province of China from 1973 to 1992 on the basis of verified DSSAT model. It was found that the optimized nitrogen fertilizer schedule in different meteorological years had significant differences, and this optimized nitrogen fertilizer schedule changed with different meteorological years and could increase maize yield by 3.9% compared with the fixed optimized nitrogen fertilizer schedule. At the same time, there was a significant positive correlation between amount of nitrogen fertilizer and rainfall in the stages of sowing, VJ and VT. In these stages, the amount of nitrogen fertilizer should be increased with the increase in rainfall. Finally, an optimized agrometeorological prediction method was proposed to provide a theoretical basis for the real-time optimization schedule of maize nitrogen fertilizer in the future.

Key words: DSSAT, maize, meteorological, nitrogen fertilizer, yield

HIGHLIGHTS

- The optimal fertilization schedule under different meteorological years.
- The nitrogen fertilizer amount along rainfall level in different growing stage.
- Contribute to the real-time fertilizer schedule.

GRAPHICAL ABSTRACT

1. INTRODUCTION

As one of the main products of China, the yield of maize has a direct impact on China’s food security. Nitrogen fertilizer is the main factor that affects the yield of maize, and excessive application of nitrogen fertilizer is used to ensure the high yield of farmland in traditional agriculture (Wang et al. 2010; Qiang et al. 2019). It was found that excessive nitrogen application and unreasonable water and nitrogen management lead to nitrate pollution in groundwater and surface water (Zhu & Chen 2002). This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (http://creativecommons.org/licenses/by/4.0/).
Therefore, how to maintain the high yield of maize without increasing environmental pollution is always a hot topic (Rajput & Patel 2006; Ajdary et al. 2007).

To reduce nitrogen fertilizer application, it is usual to increase nitrogen use efficiency (NUE) or reduce nitrogen leaching. Improving the irrigation and fertilizer schedule is one of the most effective ways to increase NUE. Conventional optimization methods for a maize nitrogen fertilizer schedule mainly include field experiment and crop model simulation (Hu et al. 2006; Ashraf et al. 2016). Synchronous application of nitrogen fertilizer with temporal and spatial changes of crop demand is considered to be a wise approach to nitrogen management, and fractional application of nitrogen fertilizer can reduce nitrogen application rate and nitrogen loss without affecting grain yield (Abrol et al. 2012). Zou et al. (2020) proved that the total yield benefit of spring maize reached maximum when the experimental irrigation amount was 474 mm and the application amount of medium and high nitrogen fertilizer was 184 kg/ha in the semi-arid area of Northwest China. Compared with field experiments, crop simulation model is a low-cost and effective tool to simulate the effects of fertilization measures on crop growth and environment (Fang et al. 2008). RZWQM2 simulation results showed that maize plants with high WUE generally had higher NUE (Zhou et al. 2020). On the basis of the same yield, compared with the conventional fertilization schedule, the optimal fertilization schedule reduced irrigation amount by 14.7% and nitrogen leaching loss by 80.5%. The DSSAT model was also used to optimize the nitrogen fertilizer regime of maize under drip irrigation in Northeast China (Bai & Gao 2021).

Researchers have identified several factors that affect agricultural nitrate leaching and groundwater pollution, including fertilizer level, fertilizer management, crop cultivation methods, soil texture, precipitation surplus, and other factors (Wick et al. 2012). Azad et al. (2019) studied the role of fertilization management in controlling nitrogen leaching. At the end of irrigation, the nitrate leaching loss for shorter fertilization time was less than that of longer fertilization time. Jeong & Bhattarai (2018) found that by adjusting the amount and time of nitrogen fertilizer application, less nitrogen fertilizer application and changing the application time could significantly reduce the leaching of nitrogen fertilizer in the case of a small amount of maize yield reduction. Meisinger et al. (2015) studied the effects of tillage and nitrogen fertilization on nitrate leaching in winter wheat. According to their results, nitrate leaching is a function of initial soil water content, duration, fertilization rate, precipitation and its occurrence time. In addition, Farneselli et al. (2015) evaluated the effects of different fertilization and/or irrigation frequencies on crop nitrogen uptake and nitrate movement in soil. In another study, Tian et al. (2018) pointed out that controlled release urea reduced nitrate leaching and increased crop yield in a cotton garlic intercropping system. He et al. (2016) used the DSSAT model to analyze the sensitivity of crop yield, soil water content and nitrogen leaching to precipitation, management measures and soil hydraulic properties in semi-arid humid areas of Canada.

The fertilization of maize is applied at a fixed time and amount according to experience. The law of rainfall is different in different meteorological years, the effect of different rainfall on nitrogen use efficiency and leaching is different too (Figure 1). If the influence of rainfall on the amount of fertilizer at each stage cannot be considered, it will lead to a decrease of NUE and an increase in nitrogen leaching, reducing the yield of maize and increasing environmental pollution. In this case, how to establish the relationship between rainfall and NUE can better increase maize yield and reduce nitrogen leaching.

Based on the DSSAT crop model and genetic algorithm (GA), this paper constructs the optimization model for a nitrogen fertilizer schedule, studies the changes in nitrogen fertilizer application amount in different periods of 20 years in Central

![Figure 1 | Schematic diagram of fertilization scheme changing with rainfall.](http://iwaponline.com/ws/article-pdf/22/2/1492/1008711/ws02201492.pdf)
Jilin, China, and explores the relationship between fertilizer application amount and rainfall. The optimization law for nitrogen fertilizer schedule in different meteorological years will also be discussed, and it can provide a theoretical reference for the regulation of optimized nitrogen fertilizer schedules in the Central Jilin Province of China.

2. DATASETS

2.1. Study area

The main study area is in the middle of Jilin Province, China, where maize is the main crop (Figure 2). The planting date is usually around May 1st, and the planting density is 62,500 plants/ha. The main model validation and calibration data are taken from Bai & Gao (2021). The irrigation method is rain fed (RF) and full drip irrigation (FIN), and the fertilizer of 187.5 kg/ha N is applied with the irrigation water in 2014 and 2015, respectively.

2.1.1. Daily weather data

The main meteorological data needed by the DSSAT crop model to simulate crop growth are daily maximum temperature, daily minimum temperature, light intensity and daily rainfall. The meteorological data from 1973 to 1992 are from Changchun meteorological station located in the middle of Jilin, China. The rainfall over the years is shown in Figure 3, and the annual rainfall is from low to high and then to low.
2.1.2. Soil profile data

Soil is the main parameter to simulate crop growth, the bulk density of the study area ranges from 1.39 to 1.52 g/cm³, the soil water content of field capacity ranges from 0.25 to 0.31 cm³/cm³, total N ranges from 0.121 to 0.147%.

2.1.3. Irrigation schedule

The drip irrigation schedule was determined from the upper and lower limits of soil water content using Equation (1), and the full crop water requirements were considered in the study:

\[ Q_i = A \times H \times (\theta_{up} - \theta_{low}) \times P / \mu \]  

where \( \theta_{up} \) and \( \theta_{low} \) denote the upper and lower limits of soil water content and were taken to be 100 and 75% of the field capacity in this study, respectively; \( A \) is the plot area (m²); \( H \) is the designed moisture layer of soil (cm); \( P \) is the percentage of wetting area, which was taken to be 0.6 in this study; and \( \mu \) is the application efficiency.

2.1.4. Fertilizer schedule

One day before planting, phosphate fertilizer (150 kg P₂O₅ ha⁻¹ as calcium superphosphate) and potassium fertilizer (120 kg K₂O ha⁻¹ as potassium sulfate) were applied at one time. Nitrogen fertilizer is applied in five times (e.g., VE (emergence) with 37.5 kg/ha, VJ (jointing) with 28.1 kg/ha, VT (tasselling) with 46.9 kg/ha, R2 (filling) with 65.6 kg/ha and R6 (physiological maturity) with 9.4 kg/ha.

2.2. Methodology

2.2.1. Brief description of the DSSAT model

DSSAT is one of the most popular crop growth simulation softwares, and can simulate the daily growth and development of crops, including phenological state, biomass and yield (Chen et al. 2017). Before DSSAT runs the model, weather factors, soil profile, specific variety parameters and field management data should be input into the model. DSSAT can track the process of carbon, nitrogen, water and energy exchange, and the corn module is composed of nonlinear dynamic mathematical functions describing the growth and development of maize, yield formation and changes of soil water and nutrients in the field. Maize module can simulate the growth and development of root, branch, leaf and stem, and the accumulation and distribution of biomass among root, branch, leaf, stem and fruit (Nouna et al. 2000; Anothai et al. 2013). The input parameters of the model can be obtained from Section 2.1.

2.2.2. Model calibration and validation

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

\[ MAE = \frac{1}{N} \sum_{i=1}^{N} |X_i - Y_i| \]  

\[ RMSE = \sqrt{\frac{\sum_{i=1}^{N} (X_i - Y_i)^2}{N}} \]  

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

The differences between the measured and simulated data are listed in Table 1. It is therefore demonstrated that the simulated values agree well with the measured values. The RMSE values of the yield in 2014 (calibration) and 2015 (validation) are 165.97 and 170.77, respectively. The MAE values of the yield in 2014 (calibration) and 2015 (validation) are 165.5 and 162.5, respectively.
2.3. The optimal method of nitrogen fertilizer schedule

2.3.1. Dynamic fertilizer schedule

In order to optimize the fertilization schedule in different meteorological years, we need a changeable fertilization schedule. Here we mainly use the GA, which is a common nonlinear optimization method. GA is mainly based on Darwin’s survival of the fittest theory, and the main steps of GA are as follows: initial population, genetic algebra, fitness, selection method, crossover method, and mutation method. The changing fertilization schedule is mainly based on the binary code of the GA. The binary code can flexibly carry out the operation of genetic crossover and mutation, and has the advantages of high precision of optimization. The GA mainly adopts binary coding and the coding length is six digits, which represents the nitrogen fertilizer application range of 0 to 200 kg/ha. In total, 10 initial populations were randomly generated.

2.3.2. Optimization steps of the fertilization schedule

The optimization of the fertilization schedule is mainly combined with the GA and DSSAT model, and the main steps are shown in the Figure 4.

![Figure 4](http://iwaponline.com/ws/article-pdf/22/2/1492/1008711/ws022021492.pdf)

**Figure 4** | The flowchart of the optimized system.
Step 1: Input the initial fertilization schedule population generated by GA and other initial parameters into DSSAT.
Step 2: Run the DSSAT model to obtain the yield of each individual population.
Step 3: According to the survival of the fittest principle, we need to choose better individuals. At this time, we use the fitness function. The fitness function in this paper is shown in the Equation (4). It is mainly based on the input–output ratio to select the population with the best economic benefit, and selection method is roulette selection:

\[ f(x) = Y_r - F_r - W_r - C_r \]  

(4)

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.

Step 4: The selected population needs crossover and mutation. The crossover method is single point crossover with crossover probability 0.1 and the mutation method is gene mutation with coefficient of mutation 0.1.

Step 5: If the genetic algebra is reached, the result will be output. If the genetic algebra is not reached, the operation of Step 2 will be repeated.

2.3.3. Correlation analysis
The rainfall and fertilizer amount were analyzed by variance tests in the SPSS 14.0 program. In all cases, differences are considered to exhibit statistical significance if \( p \leq 0.05 \).

The \( NUE \) is calculated as the kg yield for each kg nitrogen applied as fertilizer (Sui et al. 2018) and is written as:

\[ NUE = \frac{GYN}{N_{rate}} \]  

(5)

where \( GYN \) denotes the grain yield under the application of nitrogen fertilizer and \( N_{rate} \) represents the amount of nitrogen fertilizer.

4. RESULTS
4.1. The optimized nitrogen schedule in different years
The optimized fertilization schedule from 1973 to 1992 is shown in the Table 2. We can see that the minimum fertilization amount is 182 kg/hm² in 1973 and the maximum fertilization amount is 244.7 kg/hm² in 1980. Compared with the great change in fertilization amount, the change of yield was relatively small. The maximum yield was 13,985 kg/hm² in 1980, and the minimum yield was 12,942 kg/hm² in 1973, with a difference of 8.1%. The maximum NUE was 71.1 in 1973 and the minimum was 56.8 in 1980. The average fertilization amount of each stage accounted for 17.54%, 13.83%, 32.36%, 30.71% and 5.6% of the total fertilization amount. Similar to traditional fertilization, VT and R2 had the highest fertilization rate, but the annual fertilization schedule was slightly different.

4.2. The relationship between N amount and precipitation in different growth stages
The relationship between N amount and precipitation in different growth stages is shown in Figure 5. From the figure, we can seen that there is relatively more rainfall in the VT and R2 stages, and the amount of fertilizer in this stage is relatively high. During the period of warming, VJ and VT, there was a linear relationship between rainfall and fertilizer amount, and the fertilizer amount increased with the increase in rainfall. During R2 and R6, there was no significant linear relationship between rainfall and fertilization, and the overall point distribution was relatively scattered. The linear fitting effect of the VT stage is the best, R2 is as high as 0.9799, followed by 0.9645 of Sowing and 0.8755 of VJ.

4.3. The correlation between different factors
In order to explore the interaction between different factors, the correlation between rainfall, NUE, total fertilization, total rainfall and yield in each stage is shown in the Table 3. It can be seen that the total amount of fertilizer is positively correlated with the total rainfall. With the increase of rainfall, the amount of nitrogen fertilizer will also increase. There was no significant correlation between the yield and the amount of rainfall, nitrogen fertilizer and NUE. There was a significant negative correlation between nitrogen application rate and NUE. With the increase of nitrogen application rate, NUE decreased. The correlation between rainfall and total nitrogen in VT stage was the highest, followed by precipitation, VJ, R2 and R6.
5. DISCUSSION

The nitrogen fertilizer schedule in this paper is quite different from the traditional nitrogen fertilizer schedule, because it is difficult to give the optimized nitrogen fertilizer schedule in real time every year, so traditional research on N fertilizer schedules tends to the fixed amount of nitrogen fertilizer every year (Gao et al. 2020; Quan et al. 2020; Xu et al. 2020), but it is bound to be unable to achieve the maximum NUE and the optimal yield in different climate. Compared with previous studies (Bai & Gao 2021), the average yield reached 13,630 kg/ha, higher than 13,124 kg/ha. Because climates, especially rainfall, can significantly affect the use efficiency of nitrogen fertilizer, nitrogen is easy to leach when there is more rainfall, so the amount of fertilizer should be increased at this time (Gao et al. 2016; Rosolem et al. 2018). For the first three periods, the relationship between rainfall and fertilizer amount is significant, but not significant for the second two periods (Table 3).

For the contribution of water and fertilizer to yield, we found that under the optimized water and fertilizer schedule every year, the difference of yield has little to do with the application amount of fertilizer (Table 3), which indicates that the yield potential of maize has been fully developed under the optimized water and fertilizer schedule (Kifle & Laing 2016; Gonzalez et al. 2018). The relationship between the amount of nitrogen fertilizer and rainfall is very significant, effective prediction of rainfall can effectively improve the NUE, while ensuring a higher yield (Table 3).

There is a complex relationship between water and fertilizer (Silva et al. 2018). We can accurately control the amount of irrigation water through the field system, but it is difficult to control the natural rainfall. If the rainfall in a period is too large, it is bound to affect the use efficiency of fertilizer (Lo et al. 2019). Some studies have shown that with the increase in water consumption, the use efficiency of nitrogen fertilizer is gradually decreasing (Wang et al. 2019), which is consistent with our research results. There is a significant negative correlation between rainfall and nitrogen fertilizer. However, the effect of rainfall on nitrogen fertilizer was different in different growth periods. There was a significant linear positive correlation between rainfall and nitrogen fertilizer application in the first three periods, but not in the last two growth periods (Figure 5). This may be due to the incomplete root development of maize in the first three growth stages, unable to absorb the nitrogen

| Year | Sowing | V1 | V2 | V3 | V4 | Total N | Yield (kg/hm²) | NUE  |
|------|--------|----|----|----|----|---------|---------------|------|
| 1973 | 28.9   | 26.5| 60.9| 64.7| 11.0| 192.0   | 13,883        | 72.3 |
| 1974 | 34.1   | 29.0| 66.5| 64.6| 12.7| 206.8   | 13,989        | 67.6 |
| 1975 | 41.7   | 31.3| 59.8| 65.9| 11.9| 209.6   | 14,127        | 67.4 |
| 1976 | 42.4   | 30.9| 63.0| 66.4| 11.0| 213.8   | 14,505        | 62.2 |
| 1977 | 30.9   | 25.7| 74.9| 64.9| 11.5| 208.0   | 14,020        | 67.4 |
| 1978 | 39.9   | 29.8| 74.7| 66.2| 12.3| 222.9   | 14,240        | 63.9 |
| 1979 | 46.6   | 33.5| 83.2| 65.9| 11.1| 240.3   | 13,453        | 55.9 |
| 1980 | 46.9   | 34.0| 87.2| 63.9| 12.7| 244.7   | 13,256        | 54.2 |
| 1981 | 44.5   | 26.4| 82.4| 65.7| 11.2| 250.3   | 13,779        | 59.8 |
| 1982 | 44.7   | 32.4| 75.1| 65.1| 13.3| 230.5   | 13,218        | 57.4 |
| 1983 | 36.4   | 24.7| 62.0| 66.6| 11.3| 201.0   | 13,780        | 68.6 |
| 1984 | 35.1   | 30.1| 61.5| 63.9| 12.8| 203.4   | 13,666        | 67.2 |
| 1985 | 26.9   | 26.5| 71.3| 65.3| 11.1| 201.0   | 13,046        | 64.9 |
| 1986 | 44.1   | 32.5| 57.8| 65.2| 11.4| 210.9   | 13,133        | 62.3 |
| 1987 | 32.4   | 31.8| 64.4| 65.3| 10.8| 204.6   | 13,279        | 64.9 |
| 1988 | 28.4   | 34.3| 58.2| 66.2| 12.2| 199.4   | 13,040        | 65.4 |
| 1989 | 37.5   | 34.0| 76.6| 64.9| 12.6| 225.5   | 14,281        | 63.3 |
| 1990 | 33.5   | 26.9| 74.3| 66.3| 12.1| 213.1   | 13,649        | 64.1 |
| 1991 | 36.5   | 28.3| 66.2| 65.3| 11.8| 208.1   | 14,167        | 68.1 |
| 1992 | 34.5   | 24.5| 61.4| 64.0| 12.4| 196.8   | 13,110        | 66.6 |
| Mean | 37.3   | 29.4| 68.8| 65.3| 11.9| 212.6   | 13,630        | 64.4 |
Figure 5 | The relationship between N amount and precipitation in different growth stages.
leaching into the deep layer (Dechorgnat et al. 2018; Liu et al. 2020), so the more rainfall, the lower nitrogen use efficiency and the higher nitrogen application rate. In the latter two periods, the development of root system is basically complete, which can absorb the nitrogen element leached to the deep layer, resulting in the increase of nitrogen use efficiency and the decrease of nitrogen use. Conversely, the rainfall intensity will also have a certain impact on the nitrogen leaching, larger rainfall intensity will cause the splash erosion of the surface soil of cultivated land (Meisinger et al. 2015; Fang 2021), and will also take away part of the nitrogen fertilizer. This situation will slow down with the increase of LAI (Bai & Cui 2021). However, there is no simulation module for this part in the DSSAT model, which is also the focus of our next research.

In this paper, our research is mainly based on model simulation, and the prediction results need to be verified by field experiments. If we want to apply the experimental results to the field, we need to combine with the accurate climate prediction module, otherwise we cannot give the real-time water and fertilizer optimization system. In the future, we should use the combination of agrometeorological prediction system and fertilization schedule design, which can make the fertilization schedule more optimized and accurate, and combine short-term prediction with long-term prediction (Figure 6). The module of meteorological data consists of three parts, one part is real meteorological data, such as there is no real meteorological data at the beginning of the simulation. When the vegetation grows to a certain period, the data before this period can be replaced by the real meteorological data. The second part is the short-term meteorological forecast data, which is simulated according to the forecast data of the national meteorological network, with high accuracy. But the simulation period is short, so the remaining third part is to use historical meteorological data to forecast the future meteorological data through time series module or neural network algorithm.

**Table 3** | The correlation between each parameter

|   | Sowing | VJ | VT | R2  | R6   | NUE | Total N | Total precipitation | Yield |
|---|--------|----|----|-----|------|-----|---------|---------------------|-------|
| Sowing | 1      | 0.53a | 0.46a | 0.41b | 0.23 | −0.8a | 0.8a    | 0.67a               | 0.02  |
| VJ    | 1      | 0.39a | 0.33 | 0.08 | −0.73a | 0.73a | 0.57a   | −0.13               |
| VT    | 1      | 0.77a | 0.61a | −0.81a | 0.84a | 0.9a  |         |         |
| R2    | 1      | 0.51a | −0.65a | 0.68a | 0.86a | −0.24 |
| R6    | 1      | −0.46a | 0.49a | 0.66a | 0.05  |       |
| NUE   | 1      | −0.99a | −0.9a |       | −0.03 |
| Total N | 1    | 0.94a |         |       |       |
| Total precipitation | 1   |         |       |       | −0.06 |
| Yield |       |         |       |       | 1     |

a: represents $p < 0.05$; b: represents $p < 0.1$.

**Figure 6** | The method of climate prediction.
6. CONCLUSIONS

In this paper, the DSSAT model was used to analyze the optimal nitrogen fertilization schedule in different meteorological years, the main conclusions are listed follows:

1. The optimized nitrogen fertilizer schedules in different weather years are different, and the yield of the different optimized nitrogen fertilizer schedule is 3.9% higher than that of the fixed nitrogen fertilizer schedule.

2. There is a significant relationship between rainfall and fertilizer amount in the periods of warming, VJ and VT. At this time, we should pay attention to the amount of rainfall in the fertilizer application. If there is more rainfall, we should increase the amount of fertilizer application. However, there is no significant relationship between the amount of fertilizer application and rainfall in the periods of R2 and R6.

3. In view of the relationship between meteorology and fertilization schedule, an effective agricultural climate prediction method was proposed to provide a theoretical reference for the real-time optimization of maize irrigation and fertilizer schedule in the future.

DATA AVAILABILITY STATEMENT

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

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