EFFICIENCY ANALYSIS AND EVALUATION OF VARIABLE FERTILIZER SPREADING BASED ON REALTIME SPECTRAL INFORMATION ON WHEAT
/
基于实时光谱信息的小麦变量施肥效率分析与评价

Man CHEN [1], Zhichang CHANG [1], Chengqian JIN [1*], Yinyan SHI [2*]

[1] Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing, Jiangsu / China;

[2] College of Engineering, Nanjing Agricultural University, Nanjing, Jiangsu / China;

Tel: +8602584346113; E-mail: jinchengqian@126.com; shiyinyan@njau.edu.cn

DOI: https://doi.org/10.35633/inmateh-73-49

Keywords: *Wheat; Variable fertilization; Spectral information; Economic benefits*

ABSTRACT

Studying the effect of variable fertilization during the elongation stage on winter wheat production in the rice-wheat rotation area is critical for evaluating the application effect and economic benefits of variable fertilization technology. The variable fertilization experiment of wheat was carried out in Jiangsu province by using the self-developed fertilizer applicator. Three fertilization methods were used to conduct a comparative analysis of the fertilization amount, population structure, and yield of winter wheat during the elongation stage. On this basis, the economic feasibility of variable fertilization during the elongation stage was evaluated. The experimental results showed that the control accuracy of variable-rate fertilization with fertilization equipment was greater than 95%. After variable fertilization, the coefficient of variation of Normalized Difference Vegetation Index（NDVI） values in the winter wheat crop canopy spectral data remained between 0.076 and 0.125, and the Christensen uniformity coefficient remained between 0.901 and 0.940. Compared with the traditional empirical balance method for quantitative fertilization of plots, the real-time variable fertilization plot used 13.6 kg/ha less fertilizer during the elongation stage. The findings validate that implementing variable fertilization can help reduce nitrogen fertilizer input, improve nitrogen fertilizer utilization efficiency, reduce environmental pollution, and enhance the sustainability of agricultural production.

摘要

本研究以小麦品种杨麦 25 为研究对象，对自行研制的基于冬小麦生长实时信息的变量施肥机进行了研究。在江苏金坛小麦种植基地进行了不同施肥模式的田间试验。比较分析了 3 种施肥方式冬小麦的拔节期施肥量、群体机构和产量。在此基础上，对拔节期变量施肥经济性进行了评价。试验结果表明，施肥装备变量施肥的控制精度均大于95%。变量施肥后冬小麦冠层光谱数据 NDVI 值变异系数保持在 0.076 ~ 0.125 之间，克里斯琴森均匀系数保持在 0.901 ~ 0.940 之间。相比于传统经验平衡法定量施肥地块，实时变量施肥地块在拔节期少投入了 13.6 kg/ha 的肥料，但是产量却提升了 436.3 kg/ha，收益增加了 1213.6 元/ha。本研究可为在长江中下游稻麦轮作区推广变量施肥技术的试点应用提供理论参考。

INTRODUCTION

As one of the main grain crops in China, wheat ranks second only to rice in terms of planting area and total yield. As the main grain-producing area in southern China, Jiangsu mainly adopts the special planting and production method of rice-wheat rotation. The potential of grain yield is maximized through this method, and the comprehensive productivity of grain crops is also improved *(Huang et al., 2020)*.

Increasing nitrogen fertilizer application within a certain range can increase the yield and improve the quality of winter wheat. Fertilization during the elongation stage is not only beneficial for delaying the aging of winter wheat plants and improving grain yield but also for forming a reasonable population and balancing winter wheat yield. However, unreasonably increasing the application of chemical fertilizers has also caused serious problems in China, such as excessive application, an unreasonable application structure, and a low utilization rate of chemical fertilizers *(Huang et al., 2020)*.

Man Chen, Associate Prof. Ph.D. Eng.; Zhichang Chang, Stud. Eng.; Chengqian Jin, Prof. Ph.D. Eng.; Yinyan Shi, Associate Prof. Ph.D. Eng..

In China, the nitrogen fertilizer utilization rate is only 30–50% *(Wu et al., 2019)*. Excessive and unreasonable use of chemical fertilizers causes the waste of chemical fertilizers, reduces their utilization efficiency, and causes huge economic losses, as well as serious environmental pollution (e.g., water pollution and soil compaction) and even reduces the yield and quality of food *(Sun et al., 2019)*. Therefore, the rational and scientific application of fertilizers is crucial for the sustainable production of winter wheat.

Variable rate fertilization technology relies on modern advanced scientific and technological advancements. With a comprehensive understanding of field soil, crops, and environmental information, professionals can use the technology to perform fertilization operations in small areas according to quantity and demand. This approach meets the nutritional requirements of crops and also aids in achieving the goal of scientific and rational fertilization, improving fertilizer utilization efficiency, and balancing the environment and economic development *(He et al., 2023; Ma et al., 2023)*. Research on this technology has produced significant social, economic, and environmental benefits. To achieve online detection of phosphorus fertilizer, Maleki et al. used visible light near-infrared sensors and designed variable-rate fertilization machinery for the precise application of a base fertilizer to winter wheat. The actual application of phosphorus fertilizer by the machinery was 28.75 kg/ha, which was 1.25 kg/ha less than the traditional application *(Maleki et al., 2008)*.

Xinwei et al. developed a wheat fertilization expert decision-making system and a remote precision control system on the basis of using the active remote sensing spectrometer Green Seeker to diagnose wheat nitrogen nutrition. The response time and precision of the fertilization decision-making system reached an average of 3.6 s and 3.62%, respectively, meeting the accuracy requirements of remote variable control fertilization *(Li et al., 2019)*. Furthermore, *Jinbin et al.* designed a variable-rate fertilizer applicator control system for a more efficient field-spray variable-rate fertilization operation and conducted an analysis and a test. The average error of the system's fertilizer flow fluctuated around 6% *(Bai et al., 2022)*. Similarly, to achieve positioning fertilization based on the root position of corn seedlings, Shuo et al. designed a motor-driven positioning fertilization control system. He proposed a threshold control algorithm, and the average response time of the system was 0–8 s *(Zhao et al., 2019)*. Similarly, to design a real-time variable-rate fertilizer applicator in the field, Man et al. used near-Earth spectroscopy detection technology, achieving variable-rate fertilization operations based on wheat growth. The precision of the fertilizer applicator's fertilizer control exceeded 90%, which can meet the requirements of precise fertilization *(Chen et al., 2015)*. The development of the abovementioned variable fertilization equipment provides technical support for the variable fertilization operation during the *elongation stage* of winter wheat.

Currently, two main forms of fertilization operations exist based on crop growth. One form aims to obtain the spectral data of crops within the plot through remote sensing technology, to analyze crop growth offline, and to generate prescription maps. Based on geographical location information and prescription maps, variable fertilization machines implement variable fertilization operations. The second is to rely on ground sensors, which measure the crop growth in the working area in real time according to the spectral sensor at the front end of the fertilization machine to calculate the target fertilization amount, thus guiding the variable fertilization control system to achieve variable fertilization operations. Regardless of the form used, a fertilization model based on crop spectral information is a prerequisite for achieving precise variable fertilization. Models based on the normalized difference vegetation index (NDVI) *(Yu et al., 2023)*, leaf area index *(Zhang et al., 2010)*, and nitrogen fertilizer optimization algorithm *(Chen et al., 2018)* have been widely used in the variable fertilization of winter wheat. These models are all based on analyzing the differences in crop canopy spectral data in the work area, deducing the nutrients required for wheat production, and establishing precise variable decision-making models to achieve on-demand fertilizer supply within the plot.

This study focused on the Yangmai 25 wheat variety and used a self-developed variable fertilization machine based on the real-time growth of winter wheat for variable fertilization during the *elongation stage*. More specifically, this rice variety grows in the rice-wheat rotation area in the middle and lower reaches of the Yangtze River. Field experiments were conducted on increasing nitrogen fertilizer application during the winter wheat *elongation stage* in different areas with blank fertilization, traditional experience balanced fertilization, and real-time variable fertilization. These three fertilization methods were used to conduct a comparative analysis of the fertilization amount, population structure, and yield of winter wheat during the *elongation stage*. On this basis, the economic feasibility of variable-rate fertilization during the elongation stage was evaluated, providing a theoretical basis and reference for the promotion and application of precision agriculture variable-rate fertilization technology in rice-wheat rotation areas in Jiangsu. Meanwhile, this study will provide useful experience for green and sustainable production of winter wheat.

MATERIALS AND METHODS

Variable-rate fertilization system

In this study, to perform variable fertilization of winter wheat, the project team used a self-developed dual-channel-strip fertilization machine, with a width of 2 m and a spacing of 210 mm between fertilization rows. The fertilization equipment uses Green Seeker optical sensors as the monitoring mechanism for analyzing wheat nutrient requirements, the external groove wheel fertilizer applicator as the fertilizer discharge mechanism of the variable-rate fertilizer applicator, the electric motor as the driving power mechanism of the fertilizer discharge device, and the on-board computer, coordinator, and STM32 microcontroller to form the variable-rate fertilizer control execution mechanism, implementing online variable-rate fertilizer control of the variable-rate fertilizer applicator *(Chen et al., 2016)*. Fig. 1 shows the system's working principle.

In the process of variable fertilization, to obtain the normalized vegetation index of the wheat crop canopy, a spectral monitoring system first scans the wheat crop canopy, and the obtained data are transmitted to the vehicle control terminal. Next, the variable fertilization decision system is activated by the vehicle control terminal, the intelligent variable fertilization control program is executed to generate real-time target fertilization amount, and the target fertilization amount is transmitted to the STM32 controller. At the same time, the fertilization operation speed is monitored by the STM32 controller based on the GPS/BDS speed measurement system, the speed of the fertilizer applicator is monitored by the speed sensor, and the opening of the fertilizer applicator is monitored by the displacement sensor, thereby forming a closed-loop feedback control. Finally, the variable fertilization decision-making system guides the controller to adjust the real-time operation status of the motor based on the built-in algorithm, indirectly adjusting the opening and speed of the fertilizer feeder, thereby achieving online adjustment of the fertilization amount and achieving the goal of precise variable fertilization.

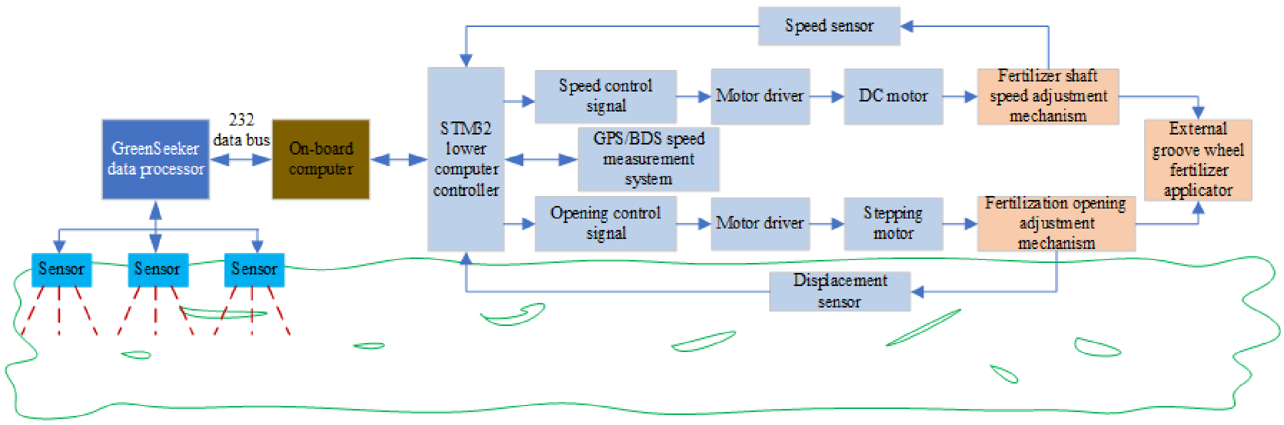


Fig. 1 – Real time measurement system for harvesting area.

Test conditions

The field experiment was conducted from November 2019 to June 2020 at the Shahu Agricultural Machinery Professional Cooperative Experimental Base in Zhulin Town, Jintan District, Changzhou City, Jiangsu (31° 73′ N and 119° 47′ E), using fertilizer in the winter wheat elongation stage. The test area is located in the Taihu Lake Basin of China. The terrain is mainly plain, with little topographic relief, and the altitude is between 10 and 60 m. The experimental area belongs to a subtropical monsoon climate with distinct four seasons, mild and humid climate, with an average annual temperature of around 15°C and abundant precipitation, with an annual precipitation of approximately 1,000 mm and an average annual sunshine of 2,000 h.

The experimental area has formed a two-crop cultivation system, with rice and wheat rotation as the main crop, and has achieved full mechanized production. The previous crop in this study was rice, and the current wheat variety was Yangmai 25. Wheat is mainly sown through mechanized drilling with a row spacing of 17–20 cm. The traditional experience balance method applies 600 kg/ha of compound fertilizer (total nutrient ≥ 45%; $N:P_2O_6:K_2O$ = 25:12:8) to the base fertilizer, and during the elongation stage, 225 kg/ha of urea (total nitrogen ≥ 46.4%) is applied. Nitrogenous fertilizers are no longer applied during other stages.

Test settings

Based on the existing planting layout of the Shahu Agricultural Machinery Professional Cooperative Experimental Base, this study randomly selected nine experimental fields: three blank control plots (marked CK-01, CK-02, and CK-03); three quantitative fertilization plots using traditional empirical balance method (marked FB-01, FB-02, and FB-03); and three real-time variable fertilization plots (marked FV-01, FV-02, and FV-03). Each experimental field adopts a unified management mode. On November 7, 2019, machine drilling was performed on each plot, and bottom fertilizer was applied. On March 11, 2020, top dressing during the jointing period was applied. On June 7, 2020, wheat was harvested using a harvester.

In all experimental areas, the base fertilizer was added with 600 kg/ha of compound fertilizer per the conventional empirical balanced fertilization method, as shown in Fig. 2(a). Fertilization during the green period was performed in different ways. Among them, the blank control area was not fertilized. The traditional experience balance method for quantitative fertilization of plots uses traditional precision fertilization machines for quantitative fertilization (225 kg/ha). A variable fertilization machine developed by the project team was used in the real-time variable fertilization plot to perform variable fertilization operations based on the real-time growth of winter wheat, as shown in Fig. 2(b). The speed of the fertilization operation should be controlled at around 1.2 m/s.

a) Bottom fertilizer application

b) Fertilization in the spring regreening stage

Fig. 2 – Fertilization of winter wheat

Test method

Based on the actual situation of winter wheat production in the Shahu Agricultural Machinery Professional Cooperative Experimental Base, a real-time target fertilization calculation model based on the NDVI value of winter wheat crop canopy was established *(Yang et al., 2015)*. The target fertilization calculation was as follows:

$$\Delta I_i = \frac{1.02}{1+e^{-11.62(D_{above0}/D_{grow}-0.25)}} \times I_{max} - I_i \quad (1)$$

$$\Delta M_i = \begin{cases} 10.213 + 2787.3\Delta I_i - 21171\Delta I_i^2 + 56776\Delta I_i^3 & \Delta I_i > 0.70 \\ 7.0405 + 1701.4\Delta I_i - 11435\Delta I_i^2 + 31065\Delta I_i^3 & 0.65 \le \Delta I_i \le 0.70 \\ 0.4502 + 1314.9\Delta I_i - 11148\Delta I_i^2 + 39654\Delta I_i^3 & \Delta I_i < 0.65 \end{cases} \text{[kg/ha]} \quad (2)$$

$$M_{vi} = \Delta M_i + M_0 \quad \text{[kg/ha]} \quad (3)$$

$$M_v = \sum_{i=1}^{n} \frac{v.L_{sf}.T}{1000} M_{vi} \quad \text{[kg]} \quad (4)$$

where:

ΔI_i is the difference between the actual NDVI value of the wheat crop canopy at the i-th sampling time and the theoretical optimal value; D_{above0} refers to the number of days when the daily average temperature remains stable above 0°C from wheat sowing to spectral measurement; and D_{grow} is the total growth cycle of winter wheat. I_{max} is the maximum NDVI value of the winter wheat crop canopy in the experimental area; I_i is the NDVI value of the winter wheat crop canopy at the i-th sampling point. Furthermore, ΔM_i is the fertilizer deficiency of the experimental plot at the i-th sampling time, [kg/ha]; M_{vi} is the target fertilization amount within the i-th sampling time, [kg/ha]; M_0 is the traditional empirical balance method quantitative fertilization amount, [kg/ha]. Additionally, M_v is the target fertilization amount within the experimental plot, [kg]; v is the real-time speed of the top-dressing operation, [m/s]. L_{sf} is the effective width of fertilization, [m]. T is the sampling period of the fertilization system, [s], and n is the number of winter wheat crop canopy NDVI values collected in the experimental area.

ΔM_i is a positive value, indicating that wheat lacks fertilizer in the early stage and needs to be supplemented with nitrogen fertilizer, based on the traditional empirical balance method for quantitative fertilization. Excessive fertilization in the early stage of wheat is indicated by a negative value of ΔM_i, meaning that it is necessary to apply less nitrogen fertilizer, based on the traditional empirical balance method for quantitative fertilization.

According to the historical data of the experimental area, I_{max} in this study was 0.732, M_0 was 225 kg/ha, L_{sf} was 2.0 m, T was 1.0 s, D_{above0} was 116, D_{grow} was 225, and M_{vi} had a maximum value of 220 kg/ha and a minimum value of 0.

The actual fertilization amount for the real-time variable fertilization plot using the variable fertilization machine developed by the project team was calculated as follows:

$$M_c = M_{cb} - M_{ca} \quad [\text{kg}] \tag{5}$$

where:

M_c is the actual fertilization amount of the real-time variable fertilization plot, [kg]; M_{cb} is the mass of fertilizer loaded into the fertilization box before fertilization, [kg]; and M_{ca} is the remaining fertilizer mass in the fertilization box after fertilization, [kg].

The control accuracy of variable-rate fertilization was calculated as follows:

$$P_M = \left(1 - \frac{|M_c - M_v|}{M_c}\right) \times 100\% \quad [\%] \tag{6}$$

where: P_M is the control accuracy of the real-time variable fertilization system, [%].

Spectral information of the winter wheat crop canopy was collected after 15 days of fertilization. Based on the distribution of NDVI values in the winter wheat crop canopy, the changes in winter wheat population structure after fertilization were analyzed along with the effectiveness of fertilization. To analyze the NDVI data of the winter wheat crop canopy, this study used the coefficient of variation and the Christiansen uniformity coefficient, as follows:

$$C_{uI} = 1 - \frac{\sum_{i=1}^{n}|I_i - \bar{I}|}{\sum_{i=1}^{n} I_i} \tag{7}$$

$$C_{vI} = \frac{\sqrt{\sum_{i=1}^{n}(I_i - \bar{I})^2 / n}}{\bar{I}} \tag{8}$$

$$\bar{I} = \frac{\sum_{i=1}^{n} I_i}{n} \tag{9}$$

where: C_{uI} is the Christiansen uniformity coefficient of NDVI in the winter wheat crop canopy; C_{vI} is the coefficient of variation of NDVI in the winter wheat crop canopy; I_i is the NDVI value of the winter wheat crop canopy at the i-th sampling point; $\bar{I}$ is the mean NDVI value of the winter wheat crop canopy in the experimental area; and n is the number of winter wheat crop canopy NDVI values collected in the experimental area.

After the season's wheat matures, the five-point sampling method was used to manually collect and thresh the wheat, weigh it, and measure its yield. Through the coefficient of variation and the Christiansen uniformity coefficient, the uniformity of winter wheat yield within the plot was analyzed:

$$C_{uY} = 1 - \frac{\sum_{i=1}^{n}|Y_i - \bar{Y}|}{\sum_{i=1}^{n} Y_i} \tag{10}$$

$$C_{vY} = \frac{\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2 / n}}{\bar{Y}} \tag{11}$$

$$\bar{Y} = \frac{\sum_{i=1}^{n} Y_i}{n} \tag{12}$$

where: C_{uY} is the Christiansen uniformity coefficient of yield within the winter wheat plot; C_{vY} is the coefficient of variation of yield within winter wheat plots; Y_i is the winter wheat yield at the i-th sampling point, [kg]; $\bar{Y}$ is the average winter wheat yield in the experimental area, [kg]; and n is the number of sampling points for winter wheat yield in the experimental area, with a value of 5.

Afterward, a wheat combine harvester was used to harvest the wheat, and a weighbridge was used to finely measure the wheat yield in each experimental area.

Based on the area of each experimental plot, the yield was converted into hectare yield, as follows:

$$Y_C = \frac{Y_S}{S} \times 10000 \quad [\text{kg/ha}] \tag{13}$$

where:

Y_s is the actual yield of the experimental area, [kg]; Y_c is the converted yield per hectare of the experimental area, [kg/ha]; and S is the area of the real-time variable fertilization plot, [m^2].

This study calculated the economic benefits of wheat top dressing in the experimental area on a hectare basis. The specific calculations were as follows:

$$P_r = P_{cw} \times Y_c - P_{cf} \times Y_{cf} \quad \text{[[yuan/ha]} \tag{14}$$

$$Y_{cf} = \frac{M_c}{S} \times 10000 \quad \text{[kg/ha]} \tag{15}$$

where: P_r is the profit per hectare of the experimental area, [yuan/ha]; Y_{cf} is the amount of fertilizer input per hectare in the experimental area, [kg/ha]; P_{cw} is the purchase price of current season wheat, [yuan/kg]; and P_{cm} is the price of urea for the current season, [yuan/kg]. In this study, the value of P_{cw} was 2.73 yuan/kg, and the value of P_{cf} was 1.645 yuan/kg.

Data analysis

The results were processed by Microsoft Office Excel (version 2021, Microsoft Corp., USA) and Matlab (version 2021a, MathWorks Corp., USA). Single factor analysis of variance (ANOVA) was carried out with IBM SPSS Statistics (version 24, IBM Corp., USA). The significance test was carried out by the Tukey test. The significance level was $p < 0.05$.

RESULTS

Analysis of variable-rate fertilization effect

In the early stage for fertilization operations, the variable fertilization machine developed by the project team was used in the variable fertilization experimental area, and Table 1 shows the fertilization amount results. The fertilization machine could calculate the target fertilization amount for each plot in real time based on the different growth of winter wheat, which was 57.14 kg, 55.43 kg, and 62.19 kg. According to the fertilizer requirements of different plots, 58.47 kg, 54.57 kg, and 63.83 kg of fertilizer were applied to the fertilization equipment. The control accuracy of variable-rate fertilization with fertilization equipment was greater than 95% in three fertilization experimental areas, with the optimal control accuracy reaching 98.42% and the lowest control accuracy reaching 97.43%. This indicates that the fertilization equipment has good variable system control performance and can ensure good system control accuracy.

Table 1

Statistical data on fertilization amount in variable fertilization areas

Plot	M_{cb} (kg)	M_{ca} (kg)	M_c (kg)	M_v (kg)	P_M (%)
FV-01	200	141.53	58.47	57.14	97.73
FV-02	200	145.53	54.57	55.43	98.42
FV-03	200	136.17	63.83	62.19	97.43

Analysis of wheat population growth structure

Figure 3 and Table 2 show the NDVI values of wheat crop canopy spectral data in each experimental area before and after the application of fertilizer in the winter wheat elongation stage.

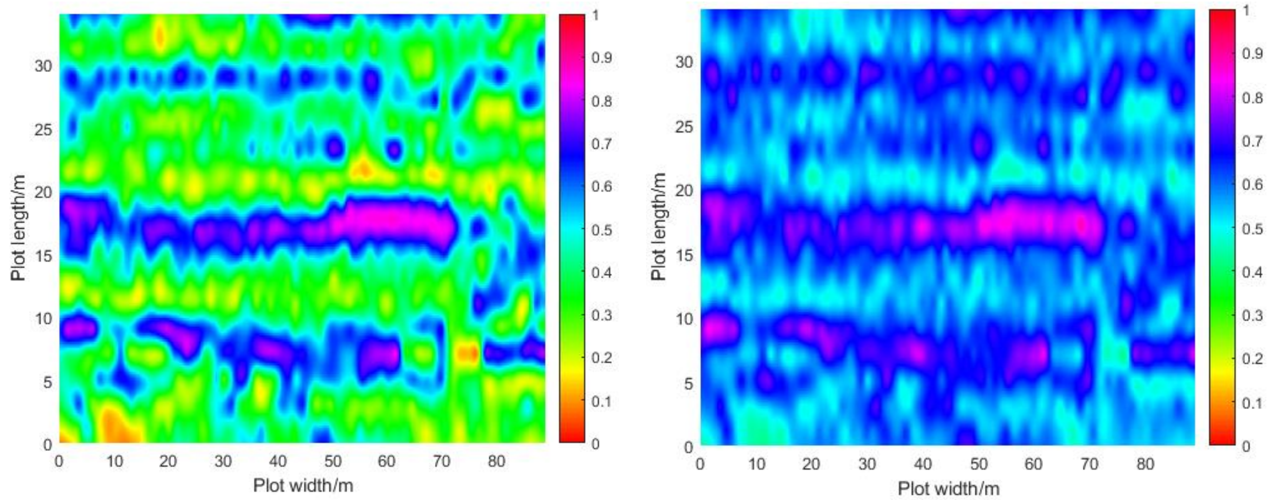
Table 2

Statistical data of wheat crop canopy spectral data in the experimental area

Plot	I_{df} (during fertilization)					I_{af} (after fertilization)				
	Max.	Min.	Mean	C_{vl}	C_{ul}	Max.	Min.	Mean	C_{vl}	C_{ul}
CK-01	0.856	0.109	0.522	0.302	0.750	0.876	0.179	0.615	0.177	0.863
CK-02	0.805	0.171	0.516	0.238	0.793	0.818	0.237	0.610	0.132	0.893
CK-03	0.829	0.218	0.541	0.330	0.708	0.847	0.294	0.615	0.192	0.835
FB-01	0.815	0.206	0.495	0.215	0.824	0.827	0.366	0.601	0.111	0.911
FB-02	0.822	0.143	0.519	0.210	0.825	0.833	0.346	0.616	0.111	0.908
FB-03	0.866	0.214	0.489	0.247	0.801	0.884	0.377	0.603	0.131	0.896

Plot	I_{df} (during fertilization)					I_{af} (after fertilization)				
	Max.	Min.	Mean	C_{vl}	C_{ul}	Max.	Min.	Mean	C_{vl}	C_{ul}
FV-01	0.782	0.175	0.577	0.166	0.871	0.797	0.475	0.659	0.076	0.940
FV-02	0.844	0.132	0.534	0.236	0.813	0.857	0.46	0.642	0.095	0.927
FV-03	0.850	0.101	0.442	0.364	0.695	0.891	0.433	0.605	0.125	0.901

As shown in Fig. 4, the growth of winter wheat in each experimental area was uneven, and there were certain spatial differences in growth. The statistical data in Table 2 show that the maximum NDVI value of winter wheat crop canopy spectral data in the experimental area was 0.866 and that the minimum value was 0.101. This indicates that there are areas with good growth and areas with poor growth in the experimental area. The spatial differences in winter wheat growth are not considered in the traditional empirical balance method for quantitative fertilization, making it difficult to achieve on-demand fertilization. Based on the spectral data of winter wheat crop canopy, variable fertilization can be quantitatively applied according to the different growth conditions of winter wheat, which can further improve the utilization efficiency of fertilizers. Moreover, owing to the adoption of a unified production management method in the early stage, there was not much difference in wheat growth among different experimental intervals. The maximum and minimum NDVI values of winter wheat crop canopy spectral data in each experimental area were 0.577 and 0.442, respectively. The maximum and minimum coefficients of variation were 0.364 and 0.166, respectively. The maximum value of the Christensen uniformity coefficient was 0.871, and the minimum value was 0.695. Therefore, the data from each experimental area are universal and can objectively reflect the production situation of winter wheat in the region.



a) during fertilization in the FV-03 area *b) after fertilization in the FV-03 area*

Fig. 3 – Visualization of wheat crop canopy spectral data before and after fertilization

As shown in Fig. 4 and Table 2, the spatial differences in winter wheat growth after the application of jointing fertilizer varied in each experimental area. No chemical fertilizer was applied during the jointing period in the blank control area, and the spatial differences of winter wheat in the planting area were not significantly improved. Among them, the NDVI coefficient of variation of winter wheat crop canopy spectral data in the CK-03 area decreased by 0.138, and the Christensen uniformity coefficient increased by 0.127, showing the best performance among all blank control areas. After the quantitative fertilization of 225 kg/ha urea during the elongation stage using the traditional experience balance method in the fertilization area, the spatial differences of winter wheat in the planting area were improved to a certain extent. Among them, the NDVI coefficient of variation of winter wheat crop canopy spectral data in the FB-03 area decreased by 0.116, and the Christensen uniformity coefficient increased by 0.095, showing the best performance among all traditional empirical balance method quantitative fertilization areas. In the real-time variable fertilization area, the spatial differences of winter wheat in the planting area were significantly improved after variable fertilization based on spectral data of the winter wheat crop canopy during the jointing period.

Among them, the NDVI coefficient of variation of winter wheat crop canopy spectral data in the FV-03 area decreased by 0.239, and the Christensen uniformity coefficient increased by 0.206, showing the best performance among all variable fertilization areas. These results indicate that variable fertilization can be applied according to the spatial differences in winter wheat growth, which effectively improves the population diversity of winter wheat in the planting area. Long-term excessive or insufficient fertilization can seriously damage the soil structure, exacerbate soil nutrient imbalance, and affect the overall growth and later yield of crops. In contrast, based on the actual growth of crops, reasonable variable fertilization and required inputs are beneficial for improving soil structure, balancing soil nutrients, and increasing crop growth and yield.

Field test result analysis

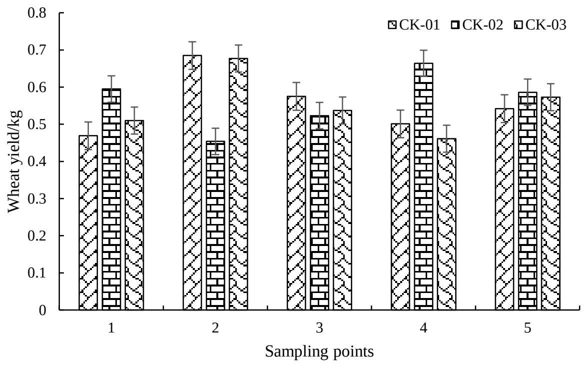
To further analyze the effect of different fertilization methods during the elongation stage on the production efficiency of winter wheat, a five-point sampling method was used to analyze the spatial differences in wheat yield among different plots in the experimental area.

Fig. 4(a) and (d) shows the yield data of each sampling point in the blank control plot. The maximum value of the yield at the sampling point was 0.685 kg, and the minimum value was 0.454 kg. The coefficient of variation between sampling points in each plot was 0.132, 0.126, and 0.134, and the Christensen uniformity coefficient was 0.894, 0.892, and 0.891.

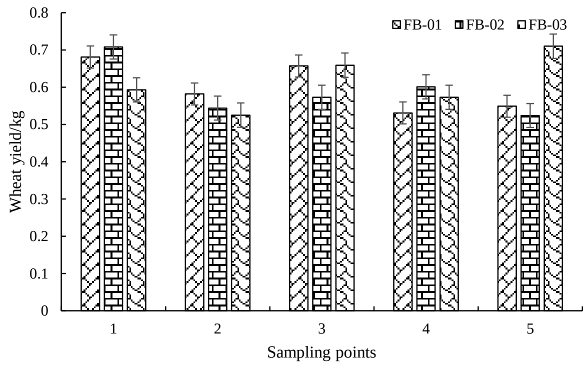
Fig. 4(b) and (d) shows the yield data of each sampling point in the traditional empirical balance method for the quantitative fertilization of plots. The maximum value of yield at the sampling points was 0.710 kg, and the minimum value was 0.524 kg. The coefficient of variation between sampling points in each plot was 0.107, 0.109, and 0.099, and the Christensen uniformity coefficient was 0.905, 0.913, and 0.908.

Fig. 4(c) and (d) shows the yield data of each sampling point in the real-time variable fertilization plot. The maximum value of the yield at the sampling point was 0.722 kg, and the minimum value was 0.585 kg. The coefficient of variation between sampling points in each plot was 0.067, 0.058, and 0.058, and the Christensen uniformity coefficient was 0.938, 0.949, and 0.947.

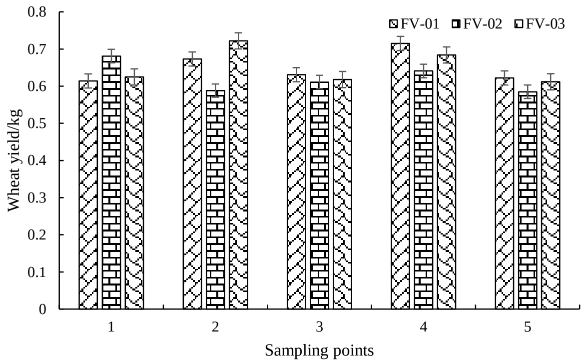
The results showed that there was a significant spatial difference in yield among the blank control plots, followed by the traditional empirical balance method for quantitative fertilization plots, while the spatial difference in winter wheat yield among the real-time variable fertilization plots was relatively balanced. Thus, variable-rate fertilization improves the population structure of winter wheat growth, provides a good foundation for crop photosynthesis, and serves as a good framework platform for the ultimate high yield of winter wheat.



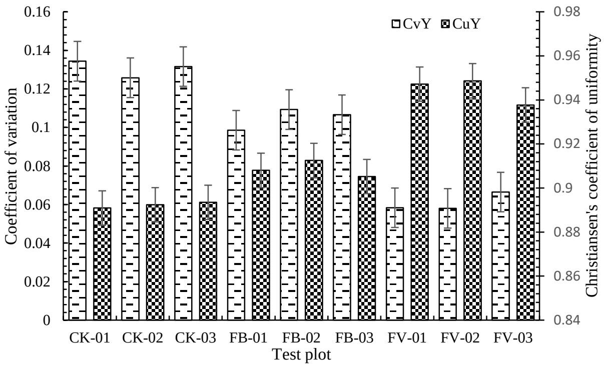
(a) Blank control plot



b) Quantitative fertilization of plots



c) Real-time variable fertilization plots



d) Spatial differences in yield in experimental areas

Fig. 4 – Sampling statistics of winter wheat yield in experimental plots

Analysis of economic benefits of fertilization during the elongation stage

In addition to the difference in fertilizer application during the elongation stage, a unified management model was adopted for winter wheat in each experimental area in this study. Therefore, it was assumed that the production management investment in each experimental area was consistent, so this paper only discusses the economic benefits of winter wheat caused by different fertilizer applications during the jointing period. Owing to the different areas of each experimental area, the measurement units were unified and the economic benefits of winter wheat on a per-hectare basis were evaluated, as shown in Table 3. The average winter wheat yield in the blank fertilized plot was 5,679.2 kg/ha, the fertilization amount during the elongation stage was 0, and the average profit was 15,504.1 yuan/ha. The average yield of winter wheat in the plot fertilized with the traditional empirical balance method was 6,060.5 kg/ha, the fertilization amount during the elongation stage was 225 kg/ha, and the average profit was 16,174.9 yuan/ha. The average winter wheat yield of the real-time variable fertilization plot was 6,496.8 kg/ha, the fertilization amount during the elongation stage was 211.4 kg/ha, and the average profit was 17,388.5 yuan/ha. From this, it can be seen that applying fertilizer during the elongation stage can effectively promote the winter wheat yield increase, increase yield by more than 381.3 kg/ha, and increase income by more than 670.8 yuan/ha. Compared with the traditional empirical balance method for the quantitative fertilization of plots, the real-time variable fertilization plot used 13.6 kg/ha less fertilizer during the elongation stage, but the yield increased by 436.3 kg/ha and the income increased by 1,213.6 yuan/ha. This indicates that implementing variable fertilization technology can effectively improve the economic benefits of winter wheat cultivation.

Table 3

Statistics for the intelligent measurement results in different job scenarios

Plot	Length (m)	Width (m)	Ys (kg)	Yc (kg/ha)	Ycf (kg/ha)	Pr (yuan/ha)
CK-01	67	32	1253.0	5844.3	0	15,954.9
CK-02	67	30	1114.0	5542.2	0	15,130.2
CK-03	67	28	1060.1	5651.0	0	15,427.1
FB-01	92	32	1758.7	5973.8	225.0	15,938.2
FB-02	92	30	1704.1	6174.3	225.0	16,485.7
FB-03	92	30	1665.2	6033.3	225.0	16,100.8
FV-01	89	30	1753.5	6567.3	219.0	17,568.5
FV-02	89	30	1675.4	6274.8	204.4	16,794.0
FV-03	89	34	2011.8	6648.3	210.9	17,802.9

CONCLUSIONS

A winter wheat jointing-stage fertilization experiment was conducted in Jintan, Jiangsu, China, to explore the effectiveness and economic benefits of variable fertilization technology in the rice-wheat rotation area in the middle and lower reaches of the Yangtze River.

（1）The control accuracy of variable fertilization equipment was greater than 95% and that it had good variable system control performance.

(2) There were certain spatial differences in the growth of winter wheat, and the population structure could be effectively improved through variable fertilization. After variable fertilization, the coefficient of variation of NDVI values in winter wheat crop canopy spectral data remained between 0.076 and 0.125, and the Christensen uniformity coefficient remained between 0.901 and 0.940. The coefficient of variation of winter wheat yield within the plot remained between 0.058 and 0.067, while the Christensen uniformity coefficient remained between 0.938 and 0.949.

(3) Compared with the traditional empirical balance method for quantitative fertilization of plots, the real-time variable fertilization plot used 13.6 kg/ha less fertilizer during the elongation stage, but the yield increased by 436.3 kg/ha and the income increased by 1,213.6 yuan/ha.

ACKNOWLEDGEMENT

We greatly appreciate the careful and precise reviews by the anonymous reviewers and editors. This research was financially supported by the Science and Technology Innovation Engineering Project of the Chinese Academy of Agricultural Sciences (Office of the Chinese Academy of Agricultural Sciences (2014) No. 216).

REFERENCES

[1] Bai, J.B., Tian, M. & Li, J.Q. (2022). Analysis and precision test of variable fertilization control system (变量施肥控制系统分析与精度试验). *Journal of Agricultural Mechanization Research*, Vol.9, pp.22-28. DOI: 10.13427/j.cnki.njyi.2022.09.040

[2] Chen, M. Shi, Y.Y., Wang, X.C., Sun, G.X. & Li, Y.B. (2015). Design and experiment of variable rate fertilizer applicator based on crop canopy spectral reflectance (基于光谱探测的小麦精准追肥机设计与试验). *Transactions of the Chinese Society of Agricultural Machinery*, Vol.46, pp.26-32. DOI: 10.6041/j.issn.1000-1298.2015.05.005

[3] Chen, M. Shi, Y.Y., Wang, X.C., Sun, G.X. & Li, Y.B. (2016). Design and experiment of optimization control system for variable fertilization in winter wheat field based on fuzzy PID (基于模糊 PID 的冬小麦变量追肥优化控制系统设计与试验). *Transactions of the Chinese Society of Agricultural Machinery*, Vol.47, pp.71-76. DOI: 10.6041/j.issn.1000-1298.2016.02.010

[4] Chen, M., Yang, Z.J., Wang, X.C., Shi, Y.Y. & Zhang, Y. (2018). Response characteristics and efficiency of variable rate fertilization based on spectral reflectance. *Int J Agric & Biol Eng*, Vol.11, pp.152-158. DOI: 10.25165/j.ijabe.20181106.4086

[5] He, Y.C., Yang, Y., Yi, X.k. & Wang, W.P. (2023). Simulation and experiment of influencing factors of fertilization accuracy based on variable rate fertilization system (基于变量施肥系统的施肥准确性影响因素仿真与试验). *Journal of Chinese Agricultural Mechanization*, Vol.44, pp.51-57, 86. DOI: 10.13733/j.jcam.issn,2095-5553.2023.10.008

[6] Huang, Q.N., Dang, H.Y., Huang, T.M., Hou, S.B. & Wang C.H. (2020). Problems in fertilization and fertilizer reduction in wheat production of China (我国小麦施肥问题与化肥减施). *Scientia Agricultura Sinica*, Vol.53, pp.4813-4815. DOI: 10.3864/j.issn.0578-1752.2020.23.008

[7] Huang, X.M., Xu, X.P., He, P., Wang, X.B., Yang, L.F., Qiu, S.J., Zhao, S.C. & Zhou, W. (2020). Yield response to NPK fertilization and the main impacts in production of winter wheat in Yangtze River catchments of China (长江流域冬小麦氮磷钾肥增产效应及其影响因素). *Journal of Plant Nutrition and Fertilizers*, Vol.26, pp.1059-1068. DOI: 10.11674/zwyf.20103

[8] Li, X.W., Tian, M. & Xiao, X. (2019). Design of wheat fertilization decision-making and control system based on quick diagnosis (基于小麦养分快速诊断的施肥决策与控制系统设计). *Journal of Northeast Agricultural Sciences*, Vol.44, pp.23-27. DOI: 10.16423/j.cnki.1003-8701.2019.02.005

[9] Ma, Xu., Zhao, X., Liu, S.S., Wang, Y.W., Wang, X.C. & Li, Z.H. (2023). Design and experiment of solid particle fertilizer variable rate fertilization device for high-speed rice transplanter (水稻高速插秧机固体颗粒肥料变量施肥装置设计与试验). *Transactions of the Chinese Society of Agricultural Machinery*, Vol.54, pp.99-110. DOI: 10.6041/j.issn.1000-1298.2023.09.010

[10] Maleki, M.R., Mouazen, A.M., Ketelaere, B.D., Ramon, H. & Baerdemaeker, J.D. (2008). On-the-go variable-rate phosphorus fertilisation based on a visible and near-infrared soil sensor. *Biosystems Engineering*, Vol.99, pp.35-46. DOI: 10.1016/j.biosystemseng.2007.09.007

[11] Sun, C.J., He, Q.M., Teng, W.J. & Wu, M.Q. (2019). Research on present situation of precision fertilization and see ding device for wheat (小麦精准施肥播种装置现状研究). *Journal of Chinese Agricultural Mechanization*, Vol.40, pp.30-34. DOI: 10.13733/.jcam.issn.2095-5553.2019.07.06

[12] Wu, L.Q., Wu, L., Cui, Z.L., Chen, X.P. & Zhang F.S. (2019). Optimal regional nitrogen, phosphorus, potassium rates recommendations and special fertilizer formulae study for wheat in China (中国小麦区域氮磷钾肥推荐用量及肥料配方研究). *Journal of China Agricultural University*, Vol.24, pp.30-40. DOI: 10.11841/i.issn.1007-4333.2019.11.04

[13] Yang, B.H., Chen, J.L., Chen, L.H., Cao, W.X., Yao, X. & Zhu, Y. (2015). Estimation model of wheat canopy nitrogen content based on sensitive bands (基于敏感波段的小麦冠层氮含量估测模型). *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, Vol.31, pp.176-182. DOI: 10.11975/j.issn.1002-6819.2015.22.024

[14] Yu, H.F., Xu, H.L., Ding, Y.Q, Yang, Z.N., Dou, X.L., Li, Q. & Guan, X.T. (2023). Wheat canopy vegetation index measurement method based on narrow band spectral image analysis (基于窄带光谱图像分析的小麦冠层植被指数测量方法研究). *Journal of Nanjing Agricultural University*, Vol.46, pp.189-199. DOI: 10.7685/jnau.202112021

[15] Zhang, J.J., Liu, H.B., Xi, L. & Ma, X.M. (2010). Construction and application of wheat variable fertilization system based on model (基于生长模型的小麦变量施肥决策系统构建与应用). *Journal of Henan Agricultural University*, Vol.44, pp.591-595. DOI: 10.1645/j.cnki.1000-2340.2010.05.012

[16] Zhao, S., Zong, Z. & Liu, G. (2019). Design and test on position fertilization control system based on motor drive (基于电机驱动的定位施肥控制系统设计与试验). *Transactions of the Chinese Society of Agricultural Machinery*, Vol.50, pp.91-114. DOI: 10.6041/j.issn.1000-1298.2019.S0.015