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Optimization of Nitrogen Fertilizer Management in the Yellow River Irrigation Area Based on the Root Zone Water Quality Model

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Abstract: Strategic management of nitrogen fertilizers can not only mitigate agricultural nitrogen pollution but also significantly enhance crop yield and nitrogen use efficiency. This study was designed to determine the optimal nitrogen fertilizer management strategy for the Yellow River irrigation area. Leveraging two years of field data related to soil water nitrogen and summer maize growth indices, parameters for the Root Zone Water Quality Model 2 (RZWQM2) were calibrated and validated. Subsequently, various scenarios were generated to simulate the impacts of different nitrogen application rates and basal chasing ratios on summer maize yield, nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery rate. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method was employed for a comprehensive evaluation. RZWQM2 can effectively simulate the dynamic changes in soil moisture and nitrogen in the Yellow River irrigation area, and the results indicated that the mean relative error (MRE) between the simulated and observed values varied from 5.77% to 14.09%, and 4.36% to 33.01%, while the root mean square error (RMSE) ranged from 0.016 to 0.037 cm^3/cm^3, and 0.111 to 1.995 mg/kg. The normalized root mean square error (NRMSE) varied between 6.20% to 14.42% and 5.24% to 17.84%, respectively. The results validate the model's effectiveness in simulating summer maize yields and nitrogen metrics under varying nitrogen fertilizer management practices. A nitrogen application rate of 180–200 kg/hm^2 (expressed in terms of pure nitrogen) in the Yellow River irrigation area could adequately meet the requirements for summer maize production. The recommended nitrogen fertilizer management strategy in the Yellow River irrigation area involves applying 200 kg/hm^2 of nitrogen in a 1:2:1 ratio during the sowing, trumpeting, and anthesis stages.

Keywords: summer maize; Yellow River irrigation area; nitrogen fertilizer management pattern; RZWQM2; yield; nitrogen use efficiency

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1. Introduction

The Yellow River irrigation area, situated in the Yellow River basin in China, boasts a rich history of cultivation and supports a wide variety of crops, rendering it a prominent grain base and agricultural demonstration site in the country. In recent years, the government's promotion of water conservation concepts and implementation of relevant policies have effectively mitigated the wastage of water resources in agriculture. Nevertheless, the annual fertilizer usage in agricultural production considerably surpasses the internationally accepted safe upper limit for fertilizer application, resulting in persistently low fertilizer utilization efficiency in China [1]. Excessive fertilizer application leads to reduced economic efficiency due to diminished crop quality, and poses the risk of irreversible ecological damage [2,3]. Consequently, the contemporary goals of nitrogen fertilizer management encompass enhancing agricultural development quality in the Yellow

River irrigation area, significantly improving fertilizer use efficiency, minimizing agricultural surface pollution, and preventing further damage to the environment.

A substantial amount of research has been dedicated to the study of nitrogen fertilizer management. Numerous academic studies demonstrate that inadequate nitrogen application leads to stunted growth and insufficient nutrient accumulation within plants [4]. Conversely, an excess of nitrogen can impede light transmission through the maize canopy [5], accelerate leaf senescence [6], and diminish maize yields [7]. Thus, determining the optimal amount of nitrogen application for crops is of paramount importance. Field trials in the sandy soil region of Ningxia, China, conducted by Yan et al. [8], recommend an optimal nitrogen application rate of 300 kg/hm^2 considering both yield and environmental benefits. Nevertheless, some researchers have noted that such an application rate does not significantly increase maize yield. Based on a seven-year field trial, Yang et al. [9] proposed that a suitable nitrogen application rate in the Guanzhong Plain should be around 180–200 kg/hm^2, taking into account maize yield and nitrogen leaching. Similarly, Huang et al. [10] suggested an optimal nitrogen application rate of 150 kg/hm^2 for maize in the Yellow Huaihai Plain, weighing both production and environmental benefits.

These studies reveal that the appropriate nitrogen application amount can vary according to regional differences in climate conditions, soil type, and other factors [11]. Current research on nitrogen fertilization concurs that a split application of nitrogen better accommodates the plant's growth and developmental needs than a single application. It also significantly mitigates nitrogen pollution in farmland [12,13]. The success of this method largely depends on the timing of each application and the distribution ratio of nitrogen fertilizer. Despite this, there is a dearth of reports on the optimal amount of nitrogen application in the Yellow River irrigation area, and how different periods and rates of nitrogen application affect the yield and physiological traits of maize, as well as its nitrogen use efficiency.

Given the numerous variables involved, conducting such studies can be both time-consuming and labor-intensive, limitations that model simulations can address. The Root Zone Water Quality Model 2 (RZWQM2) incorporates modules on the meteorological environment, field management, soil conditions, and crop growth to simulate and predict soil nitrogen transport [14], optimization of water and nitrogen regimes [15], crop growth conditions [16], and N_2O gas emissions [17]. To date, minimal research has explored the application of RZWQM2 for optimizing nitrogen fertilizer management in summer maize in the Yellow River irrigation area, and its suitability for this region remains uncertain.

This study first determines and validates the model's relevant parameters using field measurement data, then employs the validated model to simulate various nitrogen application scenarios to investigate the impacts of different nitrogen fertilizer management strategies on maize yield and nitrogen use efficiency. Combining the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, suitable nitrogen fertilizer management strategies are identified to provide scientific guidance for reducing nitrogen pollution and fostering sustainable agricultural development in the region.

2. Materials and Methods

2.1. Overview of the Experimental Area

The study site is situated at the North China University of Water Resources and Hydropower Agricultural Efficient Water Use Test Site in Zhengzhou (34.78° N, 113.76° E, 110 m above sea level). This region experiences a warm temperate continental monsoonal humid climate with high temperatures and rainfall in the summer (accounting for approximately 70% of annual rainfall) and low rainfall in spring and winter. The area has an average annual temperature of 14.3 to 14.8 °C, an average sunshine duration of 6.57 h/d, and an average annual rainfall of 584 to 667 mm. The test area's location is depicted in Figure 1. The test site has a flat terrain and sandy loam soil texture, with the corresponding physicochemical properties and mechanical composition of the soil presented in Table 1. The average soil organic matter (13.6 g/kg), readily available potassium (104.4 mg/kg), readily available phosphorus (11.8 mg/kg), and total nitrogen (1.21 g/kg) in the 0–100 cm soil layer is illustrated in Figure 2.

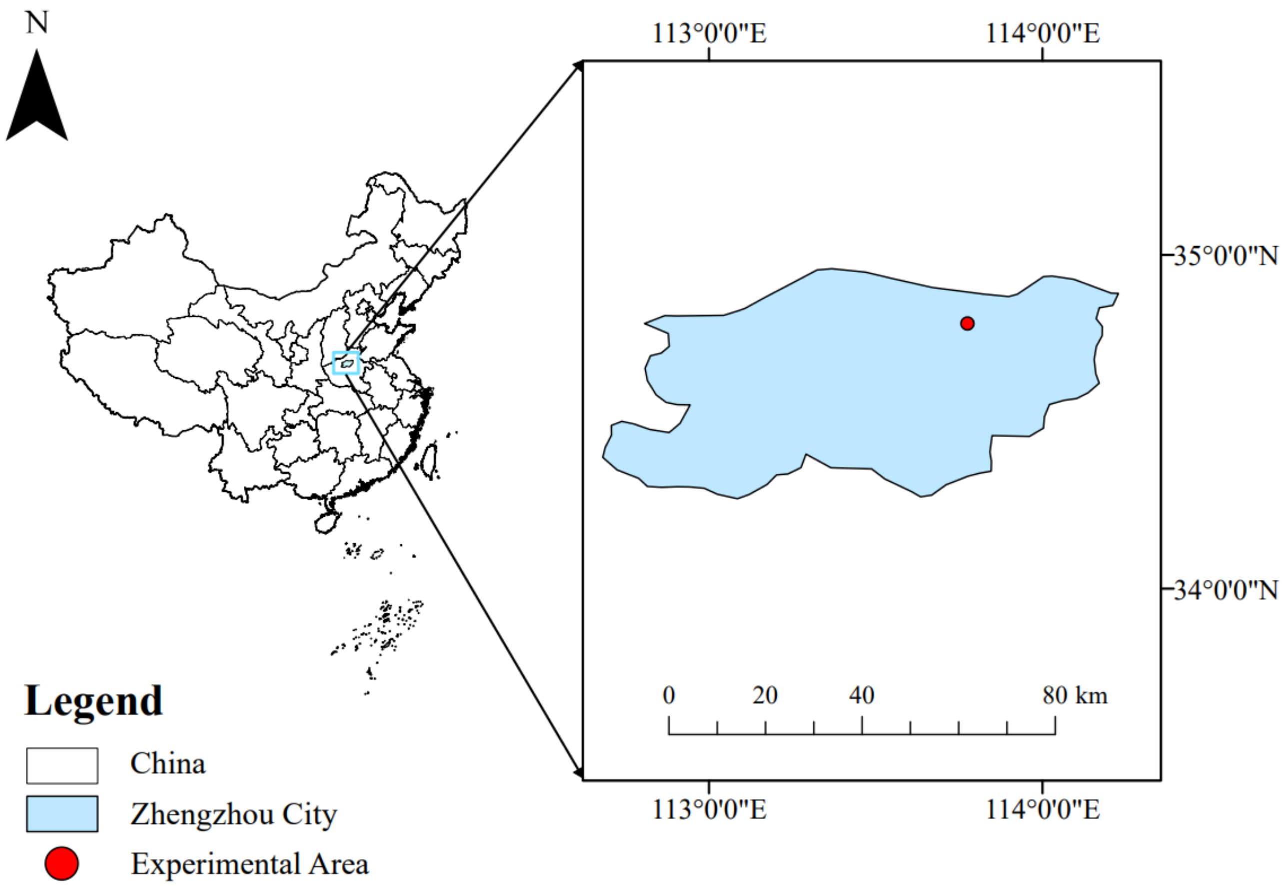


Figure 1. Location of the test area.

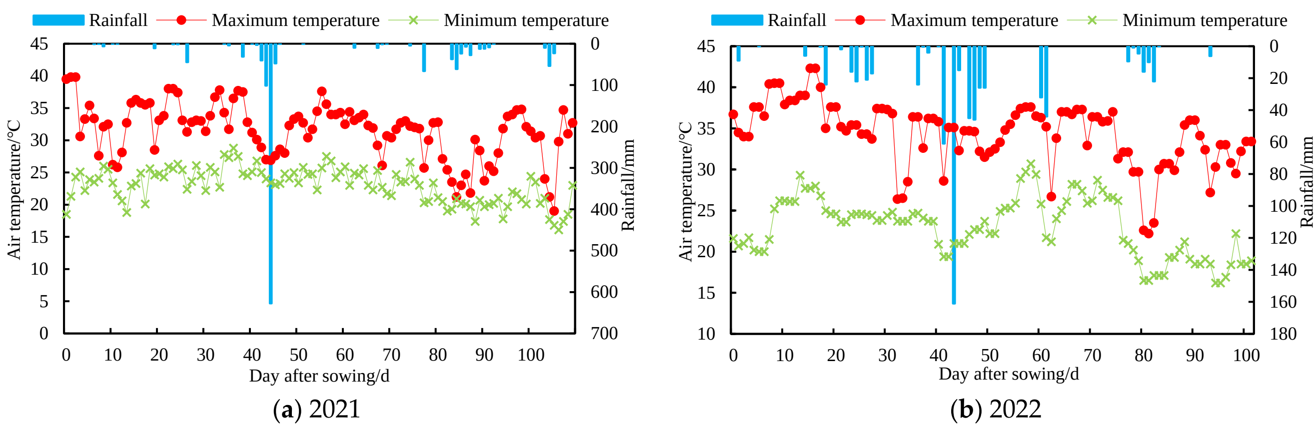


Figure 2. Air temperature and rainfall during the growth period of summer maize in 2021 and 2022.

Table 1. Basic physiochemical properties.

Soil Depth (cm)	Bulk Density ($g \cdot cm^{-3}$)	Field Water Capacity ($cm^3 \cdot cm^{-3}$)	Permanent Wilting Point ($cm^3 \cdot cm^{-3}$)	Saturated Hydraulic Conductivity ($cm \cdot h^{-1}$)	Particle Gradation Composition (%)		
					<0.002	0.002–0.05	>0.05–2.00
0–20	1.48	0.2915	0.115	1.025	4.56	46.53	48.91
20–40	1.54	0.2814	0.136	0.278	7.38	44.21	48.41
40–60	1.52	0.3025	0.131	0.196	6.23	49.25	44.52
60–80	1.46	0.2924	0.122	0.523	4.36	48.25	47.39
80–100	1.48	0.2716	0.131	3.527	12.73	45.15	42.12

2.2. Experimental Design

The experiment was conducted from June 2021 to September 2022, with summer maize as the cultivated crop. Three levels of nitrogen (all nitrogen values mentioned below are in pure nitrogen form) were applied: 120 kg/hm^2 (N_{120}), 220 kg/hm^2 (N_{220}), and 320 kg/hm^2 (N_{320}). The N fertilizer used was urea (46.3% nitrogen). In addition to the corresponding 60 kg/hm^2 of nitrogen, 60 kg/hm^2 of P_2O_5 and 60 kg/hm^2 of K_2O were also applied. Nitrogen was applied at jointing (P_1), trumpeting (P_2), and anthesis (P_3) stages, and mixed with water in the field. The experiment utilized a two-factor, three-level split-zone design (Table 2), supplemented by a control CK, with no nitrogen fertilizer applied throughout the reproductive period. This resulted in a total of 10 treatments, with each treatment replicated thrice.

Table 2. Field trial design.

Treatment	Base Fertilizer **	Topdressing **			Total **
		Jointing * (P_1)	Trumpeting * (P_2)	Anthesis * (P_3)	
$P_1P_2N_{120}$	60	30	30	0	120
$P_1P_3N_{120}$	60	30	0	30	120
$P_2P_3N_{120}$	60	0	30	30	120
$P_1P_2N_{220}$	60	80	80	0	220
$P_1P_3N_{220}$	60	80	0	80	220
$P_2P_3N_{220}$	60	0	80	80	220
$P_1P_2N_{320}$	60	130	130	0	320
$P_1P_3N_{320}$	60	130	0	130	320
$P_2P_3N_{320}$	60	0	130	130	320
CK	0	0	0	0	0

* Specific timing of nitrogen application: jointing (25 June 2021, 28 June 2022); trumpeting (15 July 2021, 18 July 2022) anthesis (8 August 2021, 7 August 2022). ** Both substrate and chase fertilizer are measured in pure nitrogen, unit kg/hm^2.

2.3. Measurement and Calculation of Observation Indicators

2.3.1. Soil Moisture Measurement

Soil moisture determination primarily involves assessing the volumetric moisture content of the soil using the drying method to measure the moisture content of the 0–100 cm soil layer, with one soil layer every 20 cm, totaling five soil layers. Measurements were taken every 7–10 days, with a one-day extension in case of rainfall.

2.3.2. Soil Nitrogen Determination

Soil nitrogen was primarily measured as soil NO_3^--N Soil samples were collected using a soil auger before sowing, after harvest, and three days before and after fertilizer application in summer maize, at 20 cm intervals up to 100 cm. Soil samples were then extracted using KCl solution and measured by UV spectrophotometry [18,19].

2.3.3. Measurement of Crop Growth Indicators

The crop growth section focused on determining the phenological stage, above-ground biomass, above-ground nitrogen content, and yield.

Phenological stages: The growth of maize at each reproductive stage was assessed by recording the time of emergence, jointing, flare, anthesis, and maturity under each nitrogen treatment. A crop was considered to have reached that stage of reproduction when 50% of the plots in each treatment exhibited fertility-specific traits.

Above-ground biomass: Three representative plants with uniform growth were selected in each plot at the maturity stage of summer maize, cut along the base of the stalk, bagged separately for leaves, stems, and fruits, placed in an oven, and heated at 105 °C for half an hour. The samples were then dried at 75 °C until constant weight (approximately 48 h) was achieved. The weight of each part of the plant was measured separately and added up to obtain the plant biomass, which was converted in accordance with the planting density to obtain the above-ground biomass of the crop.

Above-ground nitrogen content: Dried and weighed above-ground plant samples of summer maize were first crushed in a grinder, mixed, and passed through a 0.5 mm sieve. The total nitrogen content of the crop was determined using the Kjeldahl method after boiling the samples with H_2SO_4-H_2O_2.

Yield: 1 m^2 sized plots were allocated to each plot separately at summer maize harvest, and the maize was threshed, dried, and weighed. Finally, the measurements were converted to total maize yield (kg·ha^{-1}).

2.3.4. Calculation of Nitrogen Indicators

The nitrogen indicators were divided into nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery [20], and were calculated as follows:

$$AE_N = \frac{Y_1 - Y_2}{N} \tag{1}$$

$$PE_N = \frac{Y_1 - Y_2}{N_{uptake,1} - N_{uptake,2}} \tag{2}$$

$$RE_N = \frac{N_{uptake,1} - N_{uptake,2}}{N} \tag{3}$$

where: AE_N refers to nitrogen agronomic efficiency (kg/kg); PE_N represents nitrogen physiological efficiency (kg/kg); RE_N denotes to nitrogen apparent recovery (%); Y_1 represents maize yield (kg/hm^2) in the nitrogen application zone; Y_2 stands for maize yield (kg/hm^2) in the non-nitrogen application zone; $N_{uptake,1}$ represents above-ground nitrogen content (kg/hm^2) in the nitrogen application zone; $N_{uptake,2}$ refers to above-ground nitrogen content (kg/hm^2) in the non-nitrogen application zone; N represents nitrogen application (kg/hm^2).

2.4. Model Introduction

RZWQM2 is a process-based model that operates one-dimensionally (perpendicular to the soil profile). It simulates the interaction between water, nutrients, pesticides, and other elements within agricultural systems and their impact on crop growth. This model comprises six sub-modules: physical processes, soil chemical processes, nutrient processes, pesticide processes, crop growth processes, and management practices processes [21,22]. In the model, the Brooks–Corey equation [23] outlines the soil moisture characteristics curve, while the modified Green–Ampt equation [24] calculates the soil moisture infiltration process. The distribution of soil moisture across each layer is simulated by the Richards equation [25]. The organic matter and nitrogen cycle nutrient sub-model (OMNI), used in the nutrient module, depicts the main nitrogen fate [21]. The DSSAT 4.0 module [26], integrated into RZWQM2, simulates crop growth.

2.5. Input, Calibration, and Evaluation of Model Parameters

The 2021 field trial data was selected for model calibration, and the 2022 experimental data was used for validation. The calibration process followed the model developer's recommendations [27] for the soil moisture module, soil nutrient module, and crop growth module in that order. First, the measured soil hydraulic parameters were input into the model. The model output was compared with the measured values and manually fine-tuned using the trial-and-error method to improve the simulation of the volumetric soil moisture content and ultimately clarify the physical properties of the soil in the test area (Table 1). Next, the soil nutrient module was calibrated based on the measured soil nitrate-nitrogen data, and the calibrated parameters are shown in Table 3. Finally, the genetic parameters of summer maize were obtained in combination with the model's PEST conditioning (Table 3).

Table 3. Relevant parameters after calibration.

Type of Parameters	Parameter	Definition	Value Ranges	Calibration Values
Nitrogen conversion parameters	$A_{nit}/(s \cdot day^{-1} \cdot organism^{-1})$	Nitrification	1.0×10^{-10}–1.0×10^{-8}	1.73×10^{-8}
	$A_{den}/(s \cdot day^{-1} \cdot organism^{-1})$	Denitrification	1.0×10^{-14}–1.0×10^{-12}	4.51×10^{-13}
	$A_{hyd}/(s \cdot day^{-1})$	Hydrolysis of Urea	2.5×10^{-5}–2.5×10^{-3}	3.0×10^{-4}
Crop parameters	$P1/(°C \cdot d^{-1})$	Growth characteristic parameters at the seedling stage	100–400	245
	$P2/(d \cdot h^{-1})$	Photoperiod sensitivity	0.01–2.00	0.85
	$P5/(°C \cdot d^{-1})$	Characteristic parameters during the grouting stage	600–1000	800
	G2	Maximum number of grains per plant	700–1000	850
	$G3/(mg \cdot d^{-1})$	Potential grouting rate	6–12	9.2
	$PHINT/(°C \cdot d^{-1})$	Outlet leaf interval characteristic parameters	30–75	44.5

To accurately evaluate the model's simulation performance, four statistical tests were chosen for this study: root mean square error (RMSE), normalized root mean square error (NRMSE), mean relative error (MRE), and relative error (RE). During model calibration, NRMSE was employed as a benchmark to classify the simulation results into four categories: NRMSE < 10% (excellent level), 10% < NRMSE < 20% (good level), 20% < NRMSE < 30% (moderate level), and NRMSE > 30% (poor level) [28,29]. RE represents the individual deviation of the system in the forecast, with positive values indicating over-prediction and negative values indicating under-prediction; the closer it is to 0, the better the simulation [30]. The maximum allowable deviation of MRE can reach up to 50% [31]. The calculation formula is as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \quad (4)$$

$$NRMSE = \frac{RMSE}{O_{avg}} \times 100\% \quad (5)$$

$$RE = \frac{P_i - O_i}{O_i} \times 100\% \quad (6)$$

$$MRE = \frac{1}{n}\sum_{i=1}^{n}|RE_i| \quad (7)$$

where: P_i refers to the i-th simulated value, O_i stands for the i-th measured value, O_{avg} represents the average measured value, and n denotes the number of measured values.

2.6. Construction of the Decision-Making System

2.6.1. Selection of Indicators and Methods

To explore the best nitrogen fertilizer management model, four evaluation indicators were selected for this study: yield, nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery. The method used is the TOPSIS method [32], also known as the approximate ideal solution ranking method, a scientific decision-making method proposed by Hwang and Yoon [33] in 1981, which is commonly used in finite solution, multi-objective decision analysis to find out the positive and negative ideal solutions and the distance between positive and negative ideal solutions by the size of the data, and finally to obtain the relative proximity C value, and combined with the C value ranking (the closer the C value is to 1, the better), so as to arrive at the superior and inferior solution ranking.

2.6.2. General Steps of the TOPSIS Method

The TOPSIS analysis method usually consists of the following 5 steps:

Step 1: Prepare the data to be analyzed and then homotrend the data, setting the processed matrix to A;

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \tag{8}$$

Step 2: Normalize (dimensionless) the homotrended data to obtain matrix B;

$$b_{ij} = \frac{a_{ij} - \min(a_{ij})}{\max(a_{ij}) - \min(a_{ij})} \tag{9}$$

$$B = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mn} \end{bmatrix} \tag{10}$$

Step 3: Identify the positive ideal solution B^+ and the negative ideal solution B^-;

$$B^+ = \left\{ \max_{1 \le i \le m} b_{ij} | i = 1, 2, \cdots, m \right\} = \left\{ b_1^+, b_2^+, \cdots, b_m^+ \right\} \tag{11}$$

$$B^- = \left\{ \max_{1 \le i \le m} b_{ij} | i = 1, 2, \cdots, m \right\} = \left\{ b_1^-, b_2^-, \cdots, b_m^- \right\} \tag{12}$$

Step 4: Calculation of the distance D^+ and the distance D^- from the evaluation object to the positive ideal solution;

$$D_i^+ = \sqrt{\sum_{j=1}^{m} w_j \left(b_j^+ - b_{ij} \right)^2} \tag{13}$$

$$D_i^- = \sqrt{\sum_{j=1}^{m} w_j \left(b_j^- - b_{ij} \right)^2} \tag{14}$$

Step 5: Combine the distance values to calculate a relative proximity C value and rank them.

$$C_i = \frac{D_i^-}{\left(D_i^+ + D_i^- \right)} \tag{15}$$

2.7. Data Analysis

The trial used Excel 2021 and SPSS 26.0 for data analysis, processing, and graphing.

3. Results

3.1. Model Validation

3.1.1. Soil Moisture Module Validation

Figure 3 displays the simulated and measured values of soil volumetric water content in the 0–100 cm soil layer under treatments $P_xP_yN_{320}$ (x, y = 1, 2, 3, and $x < y$) in 2022. As observed in Figure 3, the simulated values of volumetric soil moisture content after calibration exhibit a similar trend to the measured values. The influence of the nitrogen application period on volumetric soil moisture content is not apparent under the same nitrogen application rate. The RMSE of simulated and measured values ranged from 0.017 to 0.037 cm^3/cm^3, MRE values ranged from 5.97% to 14.09%, and NRMSE values ranged from 6.39% to 14.42%. More detailed validation results are provided in Table 4, where the RMSE of simulated and measured values of volumetric water content for different soil layers in each treatment ranged from 0.016 to 0.037 cm^3/cm^3, MRE values ranged from 5.77% to 14.09%, and NRMSE values ranged from 6.20% to 14.42%. The simulations demonstrate good quality.

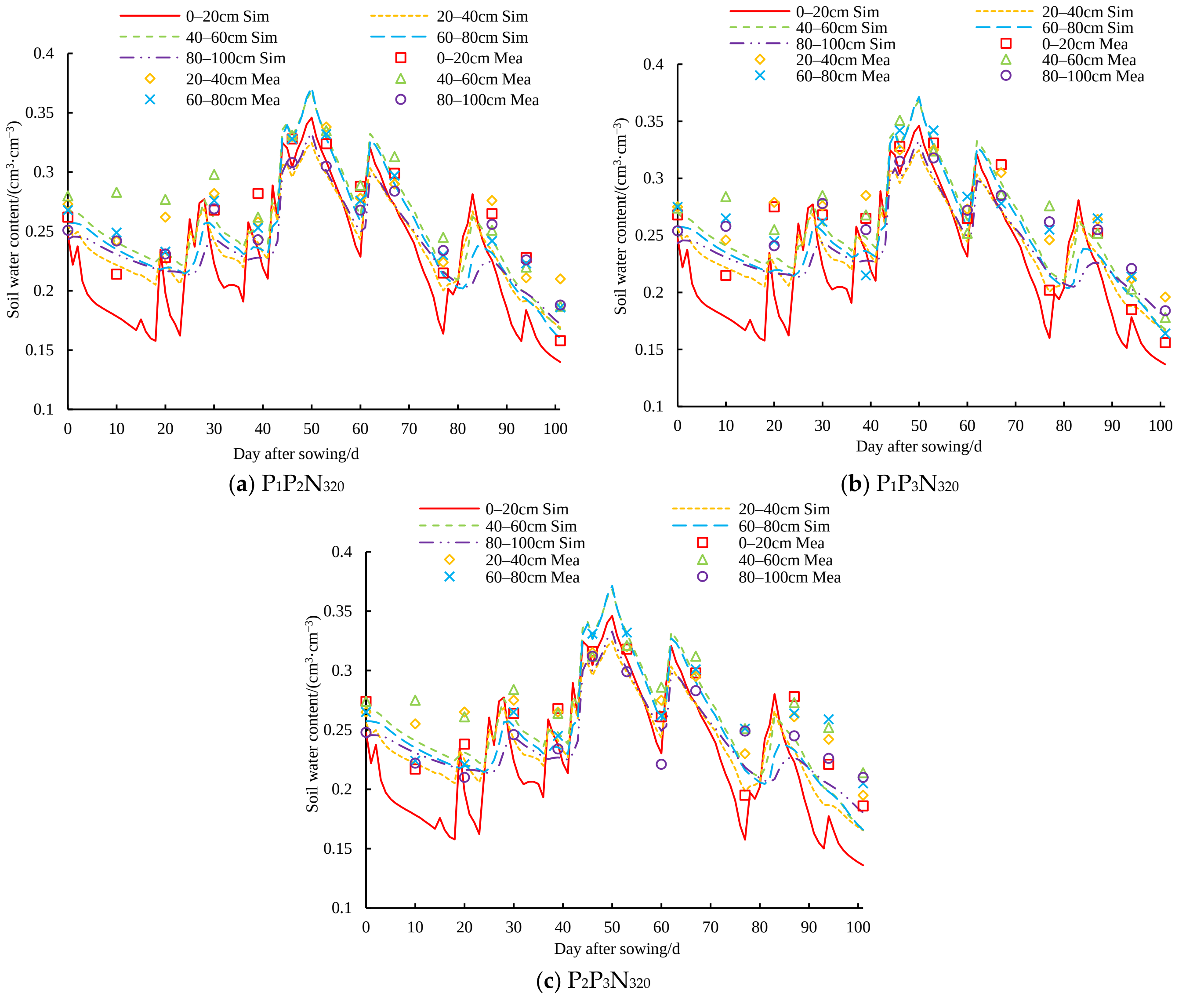


Figure 3. Measured and simulated values of soil volumetric water content of 0–100 cm soil layers under the $P_xP_yN_{320}$ (x, y = 1, 2, 3, and $x < y$) treatment in 2022. Note: In the diagram, "Sim" stands for "simulated value" and "Mea" stands for "measured value".

Table 4. Comparison of simulated and measured values of soil volumetric water content in the 0–100 cm soil layer during validation.

Treatment	Index	Soil Depth/cm				
		0–20	20–40	40–60	60–80	80–100
$P_1P_2N_{120}$	MRE/%	13.01%	12.50%	8.50%	6.95%	6.30%
	RMSE/($cm^3 \cdot cm^{-3}$)	0.036	0.035	0.026	0.021	0.018
	NRMSE/%	13.73%	12.78%	9.46%	8.12%	7.08%
$P_1P_3N_{120}$	MRE/%	12.42%	10.26%	8.80%	6.99%	7.01%
	RMSE/($cm^3 \cdot cm^{-3}$)	0.033	0.027	0.025	0.020	0.019
	NRMSE/%	13.16%	10.54%	9.27%	7.51%	7.65%
$P_2P_3N_{120}$	MRE/%	10.11%	9.71%	8.65%	6.51%	6.46%
	RMSE/($cm^3 \cdot cm^{-3}$)	0.026	0.026	0.025	0.018	0.017
	NRMSE/%	10.58%	10.15%	9.09%	6.96%	6.72%
$P_1P_2N_{220}$	MRE/%	12.73%	10.19%	8.77%	5.77%	7.28%
	RMSE/($cm^3 \cdot cm^{-3}$)	0.033	0.027	0.025	0.016	0.019
	NRMSE/%	13.05%	10.33%	9.17%	6.20%	7.57%
$P_1P_3N_{220}$	MRE/%	13.11%	10.99%	8.69%	6.93%	8.76%
	RMSE/($cm^3 \cdot cm^{-3}$)	0.034	0.029	0.025	0.020	0.024
	NRMSE/%	13.51%	11.17%	9.11%	7.71%	9.34%
$P_2P_3N_{220}$	MRE/%	12.72%	11.22%	9.39%	7.04%	8.66%
	RMSE/($cm^3 \cdot cm^{-3}$)	0.032	0.030	0.027	0.021	0.024
	NRMSE/%	12.81%	11.34%	9.78%	8.09%	9.35%
$P_1P_2N_{320}$	MRE/%	13.81%	11.18%	8.03%	6.09%	6.60%
	RMSE/($cm^3 \cdot cm^{-3}$)	0.037	0.031	0.025	0.017	0.018
	NRMSE/%	14.42%	11.68%	9.19%	6.39%	7.07%
$P_1P_3N_{320}$	MRE/%	12.88%	12.23%	6.98%	7.67%	8.55%
	RMSE/($cm^3 \cdot cm^{-3}$)	0.036	0.034	0.024	0.022	0.025
	NRMSE/%	14.26%	12.56%	9.10%	8.57%	9.42%
$P_2P_3N_{320}$	MRE/%	14.09%	11.34%	9.94%	7.11%	5.97%
	RMSE/($cm^3 \cdot cm^{-3}$)	0.036	0.031	0.029	0.025	0.017
	NRMSE/%	14.09%	11.68%	10.65%	9.41%	7.00%
CK	MRE/%	13.04%	10.68%	9.57%	6.81%	7.30%
	RMSE/($cm^3 \cdot cm^{-3}$)	0.033	0.030	0.028	0.019	0.020
	NRMSE/%	13.11%	11.11%	10.17%	7.25%	7.83%

3.1.2. Calibration and Validation of the Soil Nutrient Module

Figure 4 displays the simulated and measured nitrate-nitrogen content of the $P_xP_yN_{320}$ (x, y = 1, 2, 3, and $x < y$) treatment in 2022 during the validation process. With the application of subsoil fertilizer, nitrate nitrogen primarily accumulates in the 0–40 cm soil layer at the onset of summer maize growth. In the absence of additional nitrogen fertilizer input, the nitrate nitrogen in the upper layer is progressively absorbed by maize roots and diminished. Concurrently, nitrate nitrogen in the soil is leached and transported further to deeper soil strata due to sustained rainfall. Table 5 displays the MRE, RMSE, and NRMSE related to the nitrate nitrogen content during the validation process. The simulated values of nitrate nitrogen content across various soil layers under each treatment ranged from 4.36% to 33.01% for MRE, 0.111 to 1.995 mg/kg for RMSE, and 5.24% to 17.84% for NRMSE, signifying strong simulation outcomes.

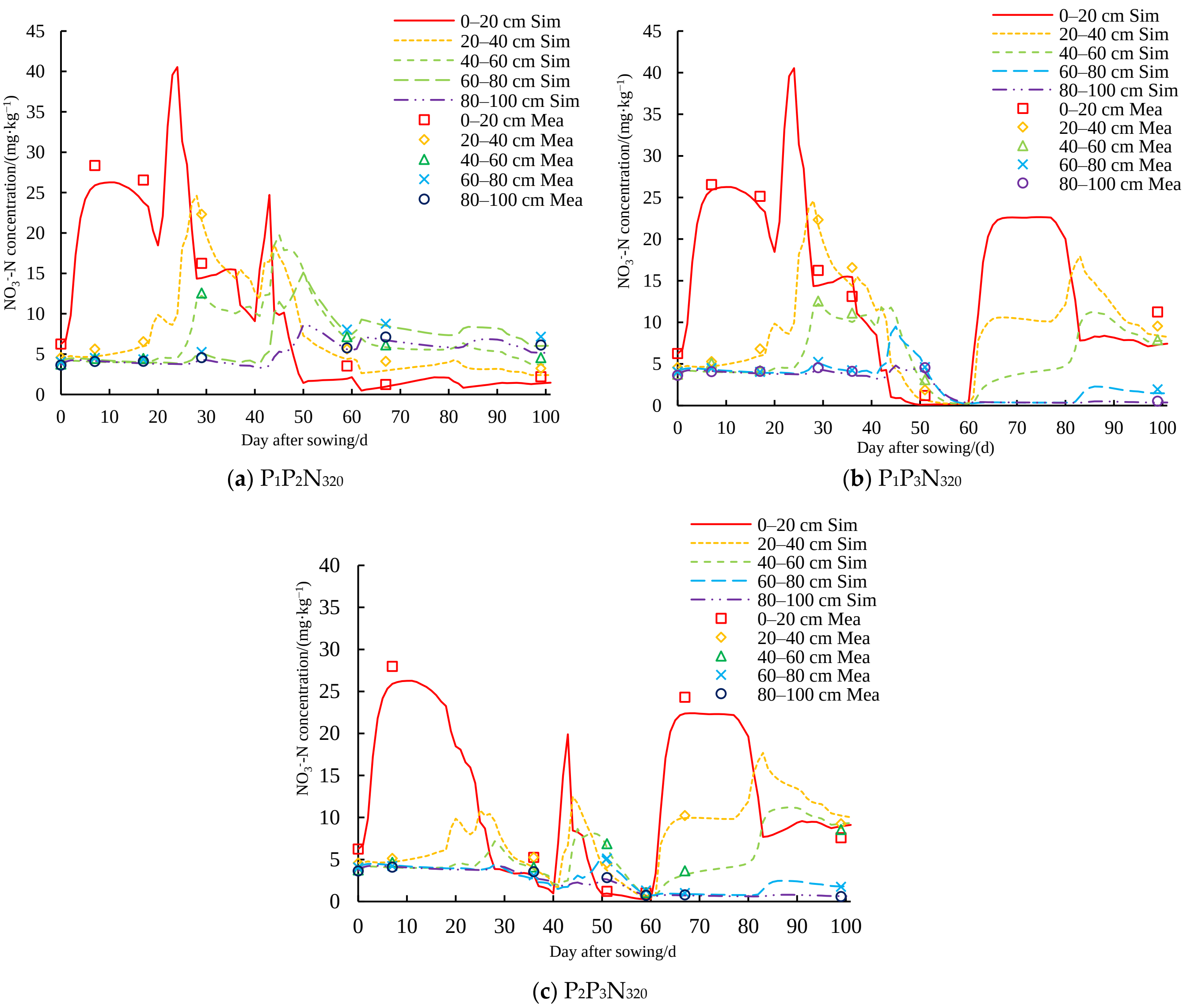


Figure 4. Measured and simulated values of NO_3^--N concentration of 0–100 cm soil layers under the $P_xP_yN_{320}$ (x, y = 1, 2, 3, and $x < y$) treatment in 2022. Note: In the diagram, "Sim" stands for "simulated value" and "Mea" stands for "measured value".

3.1.3. Calibration and Validation of the Crop Growth Module

Table 6 presents a comparison between the measured and simulated maize phenology values for different nitrogen application rates and periods of application during the validation process. The error between the observed and simulated maize phenology values for different nitrogen application rates and periods of application does not exceed three days. The analysis of observations revealed that the anthesis and maturity of maize under low-nitrogen treatments (P_1N_{120}, P_2N_{120}, P_3N_{120}, and CK) were earlier than under high-nitrogen treatments, ranging from two to three days. This finding serves as a preliminary indication of an early trend in the phenological stage of maize under low nitrogen stress. However, the simulations showed no difference in the simulated values of phenological stages between treatments. This is because the model's calculation of phenological stages primarily relies on temperature and does not consider the effects of water and nitrogen stress [34].

Table 5. Comparison of simulated and measured values of NO_3^--N concentration in the 0–100 cm soil layer during validation.

Treatment	Index	Soil Depth/cm				
		0–20	20–40	40–60	60–80	80–100
$P_1P_2N_{120}$	MRE/%	21.06%	15.26%	11.85%	7.09%	7.62%
	RMSE/(mg·kg^{-1})	1.102	0.482	0.230	0.199	0.160
	NRMSE/%	12.29%	11.94%	11.85%	5.89%	7.09%
$P_1P_3N_{120}$	MRE/%	17.77%	10.88%	4.96%	5.03%	4.98%
	RMSE/(mg·kg^{-1})	1.041	0.637	0.261	0.151	0.171
	NRMSE/%	10.49%	14.42%	8.20%	5.84%	7.33%
$P_2P_3N_{120}$	MRE/%	24.27%	14.41%	8.67%	8.37%	7.74%
	RMSE/(mg·kg^{-1})	0.911	0.312	0.206	0.116	0.160
	NRMSE/%	15.58%	13.53%	10.62%	6.53%	9.18%
$P_1P_2N_{220}$	MRE/%	20.54%	15.16%	10.34%	6.30%	4.36%
	RMSE/(mg·kg^{-1})	1.693	1.147	0.612	0.271	0.220
	NRMSE/%	13.34%	14.81%	10.38%	5.96%	5.66%
$P_1P_3N_{220}$	MRE/%	25.61%	21.54%	11.64%	15.84%	9.44%
	RMSE/(mg·kg^{-1})	1.680	0.934	0.478	0.250	0.205
	NRMSE/%	12.79%	13.84%	11.55%	8.98%	8.34%
$P_2P_3N_{220}$	MRE/%	20.95%	13.57%	7.74%	10.70%	6.81%
	RMSE/(mg·kg^{-1})	1.102	0.482	0.230	0.199	0.160
	NRMSE/%	13.09%	12.59%	8.08%	9.87%	8.43%
$P_1P_2N_{320}$	MRE/%	23.24%	16.43%	8.35%	5.40%	9.73%
	RMSE/(mg·kg^{-1})	1.995	1.141	0.636	0.215	0.313
	NRMSE/%	14.00%	11.92%	9.31%	5.24%	8.55%
$P_1P_3N_{320}$	MRE/%	19.18%	14.84%	6.94%	5.86%	5.48%
	RMSE/(mg·kg^{-1})	1.706	0.862	0.441	0.504	0.421
	NRMSE/%	14.15%	11.59%	7.16%	8.37%	8.32%
$P_2P_3N_{320}$	MRE/%	24.11%	17.65%	11.48%	11.38%	7.76%
	RMSE/(mg·kg^{-1})	1.461	0.737	0.457	0.290	0.208
	NRMSE/%	13.89%	12.89%	9.78%	9.84%	8.93%
CK	MRE/%	33.01%	12.67%	12.65%	8.34%	7.80%
	RMSE/(mg·kg^{-1})	0.510	0.233	0.136	0.133	0.111
	NRMSE/%	17.84%	13.41%	8.61%	7.36%	5.89%

Table 6. Comparison of measured and simulated maize phenological stage values at different nitrogen application rates and periods of nitrogen application during validation.

Treatment	Emergence (d)			Anthesis (d)			Maturity (d)		
	Measured	Simulated	Error	Measured	Simulated	Error	Measured	Simulated	Error
$P_1P_2N_{120}$	7	5	−2	56	57	1	98	100	2
$P_1P_3N_{120}$	7	5	−2	56	57	1	98	100	2
$P_2P_3N_{120}$	7	5	−2	56	57	1	98	100	2
$P_1P_2N_{220}$	7	5	−2	58	57	−1	100	100	0
$P_1P_3N_{220}$	7	5	−2	58	57	−1	101	100	−1
$P_2P_3N_{220}$	7	5	−2	57	57	0	100	100	0
$P_1P_2N_{320}$	7	5	−2	58	57	−1	101	100	−1
$P_1P_3N_{320}$	7	5	−2	57	57	0	101	100	−1
$P_2P_3N_{320}$	7	5	−2	58	57	−1	100	100	0
CK	7	5	−2	55	57	2	97	100	3

Note: Error = Simulated value − Measured value.

Table 7 demonstrates that the simulated values of maize yield, above-ground biomass, and above-ground nitrogen content were generally lower than the measured values under different treatments of nitrogen application periods and application rates during the validation process. The RE for maize yield ranged from −15.32% to −5.06%, the RE for above-ground biomass ranged from −15.19% to −7.07%, and the RE for above-ground nitrogen content ranged from −13.14% to −3.14%. From the RE values for each treatment, it is evident that maize yield, biomass, and nitrogen content were severely underestimated under the CK treatment. This is possibly due to the fact that the model's embedded CERES-Maize module significantly underestimated crop leaf area index (LAI) values in the stress scenario [35], affecting crop photosynthesis. Additionally, the CERES module is driven by photosynthesis as the main process [36], which contributes to this situation. Despite this, the model is reliable in simulating the yield, biomass, and nitrogen content of maize in this study (NRMSEs for yield, biomass, and nitrogen content for all treatments were less than 10%, representing an "excellent" level).

Table 7. Comparison of simulated and measured values of summer maize yield, above-ground biomass, and above-ground nitrogen content at different nitrogen application periods and nitrogen application rates during validation.

Treatment	Yield ($kg\cdot hm^{-2}$)			Aboveground Biomass ($kg\cdot hm^{-2}$)			Aboveground Nitrogen Uptake ($kg\cdot hm^{-2}$)		
	Simulated	Measured	RE	Simulated	Measured	RE	Simulated	Measured	RE
$P_1P_2N_{120}$	5859.56	6355 ± 110.62 de	−7.80%	14,005.97	15,112.74 ± 243.16 c	−7.32%	118.11	124.81 ± 9.33 d	−5.36%
$P_1P_3N_{120}$	5545.56	6014.95 ± 141.57 e	−7.80%	13,727.36	14,813.77 ± 157.37 c	−7.33%	120.83	129.53 ± 13.24 d	−6.72%
$P_2P_3N_{120}$	5923.67	6433.72 ± 203.74 d	−7.93%	14,163.88	15,241.36 ± 203 c	−7.07%	122.74	127.39 ± 6.13 d	−3.65%
$P_1P_2N_{220}$	7987.17	8508.75 ± 132.73 ab	−6.13%	16,430.72	18,139.29 ± 218.05 ab	−9.42%	176.72	183.58 ± 12.72 c	−3.74%
$P_1P_3N_{220}$	7789.50	8204.99 ± 211.13 bc	−5.06%	16,101.62	17,719.27 ± 96.95 b	−9.13%	181.39	188.33 ± 8.3b c	−3.68%
$P_2P_3N_{220}$	8123.89	8623.67 ± 126.56 a	−5.80%	16,872.32	18,311.01 ± 123.96 ab	−7.86%	183.39	189.33 ± 10.02 bc	−3.14%
$P_1P_2N_{320}$	7620.98	8173.75 ± 78.36 bc	−6.76%	16,562.23	18,256.32 ± 216.02 ab	−9.28%	201.97	209.84 ± 11.16 ab	−3.75%
$P_1P_3N_{320}$	7545.50	7975.9 ± 147.79 c	−5.40%	16,352.56	17,992.32 ± 135.89 ab	−9.11%	203.78	213.87 ± 12.26 ab	−4.72%
$P_2P_3N_{320}$	7789.60	8369.32 ± 203.53 abc	−6.93%	17,025.56	18,411.74 ± 206.8 a	−7.53%	205.69	219.81 ± 8.76 a	−6.42%
CK	4356.56	5144.76 ± 194.92 f	−15.32%	10,234.26	12,066.73 ± 636.59 d	−15.19%	71.52	82.34 ± 9.35 e	−13.14%
RMSE		535.59			1483.58			8.68	
NRMSE		7.26%			8.93%			5.20%	
MRE		7.49%			8.92%			5.43%	

Note: Different lowercase letters in the same column indicate significant differences among treatments ($p < 0.05$).

3.1.4. Comparison of Simulated and Measured Values of Nitrogen Indicators

Nitrogen indicators calculated based on model simulations were analyzed in comparison with those based on actual measurements, and the comparisons are demonstrated in Table 8. The MRE values for nitrogen agronomic efficiency were 15.29%, RMSE 1.720 kg/kg, and NRMSE 15.25% based on simulated and measured values, demonstrating a good level. The MRE values for nitrogen physiological efficiency were 10.33%, RMSE 2.820 kg/kg, and NRMSE 10.62%, being at a good level. The MRE values for nitrogen apparent recovery were 4.50%, RMSE 0.020, and NRMSE 4.75%, representing an excellent level. The trend of the nitrogen indicators was consistent, showing an increase followed by a decrease ("same period, different nitrogen application" or "same nitrogen application, different period"). In summary, the model is suitable for simulating nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery.

3.2. Analysis of Field Experiment Results

The results of field trials demonstrate that the amount and period of nitrogen application significantly influence the yield, above-ground biomass, and above-ground nitrogen content of summer maize. The yield of summer maize increased with increasing nitrogen application when the application period was consistent and began to decrease when the nitrogen application rate exceeded 220 kg/hm^2. However, the above-ground biomass and above-ground nitrogen content exhibited a continuous increase with the increase of the nitrogen application rates. Yield, above-ground biomass, and above-ground nitrogen content were highest for P_2P_3 (trumpeting and anthesis) when applied at the same nitrogen level but at different times of the year. As illustrated in Figure 5, nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery all exhibit an increase followed by a decrease with the increase of the nitrogen application for the same period, with the maximum value occurring at 220 kg/hm^2 of applied nitrogen. Yield, nitrogen agronomic efficiency, and apparent nitrogen recovery were all maximized at P_2P_3 when nitrogen was applied at the same rate, while nitrogen physiological efficiency was maximized at P_1P_2 (jointing and trumpeting). By using yield, nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery as indicators and based on the TOPSIS method (Table 9), it becomes evident that the P_2P_3 period is the most suitable for fertilizer application at the same nitrogen application level.

Table 8. Comparison of simulated and measured values of nitrogen indicators.

Treatment	Nitrogen Agronomic Efficiency (kg/kg)			Physiological Efficiency of Nitrogen (kg/kg)			Apparent Recovery of Nitrogen (%)		
	Measured	Simulated	RE	Measured	Simulated	RE	Measured	Simulated	RE
$P_1P_2N_{120}$	10.09	12.53	24.13%	28.5	32.26	13.18%	35.39	40.93	9.72%
$P_1P_3N_{120}$	7.25	9.91	36.67%	18.4	24.12	30.78%	39.32	43.19	4.47%
$P_2P_3N_{120}$	10.74	13.06	21.59%	28.61	30.60	6.95%	37.54	44.78	13.69%
$P_1P_2N_{220}$	15.29	16.50	7.93%	33.23	34.51	3.86%	46.02	48.96	3.90%
$P_1P_3N_{220}$	13.91	15.60	12.18%	28.87	31.25	8.23%	48.18	51.09	3.66%
$P_2P_3N_{220}$	15.81	17.12	8.31%	32.52	33.68	3.55%	48.63	52.00	4.57%
$P_1P_2N_{320}$	9.47	10.20	7.72%	23.76	25.02	5.32%	39.84	41.55	2.33%
$P_1P_3N_{320}$	8.85	9.97	12.60%	21.52	24.11	12.04%	41.10	42.12	0.56%
$P_2P_3N_{320}$	10.08	10.73	6.43%	23.46	25.59	9.07%	42.96	42.72	−2.40%
CK	-	-	-	-	-	-	-	-	-
MRE		15.29%			10.33%			4.50%	
RMSE		1.720			2.820			0.020	
NRMSE		15.25%			10.62%			4.75%	

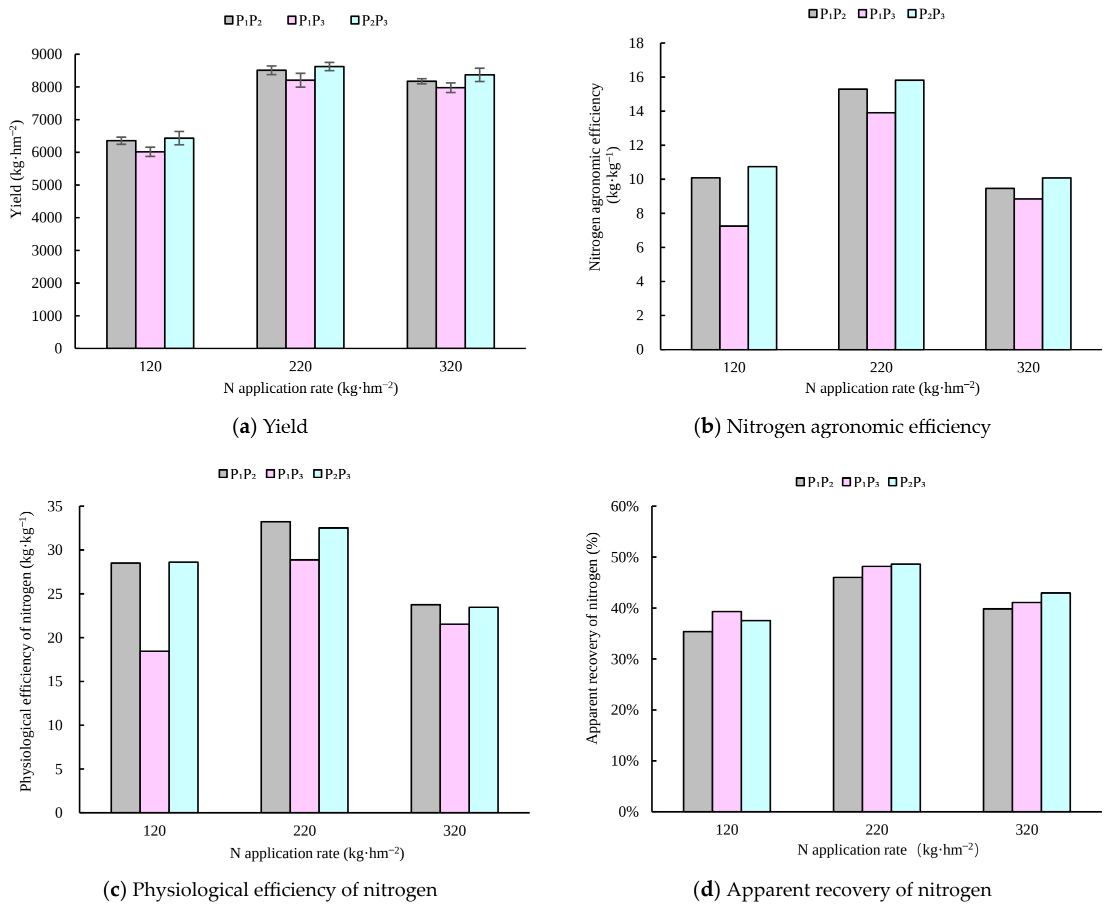


Figure 5. Comparison of summer maize yield, nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery at different nitrogen application periods and rates and apparent recovery of nitrogen in 2022.

Table 9. TOPSIS analysis table for field trials.

Scenario	Positive Ideal Solution Distance (D^+)	Negative Ideal Solution Distance (D^-)	Relative Proximity (C)	Sorting Result
$P_1P_2N_{120}$	0.225	0.149	0.398	6
$P_1P_2N_{220}$	0.026	0.324	0.926	2
$P_1P_2N_{320}$	0.228	0.135	0.373	7
$P_1P_3N_{120}$	0.334	0.031	0.085	9
$P_1P_3N_{220}$	0.079	0.269	0.773	3
$P_1P_3N_{320}$	0.255	0.113	0.307	8
$P_2P_3N_{120}$	0.203	0.163	0.445	4
$P_2P_3N_{220}$	0.009	0.338	0.975	1
$P_2P_3N_{320}$	0.209	0.156	0.428	5

3.3. Situational Application Analysis

3.3.1. Scenario Building

Based on field trials, the appropriate secondary nitrogen application timings for summer maize in this region are the trumpeting and anthesis stages. Nitrogen application rates of 160–320 kg/hm^2 were subdivided into nine scenarios of 160, 180, 200, 220, 240, 260, 280, 300, and 320 kg/hm^2, and the nitrogen application periods were set at the trumpeting and anthesis stages, with three levels of basal chasing ratios of 1:1:2, 1:2:1, and 2:1:1, as presented in Table 10. The model was simulated to find the optimal nitrogen fertilizer management model using the TOPSIS method with yield, nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery as indicators.

Table 10. Scenario simulation design.

Treatment	Base Fertilizer	Topdressing		Fertilizer Application Rate	Total
		Trumpeting	Anthesis		
$N_{160\ (1:1:2)}$	40	40	80	1:1:2	160
$N_{160\ (1:2:1)}$	40	80	40	1:2:1	160
$N_{160\ (2:1:1)}$	80	40	40	2:1:1	160
$N_{180\ (1:1:2)}$	45	45	90	1:1:2	180
$N_{180\ (1:2:1)}$	45	90	45	1:2:1	180
$N_{180\ (2:1:1)}$	90	45	45	2:1:1	180
$N_{200\ (1:1:2)}$	50	50	100	1:1:2	200
$N_{200\ (1:2:1)}$	50	100	50	1:2:1	200
$N_{200\ (2:1:1)}$	100	50	50	2:1:1	200
$N_{220\ (1:1:2)}$	55	55	110	1:1:2	220
$N_{220\ (1:2:1)}$	55	110	55	1:2:1	220
$N_{220\ (2:1:1)}$	110	55	55	2:1:1	220
$N_{240\ (1:1:2)}$	60	60	120	1:1:2	240
$N_{240\ (1:2:1)}$	60	120	60	1:2:1	240
$N_{240\ (2:1:1)}$	120	60	60	2:1:1	240
$N_{260\ (1:1:2)}$	65	65	130	1:1:2	260
$N_{260\ (1:2:1)}$	65	130	65	1:2:1	260
$N_{260\ (2:1:1)}$	130	65	65	2:1:1	260
$N_{280\ (1:1:2)}$	70	70	140	1:1:2	280
$N_{280\ (1:2:1)}$	70	140	70	1:2:1	280
$N_{280\ (2:1:1)}$	140	70	70	2:1:1	280
$N_{300\ (1:1:2)}$	75	75	150	1:1:2	300
$N_{300\ (1:2:1)}$	75	150	75	1:2:1	300
$N_{300\ (2:1:1)}$	150	75	75	2:1:1	300
$N_{320\ (1:1:2)}$	80	80	160	1:1:2	320
$N_{320\ (1:2:1)}$	80	160	80	1:2:1	320
$N_{320\ (2:1:1)}$	160	80	80	2:1:1	320

3.3.2. Analysis of Scenario Results

Figure 6 provides a comparative analysis of summer maize yield, nitrogen use efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery under varying nitrogen application rates and basal chasing ratios. The data indicate that the summer maize yield, nitrogen agronomic efficiency, and nitrogen apparent recovery for different basal chasing ratios from 180 to 320 kg/hm^2 initially show an increasing trend, followed by a decrease. However, nitrogen physiological efficiency consistently decreases over this range. Under identical nitrogen application rates, the crop yield, nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery were greater with a 1:2:1 base-to-chase ratio than with the other two tested ratios. This suggests that a light application of base-to-flower fertilizer, combined with a heavy application of trumpet fertilizer, supports optimal maize growth. As illustrated in Figure 6a, the rate of yield increase surpassed the rate of yield decrease at an application rate of 220 kg/hm^2. The relationship between yield at different basal chasing ratios with increasing nitrogen application followed the order: 1:2:1 > 2:1:1 > 1:1:2. According to Figure 6b, the relationship between nitrogen agronomic efficiency and yield at different basal chasing ratios remained consistent with the increase in nitrogen application, but the difference in nitrogen agronomic efficiency at varying basal chasing ratios was insignificant. As shown in Figure 6c, nitrogen physiological efficiency remained at a high level when the application rate ranged between 180 and 220 kg/hm^2. However, Figure 6d depicts that when the nitrogen application rate exceeded 200 kg/hm^2, the plant's nitrogen uptake was lower than the increase in nitrogen, resulting in a decrease in the apparent recovery of nitrogen as the nitrogen application rate increased.

3.3.3. Selection of Optimal Scenarios

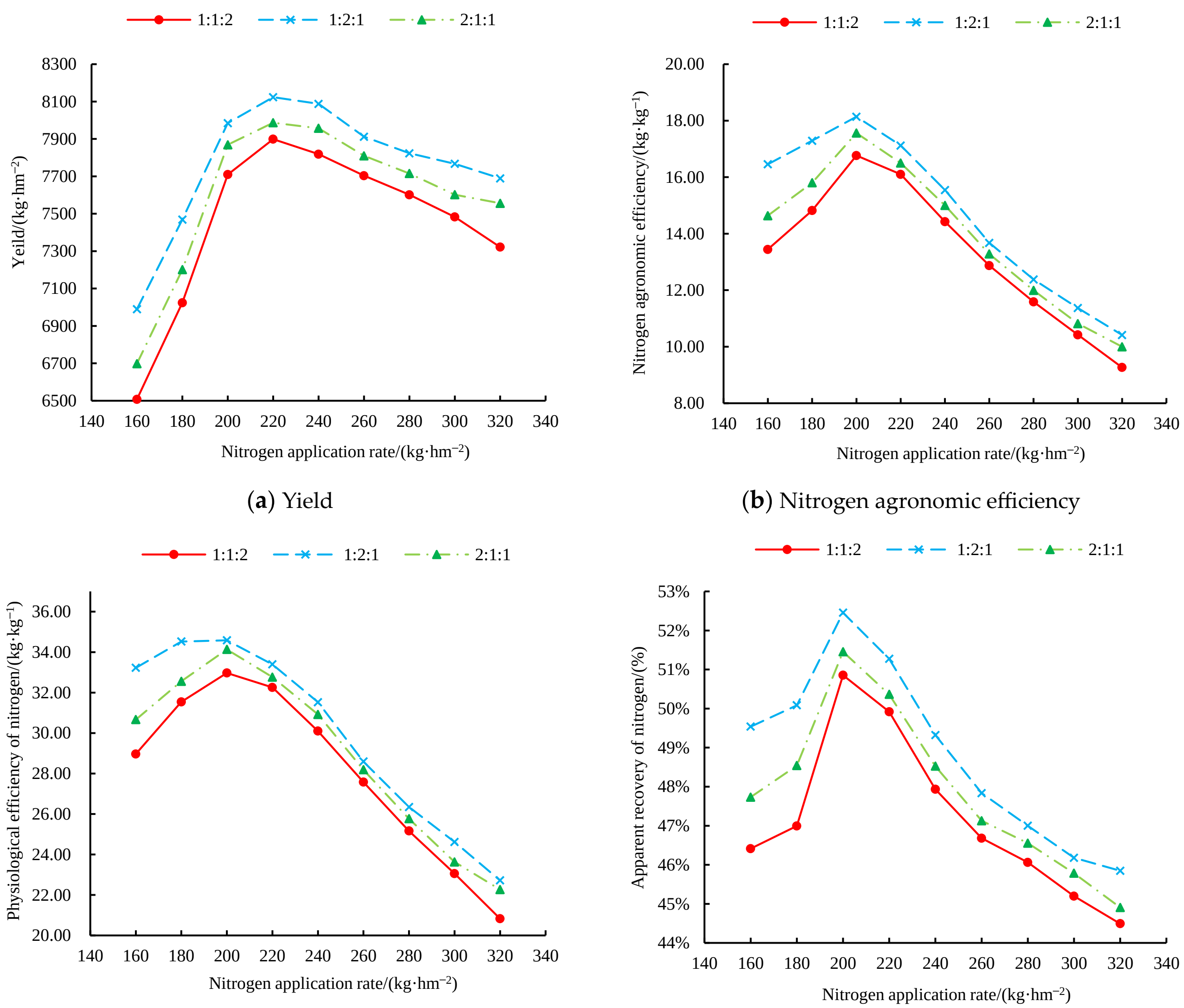
The results of the TOPSIS analysis are depicted in Table 11. In the top 2 scenarios, the basal chasing ratio was 1:2:1, indicating that a basal chasing ratio of 1:2:1 at the trumpeting and anthesis stages was the optimal nitrogen allocation, consistent with the results obtained from Figure 5. A more reasonable nitrogen application range is 180–200 kg/hm^2. The optimal scenario is 200 kg/hm^2 of nitrogen and a 1:2:1 basal chasing ratio.

Table 11. TOPSIS analysis table for scenario simulation.

Scenario	Positive Ideal Solution Distance (D^+)	Negative Ideal Solution Distance (D^-)	Relative Proximity (C)	Sorting Result
$N_{160\ (1:1:2)}$	0.084	0.082	0.494	17
$N_{160\ (1:2:1)}$	0.038	0.131	0.776	8
$N_{160\ (2:1:1)}$	0.065	0.101	0.610	14
$N_{180\ (1:1:2)}$	0.059	0.106	0.643	12
$N_{180\ (1:2:1)}$	0.022	0.145	0.869	4
$N_{180\ (2:1:1)}$	0.043	0.120	0.737	9
$N_{200\ (1:1:2)}$	0.024	0.134	0.847	5
$N_{200\ (1:2:1)}$	0.004	0.157	0.978	1
$N_{200\ (2:1:1)}$	0.011	0.148	0.929	2
$N_{220\ (1:1:2)}$	0.034	0.125	0.788	7
$N_{220\ (1:2:1)}$	0.017	0.142	0.892	3
$N_{220\ (2:1:1)}$	0.027	0.132	0.83	6
$N_{240\ (1:1:2)}$	0.061	0.098	0.616	13
$N_{240\ (1:2:1)}$	0.043	0.117	0.733	10
$N_{240\ (2:1:1)}$	0.052	0.108	0.678	11
$N_{260\ (1:1:2)}$	0.088	0.072	0.451	18
$N_{260\ (1:2:1)}$	0.075	0.086	0.536	15
$N_{260\ (2:1:1)}$	0.081	0.080	0.496	16
$N_{280\ (1:1:2)}$	0.111	0.051	0.313	21

Table 11. *Cont.*

Scenario	Positive Ideal Solution Distance (D^+)	Negative Ideal Solution Distance (D^-)	Relative Proximity (C)	Sorting Result
$N_{280\ (1:2:1)}$	0.097	0.065	0.399	19
$N_{280\ (2:1:1)}$	0.104	0.058	0.357	20
$N_{300\ (1:1:2)}$	0.132	0.033	0.198	25
$N_{300\ (1:2:1)}$	0.115	0.049	0.299	22
$N_{300\ (2:1:1)}$	0.125	0.039	0.239	23
$N_{320\ (1:1:2)}$	0.154	0.021	0.118	27
$N_{320\ (1:2:1)}$	0.133	0.036	0.213	24
$N_{320\ (2:1:1)}$	0.140	0.030	0.175	26



(**a**) Yield (**b**) Nitrogen agronomic efficiency

(**c**) Physiological efficiency of nitrogen (**d**) Apparent recovery of nitrogen

Figure 6. Comparison of summer maize yield, nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery at different nitrogen application and basal chasing ratios.

4. Discussion

4.1. Adaptation Analysis of the RZWQM2 Model

In this study, the soil moisture module, soil nutrient module, and crop growth module of the RZWQM2 model were calibrated and validated based on field measurement data, and the results demonstrated a high simulation accuracy. For the moisture module, the MRE of soil volumetric moisture content for each soil layer under different treatments ranged from 5.58% to 14.09%, RMSE from 0.016 to 0.037 cm^3/cm^3, and NRMSE from 6.20% to 14.42%. The simulation performance of the upper soil layer's moisture content was lower than that of the lower soil layer, which differed from the simulation results of Zhou et al. [37]. This discrepancy may be due to (a) the upper soil layer's moisture state being more susceptible to instability from rainfall, plant root growth, evaporation, and other factors, making accurate simulation challenging; and (b) the surface soil capacity, field water holding capacity, and saturated hydraulic conductivity being prone to significant spatial and temporal variability due to external condition changes, which the model does not account for [38]. The simulated values of soil volumetric moisture content were greater than the measured values, primarily because the trial period had high rainfall, and the model input is an average of the time periods, differing from the actual instantaneous rainfall in the field [39].

For the nutrient module, the MRE for nitrate nitrogen content in each soil layer ranged from 4.36% to 33.01%, RMSE from 0.111 to 1.995 mg/kg, and NRMSE from 5.24% to 17.84%, with the upper layer being less effectively simulated than the lower layer. This is not only related to the poor simulation accuracy of the topsoil layer's water content, but may also be due to the top layer of the soil being prone to ammonia volatilization and denitrification reactions. This is probably because ammonia volatilization and denitrification are likely to occur in the top layer of the soil, making accurate simulation difficult. For the plant growth module, the simulated value of the phenological period is within three days of the measured value. Both Ma et al. [35] and Fang et al. [40] reported a simulation error of approximately 4–5 days regarding maize phenology. In comparison, the simulations in this study proved to be more accurate. MRE, RMSE, and NRMSE for yield were 7.49%, 535.59 kg/hm^2, and 7.26%, respectively; MRE, RMSE, and NRMSE for above-ground biomass were 8.92%, 1483.58 kg/hm^2, and 8.93%, respectively, and MRE, RMSE, and NRMSE for above-ground nitrogen content were 5.43%, 8.68 kg/hm^2, and 5.20%. The model simulation underestimates the three of these indicators, potentially because the model underestimates the LAI values at the time of filling, resulting in a reduction in plant organic matter accumulation and consequently in biomass, nitrogen content, and yield. The nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery calculated based on the simulated values fail to differ significantly from the values calculated from the field measurements. Thus, the RZWQM2 model can be effectively applied to simulate summer maize nitrogen fertilizer management in the Yellow River irrigation area.

4.2. Suitable Nitrogen Fertilizer Management Patterns for Summer Maize

The appropriate amount of nitrogen application not only increases crop yield but also provides significant environmental benefits. Through field trials in the North China Plain, Wang et al. [41] identified a suitable nitrogen application rate of 185 kg/hm^2. Despite a slight 2% decrease in yield, this rate led to a notable 30% reduction in nitrate nitrogen residues and wetting. The results of these trials indicated that, for a constant nitrogen application period, maize yield initially rises and then declines with increasing nitrogen application. This suggests that a certain nitrogen threshold exists for maize seed formation, beyond which the yield decreases. This finding echoes a 2-year field trial in Shandong by Shi et al. [7] and supports the phenomenon referred to as the "law of diminishing returns" by Meng et al. [42]. Notably, after reaching the threshold, above-ground biomass barely increases, and above-ground nitrogen content significantly increases, a trend that contradicts yield, A similar phenomenon emerged during the study by Yu et al. [43] and Li et al. [44]. This may be due to the inhibition of nitrogen transport from the maize organ to the kernel after a certain nitrogen application threshold, and the continued accumulation of nitrogen in the stems and leaves of the plant, leading to a reduction in yield. In the scenario simulation, combined with the TOPSIS method analysis, applying 180–200 kg/hm^2 of nitrogen fertilizer can essentially meet the needs of high and stable yield of summer maize. Compared to the traditional fertilizer application of 360 kg/hm^2 by farmers in the

Yellow River irrigation Area [45], the reduction of 160–180 kg/hm^2 of nitrogen fertilizer reduces agricultural surface source pollution as well as significantly improves nitrogen utilization efficiency.

Field trial results demonstrated that crop yield, above-ground biomass, and above-ground nitrogen content did not differ significantly between the P_1P_2 and P_2P_3 periods of nitrogen application at the same nitrogen application level, while it was observed in the field that treatments with nitrogen follow-up at the jointing period were prone to lodging when encountering higher-intensity rainfall, a phenomenon also found by Tang et al. [46] and others. This is possibly because the follow-up at the jointing period tends to bring about high plant height and ear position of maize, so the follow-up period could be delayed until the trumpeting stage, if possible. Ding et al. [47] showed that maize absorbed 43.9% to 50.9% of the plant's nitrogen accumulation after anthesis, explaining the reason that plants with over-treated nitrogen at anthesis contained higher nitrogen than other treatments. The combination of yield, nitrogen physiological efficiency, nitrogen agronomic efficiency, and nitrogen apparent recovery, based on TOPSIS analysis, resulted in the best fertilizer follow-up at P_2P_3.

The use of different nitrogen fertilizer application rates for the same period of maize significantly affects maize growth, development, and yield [43,47–50]. In the scenario simulations, the basal chasing ratios of 2:1:1, 1:2:1, and 1:1:2 represented heavy application of basal fertilizer, heavy application of trumpet fertilizer, and heavy application of anthesis fertilizer, respectively. The simulation results revealed that heavy application of basal fertilizer resulted in excessive nitrogen concentration in the maize seedling stage, where maize failed to possess a high demand for nitrogen [51], leading to serious nutrient wastage and resulting in low yield and nitrogen use efficiency. Heavy application of anthesis fertilizers stunted maize growth during critical fertility periods, affecting nutrient accumulation and not fully exploiting maize yield and nitrogen use efficiency despite its high nitrogen content. Conversely, heavy application of trumpet fertilizer met the nutrient requirements of the nutritional stage and supplemented post-anthesis nitrogen requirements, ultimately allowing yields and nitrogen use efficiency to be maintained at a high level. However, the above conclusion contradicts the findings of Liu et al. [13] who concluded that heavy application of pulling fertilizer is more appropriate. The authors posit that although maize nitrogen-chasing typically occurs during the pulling stage. The maize plants fertilized during the pulling stage demonstrated higher plant height and ear position, and were less resistant to lodging, with a quite high intensity of rainfall in summer. The combination of the above plants' physiological factors and external environmental factors further elevates the risk of lodging. Consequently, a heavy application of trumpet fertilizer is more advantageous than a heavy application of pulling fertilizer.

5. Conclusions

Based on a two-year summer maize trial in the field, this study investigated the response of summer maize to different nitrogen application rates and periods of application. RZWQM2 was calibrated and validated using field-measured data. Based on the field trial results, different scenarios were created using RZWQM2 to examine the effects of different nitrogen application rates and basal chasing ratios on summer maize yield, nitrogen agronomic efficiency, nitrogen physiological efficiency, and nitrogen apparent recovery. The TOPSIS method was utilized for a comprehensive evaluation, yielding the following conclusions:

(1) The simulation errors of the RZWQM2 model for soil moisture, soil nitrogen, and crop growth during the summer maize fertility period remained within reasonable limits. The simulated yields responded significantly to different nitrogen fertilizer management patterns, and the nitrogen indicators calculated based on the simulated values were generally consistent with the field measurements. Consequently, the RZWQM2 model is appropriate for research related to summer maize in the Yellow River irrigation area.

(2) In accordance with the field trials and scenario simulations, a more appropriate nitrogen application rate for the Yellow River irrigation area, determined by applying the TOPSIS evaluation method, is 180–200 kg/hm^2. The optimal nitrogen fertilizer management pattern involves applying 200 kg/hm^2 of nitrogen with a 1:2:1 basal chasing ratio at the sowing, trumpeting, and anthesis stages.

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