*Pak. J. Bot.*, 57(6): DOI: http://dx.doi.org/10.30848/PJB2025-6(10)

# SIMULATION OF WATER-NITROGEN MOVEMENT AND NITROGEN UTILIZATION RATE IN BLACK SOIL MAIZE FIELDS USING THE WHCNS MODEL

XIN SUN[1†], DAN WEI[2*], LIANG JIN[2†], LEI WANG[2*], PENG WANG[1], DAWEI YIN[1], GUOYUAN ZOU[2], YAN LI[2], JIAN LI DING[2], LINA LIANG[2], QIANG ZUO[2], SEN XU[2], LEI SUN[3], WEI WANG[3], HUIBO SHEN[4], YUXIAN WANG[4], JUNQIANG WANG[4], HANYE HUI[4] AND KUIFENG XU[3]

*[1]College of Agricultural Science and Technology, Heilongjiang Bayi Agricultural University, Daqing, Heilongjiang 163319, China*
*[2]Institute of Plant Nutrition, Resources and Environment, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China*
*[3]Heilongjiang black soil protection and Utilization Research Institute, Heilongjiang Academy of Agriculture and Sciences, Haerbin, 100094, Heilongjiang Province, China*
*[4]Qiqihar Branch of Heilongjiang Academy of Agricultural Sciences, Qiqihar 161006, China*
*[5]Northeast Agricultural University, Haerbin, China*
*[*]Corresponding author's e-mails: wd2087@163.com; yzswanglei@163.com*
*[†]Authors contributed equally to this work*

**Abstract**

Straw returning is essential for soil conservation and mitigating wind erosion in semiarid regions bearing black soil areas. Quantitative studies on crop development and soil water-nitrogen dynamics processes under complete straw returning are fundamental for establishing a rational farmland management system. To model crop yields and soil profile water-nitrogen distribution under various fertilization treatments, we used the soil water heat carbon nitrogen simulator (WHCNS), namely CK (no fertilization), T1 (compound fertilizer), T2 (compound fertilizer + straw returning), and T3 (humic acid fertilizer + straw returning). We calibrated and evaluated the performance of the WHCNS model by using soil water content, nitrate nitrogen content, aboveground dry matter mass, and yield data collected from the Meilisi Daur District experimental farm in Qiqihar, Heilongjiang Province, in 2022. We also simulated the effects of different fertilization methods on spring maize field evapotranspiration, crop yield, and water-nitrogen use efficiency. The results indicate that the hydraulic parameters Qs and n significantly impacted the soil water content in the parameter sensitivity analysis. In contrast, SLAmax had the largest impact on soil nitrate nitrogen content among crop parameters, and Ts was the most influential factor on crop yield. The relative root mean square errors of simulated and observed soil water storage, nitrate nitrogen content, and aboveground dry matter mass were all lower than 32%. Consistency indices for the 0–60 cm and 60–100 cm soil layers were greater than or equal to 0.68 and 0.30, respectively. Finally, the Nash coefficients were within reasonable ranges. The evapotranspiration rate under the straw returning treatment (T2) was 6.33% lower than without straw returning (T1). T2 exhibited the highest water-nitrogen use efficiency among all treatments, and compared with T1 and T3, water-nitrogen use efficiency increased by 10.27%, 7.78%, 26.71%, and 48.15%, respectively. These findings suggest that straw returning can effectively reduce evapotranspiration and improve resource utilization efficiency. Overall, the calibrated WHCNS model can reliably simulate the dynamics of soil water–nitrogen movement and crop growth under straw returning in the semiarid regions of northeastern China.

**Key words:** Soil, WHCNS model; Evapotranspiration; Water use efficiency; Nitrogen use efficiency.

## Introduction

Water resources are exceedingly scarce in the northern Chinese regions, with the six provinces in North China accounting for only 4.56% of China's total water resources (Fu, 2008). The water distribution in these water-scarce regions is limited and unevenly distributed across seasons (Jia *et al.*, 2004), making the efficient use of water resources critically important. Water is an essential resource consumed in agricultural production, and field irrigation plays a positive role in expected crop growth. However, water wastage is often encountered in agricultural irrigation (Zhang, 2023). Therefore, the quantitative utilization of water resources, which aims to increase the efficiency of precipitation and supplementary irrigation, represents a scientific and efficient approach. Nitrogen is a crucial component of many essential compounds within plants and is a critical factor in crop yield formation. This component is an indispensable nutrient for crops. A large amount of chemical nitrogen fertilizer is applied in agricultural production for high yields. Nitrogen fertilizer is a crucial nutrient element that affects the growth and development of maize. Proper nitrogen application can significantly increase maize yield (Li, 2021; Qu *et al.*, 2022). However, excessive nitrogen application in pursuing high maize yields has become increasingly problematic (Xie *et al.*, 2020). Low utilization rates of nitrogen fertilizers raise the costs of agricultural production and lead to several environmental issues, such as declining soil fertility, soil compaction, air pollution from nitrogen oxides, the greenhouse effect, water pollution from nitrate, and eutrophication, all of which hinder sustainable agricultural development (Jumadi *et al.*, 2020; Zheng *et al.*, 2020). Rational water-nitrogen management improves leaf photosynthetic performance and significantly regulates nitrogen accumulation, translocation, and utilization (Liu *et al.*, 2018).

Due to the long-term lack of significant improvements in water-nitrogen management in the black soil region of Qiqihar, coupled with the nutrient leaching losses caused by the annually increasing use of fertilizers, the efficiency of fertilizer utilization remains low. This has exacerbated the growing discrepancy between soil productivity and the steadily increasing demand for food among the population. Therefore, proposing rational water–nitrogen management models is critically important.

Utilizing models to simulate different crops has emerged as an effective method for researching soil water-nitrogen use and crop growth in recent years. The root zone water quality model-version (RZWQM) is one of the models now available for simulating soil water dynamics and crop growth processes, such as the simulator for agricultural production systems (APSIM), the denitrification-decomposition (DNDC) and erosion-productivity impact calculator (EPIC). Ma *et al*., (2022) used the APSIM model to simulate the yield of spring maize under different fertilization treatments. Lin *et al*., (2011) employed the Water and Nitrogen Management Model (WNMM) to simulate soil water dynamics and nitrogen fate under different fertilization regimes in maize seasons. Li *et al*., (2023) employed the HYDRUS-1D model to simulate water level fluctuations in the vicinity of the Wuqiangxi Reservoir.

Although these models are capable of simulating crop growth, development, and water transport, they each exhibit certain limitations. For instance, the HYDRUS-1D model lacks the ability to accurately simulate nitrogen dynamics and does not incorporate crop growth and development processes. Likewise, the RZWQM model, despite offering multiple scenario modes, fails to consider intensive cultivation practices such as mulching and rotary tillage. To address the specific needs of modern agricultural production in China, the water heat carbon nitrogen simulation (WHCNS) model was developed by integrating key components from internationally recognized models (RZWQM, HYDRUS-1D, Daisy, FAO, and PS123) and further refined through subsequent modifications. This model effectively couples soil water and thermal solute transport processes with soil carbon and nitrogen dynamics. It enables a comprehensive analysis of soil water movement, solute transport, carbon and nitrogen transformations, and the effects of water and nitrogen stress on crop yield. Liang *et al*., (2016) developed the WHCNS model specifically to simulate the water, heat, carbon, and nitrogen processes in soil-crop systems. It has been successfully applied in simulating soil water movement and crop growth in the wheat–maize rotation areas of the North China Plain. To date, numerous Chinese scholars have focused their quantitative research on the numerical simulation and analysis of resource utilization, including soil moisture distribution, solute transport, crop growth dynamics, and yield in agricultural lands. However, limited attention has been paid to the study of soil water and nitrogen transport under straw mulching conditions (where straw is returned to the field), particularly in semi-arid regions where the combined simulation of crop yield and dry matter accumulation remains underexplored.

In this study, the WHCNS model was employed to simulate soil water transport and crop growth under different fertilization treatments. Field measurements of soil water storage, nitrate nitrogen content, aboveground dry matter mass, and yield under various fertilization regimes were obtained from the experimental farm in the Meilisi Daur District, Qiqihar, Northeast China, to calibrate the model. This model was then used to evaluate the effects of straw returning techniques on crop water consumption, yield, and water use efficiency (WUE), thereby providing theoretical and technical support for the optimization of agricultural practices in China.

## Materials and Methods

**Overview of the study area:** The study was conducted at a long-term fixed-position farmland experiment base in Qiqihar, Heilongjiang Province, located in Northeast China (47°16.26′N, 123°41.46′E). This area is part of the semiarid western region of the Songnen Plain and is characterized by a continental monsoon climate. Winters are dry and cold, while summers are hot and rainy. The average temperature every year is between 0.7℃ and 4.2℃. Annual rainfall is approximately 500 mm, and the annual evaporation rate ranges from 1,000 to 1,500 mm. The frost-free period lasted from 122 to 151 days. The topography consists of mountains and plains with an altitude of 149 m. The soil type in the region is chernozem.

**Experiment design:** Three replicates of the field plot experiment were conducted using a randomized block design, with ditches separating each plot. Four fertilization modes were established: T0: control (no fertilization, CK); T1: compound fertilizer; T2: compound fertilizer + straw returning; T3: humic acid fertilizer + straw returning. The area of each plot was 40 $m^2$. The row spacing for ridging was 65 cm, and the plant spacing for maize was 25 cm (4,000 plants per mu). The maize variety used was "Nendan 19." The fertilization rates were as follows: compound fertilizer at 50 kg/mu (N: $P_2O_5$: $K_2O$ = 26: 10: 2), and humic acid fertilizer at 30 kg/mu, with a humic acid content of 10%. Each experimental plot was effectively established with an area of 39 $m^2$.

**Measurement indicators and methods:** Before the start of the experiment, soil profiles were excavated in the designated experimental area, and samples were collected from five soil layers (each 20 cm in depth) to determine the mechanical composition, bulk density, and other soil hydraulic properties, as listed in Table 1. The soil's mechanical composition was analyzed using the pipette method. Bulk density and saturated moisture content were determined using the ring knife method. Saturated hydraulic conductivity was measured using the constant head method. Residual water content was determined via the oven-drying method. Field water-holding capacity and wilting point were determined using a pressure plate apparatus (Model 1500FI, USA) at applied pressures of 0.033 MPa and 1.5 MPa, respectively.

**Table 1. Field management of spring maize rotation experiment in 2022.**

| Treatments | Sowing data | Harvesting data | Nitrogen application rate (kg/hm) | Carbon content (kg/hm$^2$) |
|---|---|---|---|---|
| CK | 2022-04-25 | 2022-10-08 | 0 | 0 |
| T1 | | | 195 | 0 |
| T2 | | | 195 | 6000 |
| T3 | | | 95.4 | 87.75 + 6000 |

The soil water content, nitrate nitrogen content, and crop growth were monitored during the experiment. The soil water content was determined using the oven-drying method with aluminum boxes, and nitrate nitrogen was measured using flow analysis. Each treatment was repeated three times, and measurements were taken once during each key growth stage (e.g., seedling, jointing, silking, grain filling, and maturity), from 0 to 100 cm soil depth, in layers of every 20 cm. The aboveground dry matter mass was measured during the critical growth stages of the crops (e.g., seedling, jointing, silking, grain filling, and maturity). For each treatment, samples were taken from three uniformly grown plants, then placed in a laboratory oven at 105℃ for 30 min to induce wilting and dried at 80℃ until a constant mass was reached to determine their aboveground dry matter mass. Following crop maturation, three 1 m2 quadrats with uniform growth were selected from each treatment. The grains were threshed and sun-dried, and the mass was weighed to measure crop yield. Meteorological data for the research area came from the nearby Qiqihar meteorological station, including daily temperature (e.g., maximum, minimum, and average), relative humidity, sunshine hours, precipitation, and wind speed, among other meteorological elements.

**Model introduction:** WHCNS V1.0 is a simulation program designed for modeling soil–plant–atmosphere systems. It consists of multiple modules addressing weather, soil water, heat and nitrogen transport, crop growth, organic matter decomposition, root water and nitrogen uptake, inorganic nitrogen dynamics, and field management. The WHCNS model is capable of simulating most key processes in soil-plant systems. It incorporates the meteorological module from the Food and Agriculture Organization of the United Nations (FAO) (Luis *et al.*, 2024) and the PS123 crop model from the Netherlands (Driessen & Konijn 1992), drawing upon the relevant theories of water solute transport from the Daisy, Hydrus-1D, RZWQM, and LeachM models and modifying and improving upon them.

The model operates with a day as the step length, capable of analyzing soil water and heat dynamics, nitrogen fate, organic matter turnover, crop growth, and greenhouse gas emissions. The WHCNS model is a comprehensive tool that enables quantitative analysis of how management measures related to water and fertilizer in the field impact crop production and the environment.

**Evaluation of model simulation performance:** The efficacy of the model simulation is assessed using the following three statistical indicators: the relative root mean square errors (nRMSE), index of agreement (d), and Nash-Sutcliffe efficiency (NSE). The nRMSE represents the relative error in the model simulation, with values closer to zero indicating a closer approximation of the simulation values to the observed values, thus denoting superior model simulation performance. Some scholars indicate that nRMSE values lower than 15%, between 15% and 30%, and greater than 30% represent excellent, good, and poor model simulation performance, respectively. The index of agreement (d) can be used to evaluate the predictive capability of the model. Its value range is between 0 and 1. Values approaching 1 signify better simulation performance. The value range for NSE is from $-\infty$ to 1, with values closer to 1 representing better simulation outcomes. Based on prior research, it is suggested that $d \geq 0.75$ and $NSE \geq 0$ serve as the minimum thresholds for evaluating the simulation performance of crop growth indicators. In contrast, $d \geq 0.60$ and $NSE \geq -1.0$ are recommended as the minimum thresholds for assessing the simulation performance of soil indicators (Ren *et al.*, 2022).

## Results and Analysis

**Model calibration results:** The model was calibrated using observed data from the spring maize growing season of 2022, which includes the water content of the soil, nitrate nitrogen, aboveground dry matter mass, and yield for each treatment at depths ranging from 0 to 100 cm of soil depth. Table 2 shows the input of the measured soil parameter values. The baseline values for crop parameters were derived from previous research conducted in Northern China (Li *et al.*, 2015). A "trial and error" method was employed to adjust the crop parameters until the model outputs closely matched the observed values. The final calibrated crop parameters are listed in Table 3. Upon completion of calibration, the model parameters were fixed, and the model was validated using observed data from the 2022 spring maize growing season. Data from treatments CK and T1 were used for parameter calibration, while treatments T2 and T3 were used for model validation.

**Table 2. Soil basic physical properties in the study area.**

| Soil layer (cm) | Sand particle (%) | Silt particle (%) | Clay particle (%) | Bulk density (g·cm-3) | Saturated hydraulic conductivity (cm·d$^{-1}$) | Saturated moisture content (cm$^3$·cm$^{-3}$) | Residual water content (cm$^3$·cm$^{-3}$) |
|---|---|---|---|---|---|---|---|
| 0-20 | 17.2 | 25.3 | 57.5 | 1.52 | 6.37 | 0.4387 | 0.0944 |
| ＞20-60 | 19.5 | 26.2 | 54.3 | 1.63 | 4.05 | 0.4038 | 0.0888 |
| ＞60-100 | 21.5 | 26.9 | 51.6 | 1.76 | 2.23 | 0.3660 | 0.0820 |

**Table 3. Calibration results of crop parameters for winter wheat–summer maize rotation under different tillage treatments.**

| Crop | Treatments | Crop coefficient | | | Total effective accumulated temperature/ ℃ | Specific leaf area/ (m$^2$·kg$^{-1}$) | | $CO_2$ assimilation rate/(kg·hm$^{-2}$·h$^{-1}$) | | Maximum root length/ cm |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Initial stage | Middle stage | End stage | | Maximum | Minimum | Maximum | Minimum | |
| Spring maize | CK | 0.65 | 0.8 | 1.45 | 1700 | 25 | 15 | 60 | 0.35 | 120 |
| | T1 | | | | | 30 | 15 | 60 | 0.31 | |
| | T2 | | | | | 30 | 15 | 60 | 0.35 | |
| | T3 | | | | | 30 | 15 | 59 | 0.32 | |

Figure 1 depicts the comparison between the simulated and observed soil water contents. The simulated soil water content for each treatment was consistent with the observed values, increasing with rainfall and decreasing with increased crop water consumption. The amount of water in the soil's top layer fluctuated more significantly as a result of direct precipitation and severe surface evaporation, with its water content varying between 19.64% and 41.56%. The changes in soil water content during the growing season for spring maize display a trend of initially increasing and then decreasing over time. This was because the water requirement of crops was low in the initial stages of the growing season for spring maize but became significantly high in the middle and late stages. Despite multiple rainfall events occurring in later stages, they could not enhance the water storage capacity of the soil. Overall, the dynamic changes in soil water content among the treatments did not show significant differences.

The simulated and observed values of aboveground dry matter mass and soil nitrate nitrogen content are compared in Figs. 2 and 3, respectively. As shown in Fig. 2, following fertilizer application, nitrate nitrogen concentrations in the 0–20 cm soil layer peaked initially across all treatments, with values ranging from 14.56 mg N/kg to 64.21 mg N/kg. Following the silking stage, there was a declining trend in nitrate nitrogen content, with a narrow range of fluctuations between 3.97 mg N/kg and 46.24 mg N/kg. Concentrations in the 60–100 cm layer increased initially to 3.97–26.34 mg N/kg and then decreased to 2.97–20.31 mg N/kg in all treatments. Figure 3 shows no noticeable disparities in the aboveground dry matter across the different treatments.

The model's simulation impacts on soil water content, soil nitrate nitrogen content, and aboveground dry matter mass are displayed in Figure 4. The simulated soil water content nRMSE, d, and NSE values compared to the observed values for the four treatments ranged between 5.77–10.26%, 0.30–0.98, and 0.16–0.94, respectively. This result indicates a high consistency between the simulated and observed values. The nRMSE, d, and NSE values of the simulated soil nitrate nitrogen content compared to the observed values were between 11.52–31.60%, 0.66–0.98, and −2.33–0.92, respectively. The simulation values align well with the observed values in the 0–60 cm soil layer, but the simulation is less accurate in the 60–100 cm soil layer. According to the study by Liang (Liang,2017), lower NSE values are usually acceptable, considering the complexity of soil nitrogen transformation processes. The nRMSE, d, and NSE values of the simulated aboveground dry matter mass compared to the observed values range between 13.63–20.69%, 0.98–0.99, and 0.92–0.95, respectively. The observed values and the simulated values agree quite well.

**Parameter sensitivity analysis:** Process-based soil-crop system models require numerous input parameters, challenging the model parameter calibration process and introducing significant uncertainties. Sensitivity analysis can quantitatively assess the impact of model parameters on output results, allowing users to better understand the model. Sensitivity analysis can identify low-sensitivity parameters, which can be fixed during the model parameter calibration process, thereby simplifying model input. Users can focus on adjusting high-sensitivity parameters during model tuning and policy-making processes. The sensitivity of the model parameters is related to the local environmental circumstances in which the model is used. For example, different climates, soils, and field management situations will yield different results. Therefore, analyzing the sensitivity of model parameters in different environments is particularly important and necessary.

This section uses experimental data from the CK treatment in the Meilisi Daur District of Qiqihar No. 2 plot to analyze the model parameter sensitivity. The parameters of the tested WHCNS model can be categorized into three types: soil hydraulic parameters, crop parameters, and nitrogen transformation parameters. Local sensitivity analysis was conducted by individually altering the values of input parameters in the model while keeping the remaining parameters constant to observe the impact of variations in input parameters on the model output results. In this study, each input parameter was varied by ± 10%, and subsequently the fluctuations in crop dry matter mass and crop yield, as well as the changes in soil water and nitrate content in the 0–0.9 m profile, were observed. From this, the sensitivity of each parameter could be determined.

Figure 5 shows that the impact of soil hydraulic parameters and crop parameters on soil water content was more significant than that of nitrogen transformation parameters, which had a low influence on soil water content. Qs significantly impacted soil water content, most among the soil hydraulic parameters. The sensitivity of the nitrogen transformation parameters was lower than the soil hydraulic parameters, aligning well with the studies of Sun *et al.*, on the RZWQM2 model (Sun *et al.*, 2014). The results of the sensitivity test of the WNMM model parameters by Li *et al.*, (2007) showed that the hydraulic parameters Qs and n had the highest impact on soil water content (Li *et al.*, 2007), a conclusion consistent with the findings of this study.

Figure 6 indicates that the influence of soil hydraulic parameters and crop parameters on soil nitrate nitrogen content was more significant than that of nitrogen transformation parameters, with the latter having a low impact on soil nitrate nitrogen content. Only Qs significantly influenced soil nitrate nitrogen content among the soil hydraulic parameters. Among crop parameters, SLAmax had the most substantial impact on soil nitrate nitrogen content, exceeding 5% in every case.

Crop parameters influence the total dry matter weight (Fig. 7). In contrast, hydraulic parameters have a negligible impact, and nitrogen transformation parameters have a minimal effect on total dry matter weight. SLAmax from crop parameters had the most significant impact on dry matter weight, exceeding 5% in all cases. Crop parameters also significantly influenced crop yield (Fig. 8), which was more sensitive to hydraulic parameters than nitrogen transformation parameters. Of all the agronomic characteristics, Ts had the greatest impact on yield, as it controls the developmental timeline of crop growth. All other parameters within the crop parameters had different effects on crop yield. Richter analyzed the sensitivity of the Dutch crop model and found that the developmental process (Ts) of crop growth was the most sensitive parameter affecting crop yield (Richter *et al.*, 2010), aligning well with the conclusions of this study.

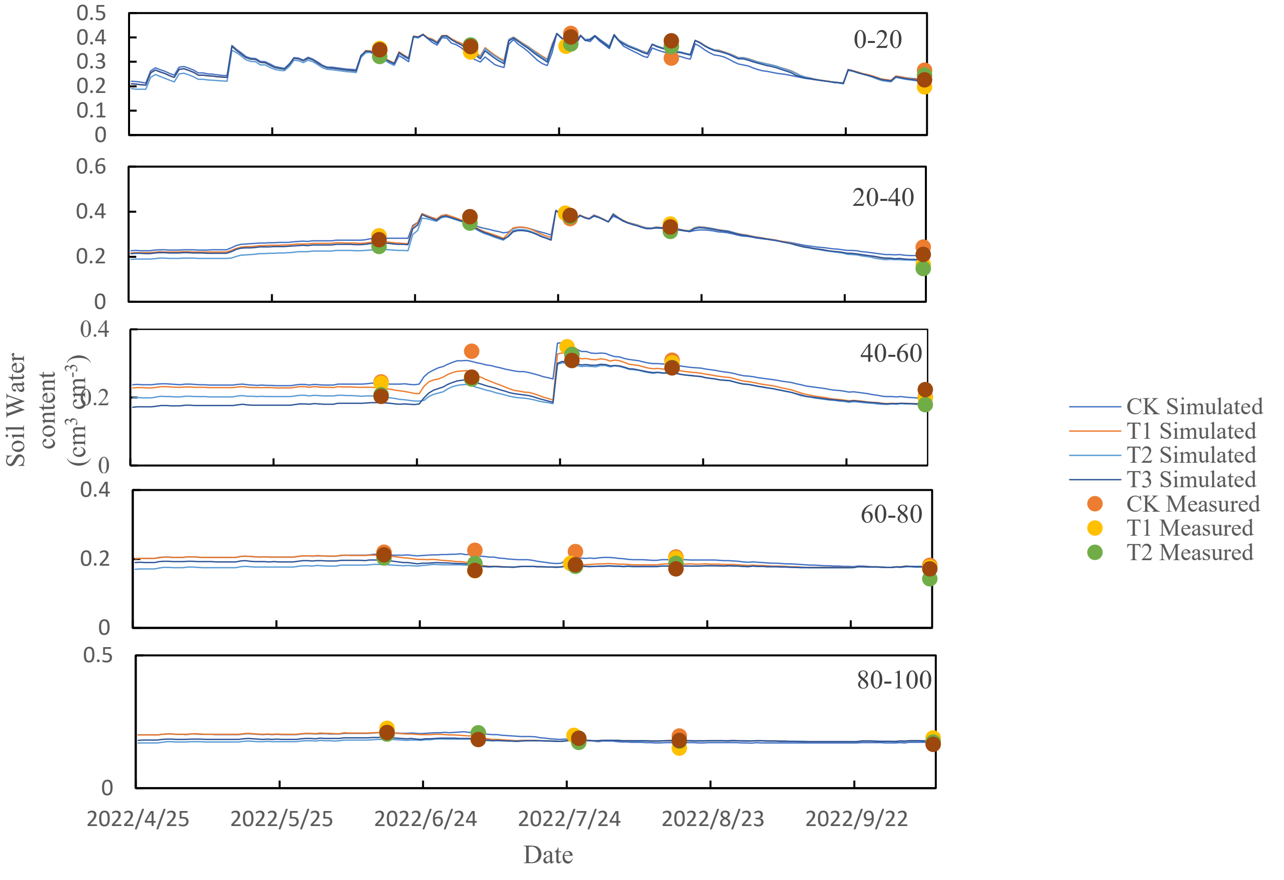


Fig. 1. Comparison of simulated and measured soil water contents across various soil layers under different treatment conditions

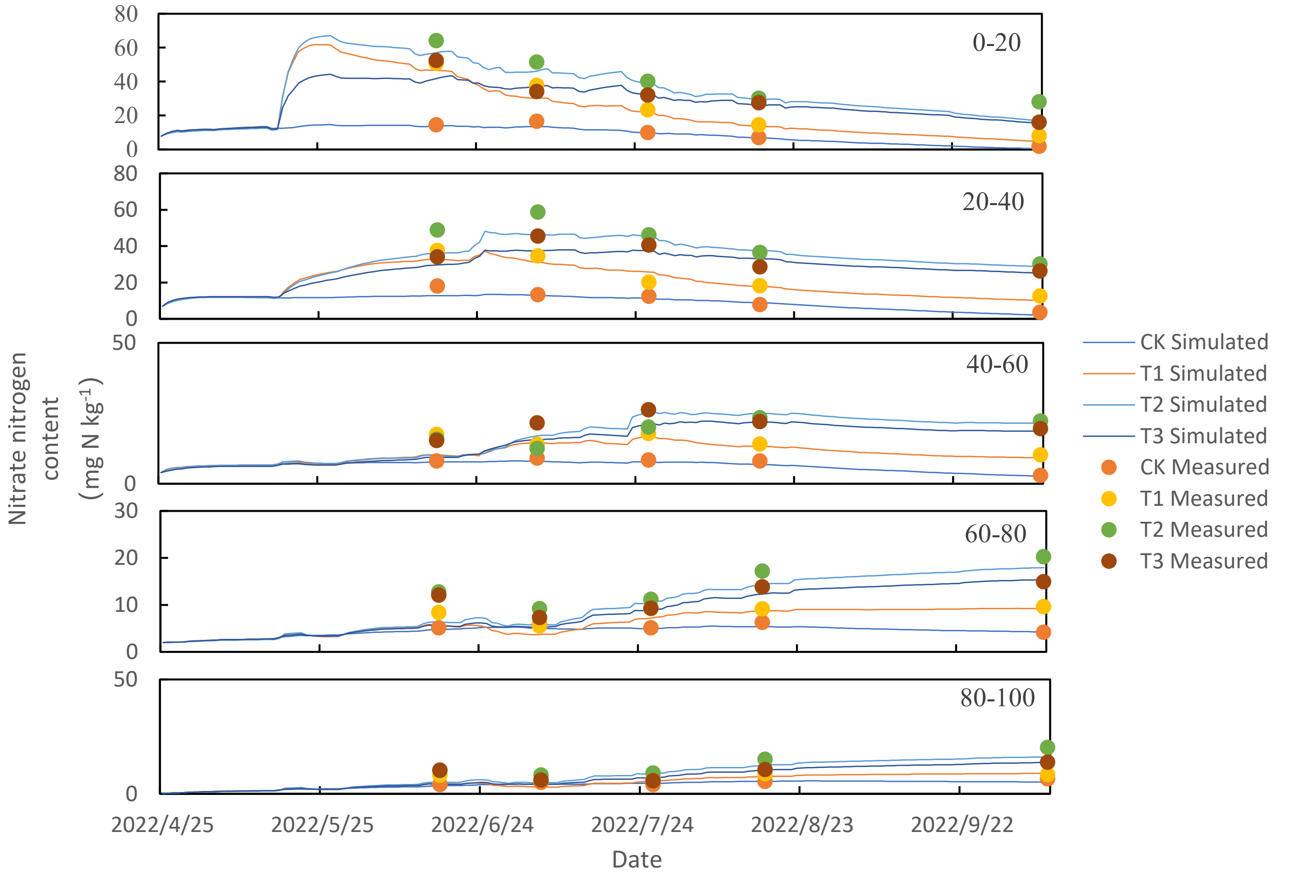


Fig. 2. Comparison between measured and simulated soil nitrate nitrogen content in different soil layers under various treatments.

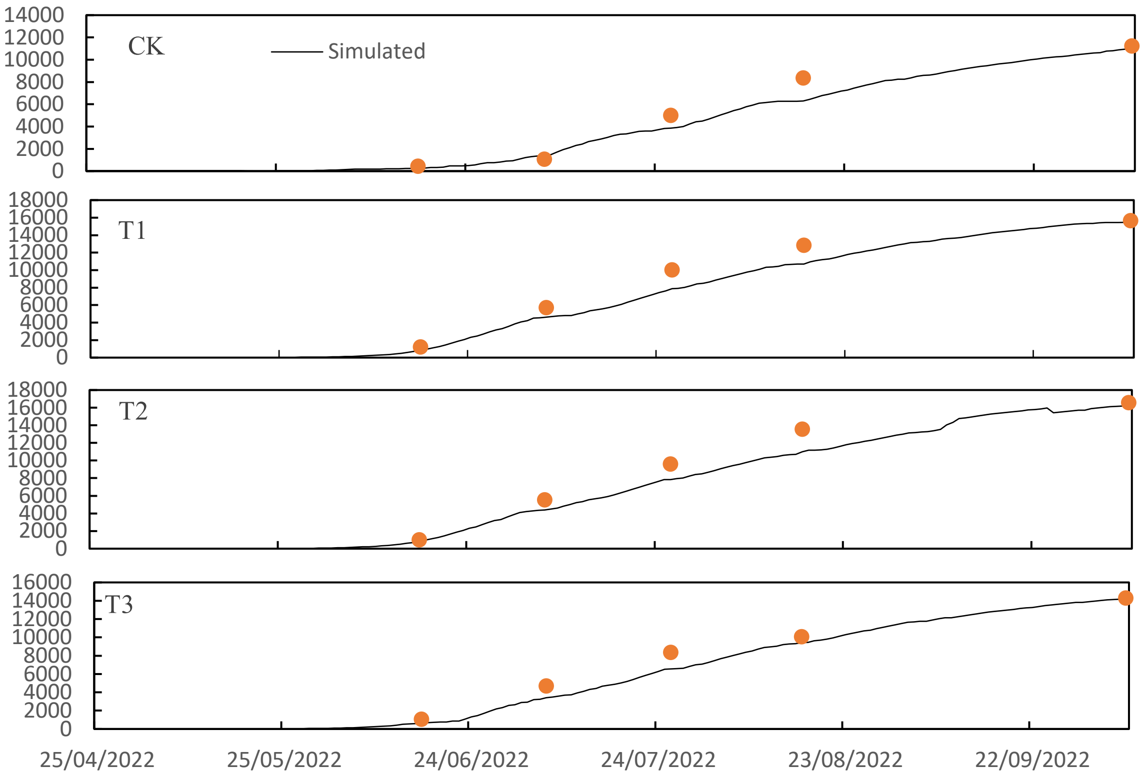


Fig. 3. Comparison between measured and simulated dry matter weight under various treatments.

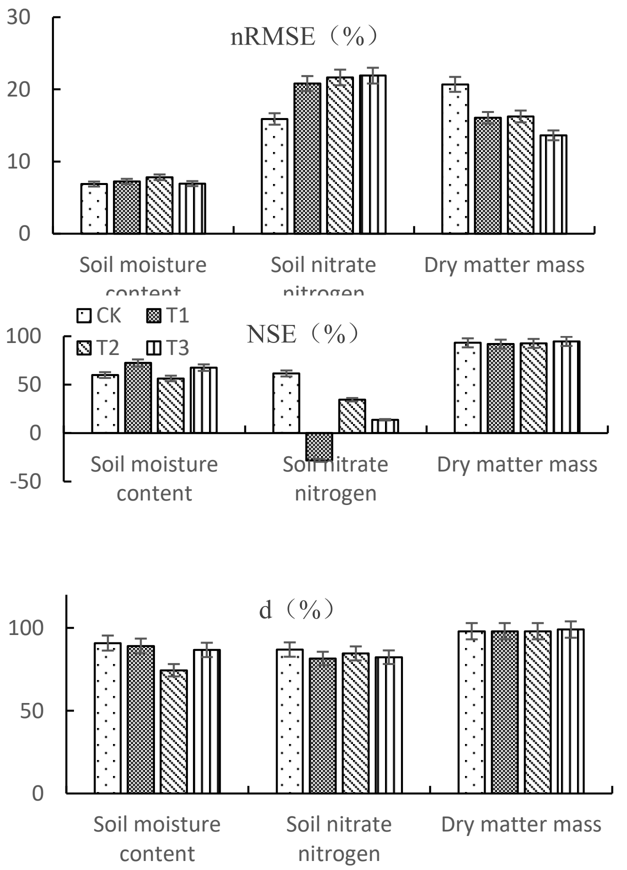


Fig. 4. Model simulation effect of soil moisture content, nitrate nitrogen content and aboveground dry matter quality

**Note:** nRMSE is the relative root mean square error; d is the consistency index; NSE is the Nash coefficient.

**Impact of different fertilization methods on the model's simulations of evapotranspiration, crop production, and water-nitrogen utilization efficiency**

**Impact of different fertilization methods on evapotranspiration:** The results of evapotranspiration under different fertilization methods are shown in Table 4. Examining the evapotranspiration results, the order of spring maize under various treatments is CK > T1 > T3 > T2, where CK treatment increased by 2.36%, 8.22%, and 9.28% compared to T1, T3, and T2 treatments, respectively. From the evapotranspiration results, the T2 treatment had the lowest evapotranspiration among the four fertilization methods.

**Crop yield and water-nitrogen use efficiency:** Table 4 presents simulated results of crop yield and WUE under different fertilization regimes. Distinct differences were observed in the spring maize yields across treatments, with T2 producing the highest yield and CK the lowest. The order for spring maize WUE was T2 > T3 > T1 > CK, with T2 being the highest, showing increases of 10.27%, 26.71%, and 75.86% compared to T3, T1, and CK, respectively.

Table 5 shows the simulated crop yield and nitrogen use efficiency (NUE) results under different fertilization methods. The order of spring maize NUE was T2 > T3 > T1 > CK, with T2 being the highest, showing increases of 7.78%, 48.15%, and 96.73% compared to T3, T1, and CK, respectively.

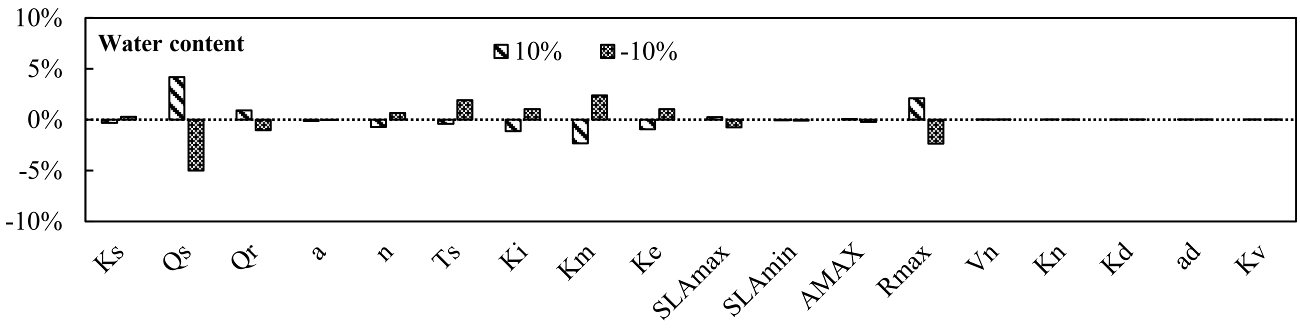


Fig. 5. Sensitivity of a single input parameter of the WHCNS model to soil water content.

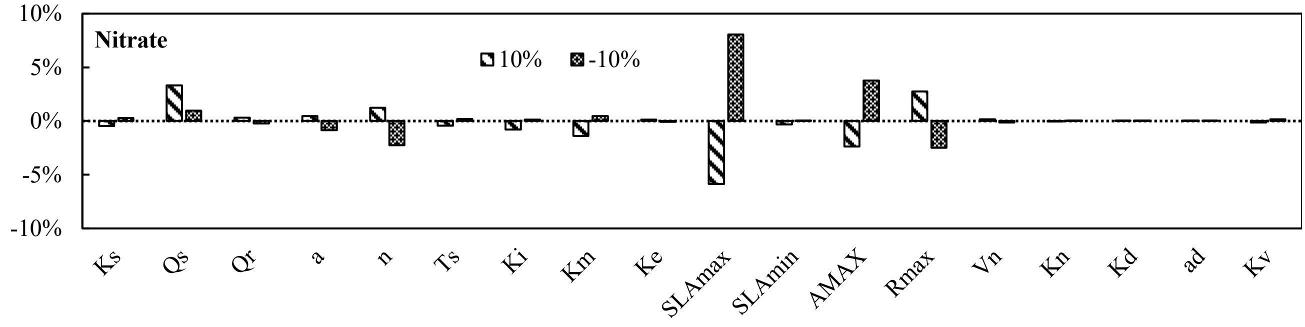


Fig. 6. Sensitivity of a single input parameter of the WHCNS model to soil nitrate nitrogen.

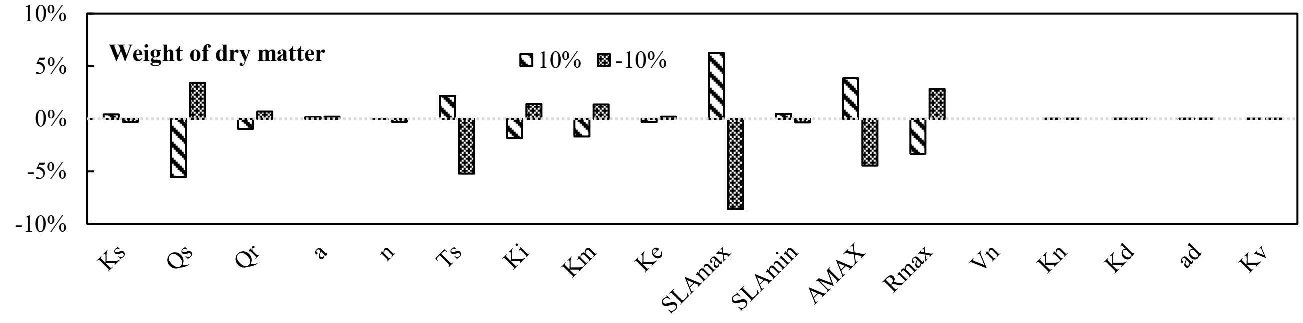


Fig. 7. Sensitivity of single input parameter of WHCNS model to total dry matter weight.

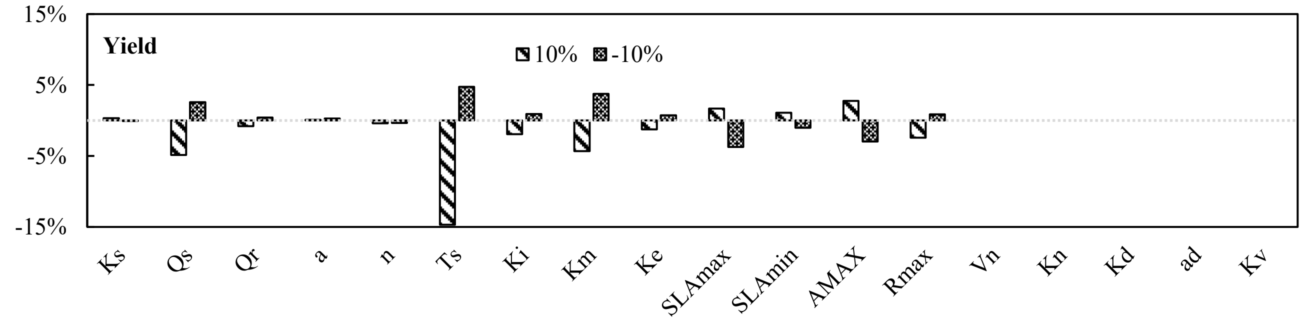


Fig. 8. Sensitivity of single input parameter of WHCNS model to yield.

**Table 4. Simulated results of evaporation, transpiration, evapotranspiration, crop yield, and water use efficiency under different treatments.**

| Crop | Treatments | Year | Evapotranspiration/ nm | Crop yield/ (kg $hm^{-2}$) | Water use efficiency (kg $m^{-3}$) |
|---|---|---|---|---|---|
| Spring maize | CK | 2022-04-25 – 2022-10-08 | 512.4 | 5925 | 1.16 |
| | T1 | | 500.6 | 8066 | 1.61 |
| | T2 | | 468.9 | 9568 | 2.04 |
| | T3 | | 473.5 | 8791 | 1.85 |

**Table 5. Simulated results of evaporation, transpiration, evapotranspiration, crop yield, and nitrogen use efficiency under different treatments.**

| Crop | Treatments | Date | Ammonia volatilization (kg N ha$^{-1}$) | Crop absorption (kg N ha$^{-1}$) | Leaching loss (kg N ha$^{-1}$) | Denitrification (kg N ha$^{-1}$) | Nitrogen use efficiency (kg kgN) |
|---|---|---|---|---|---|---|---|
| Spring maize | CK | 2022-04-25 – 2022-10-08 | 112.44 | 158.4 | 0 | 52.94 | 18.3 |
| | T1 | | 86.4 | 201.7 | 0 | 43.8 | 24.3 |
| | T2 | | 51.5 | 194.7 | 0 | 19.5 | 36.0 |
| | T3 | | 48.4 | 175.8 | 0 | 39.0 | 33.4 |

## Discussion

**Evaluation of the simulation effectiveness of the WHCNS model for different fertilization methods:** Several scholars have deployed different models to conduct simulation research on soil water movement and crop growth using different fertilization methods. Liang *et al*., (2021) utilized the WHCNS model to simulate the dynamic variations in the soil water content of paddy fields at the Kunshan Outdoor Irrigation and Drainage Experiment Station of Hohai University, which is part of the State Key Laboratory of Hydrology, Water Resources and Hydraulic Engineering, achieving an nRMSE of less than 10.79%. The nRMSE value for the soil water content simulation effectiveness evaluation index of the WHCNS model in this study was less than 10.26%, broadly aligning with prior results, validating the proficiency of the model in accurately simulating the dynamic processes of soil water content. Cui *et al*., (2023) utilized the HYDRUS-2D model in Hanggin Rear Banner County, Bayannur City, Inner Mongolia Autonomous Region, to simulate nitrate nitrogen content in the 0-100 cm soil layer, achieving a high degree of fit in the 0–60 cm soil layer, with d values ranging from 0.91 to 0.99. In this study, the d value range for the 0–60 cm soil layer was 0.91–0.98, broadly coherent with earlier studies, while it fluctuated between 0.30 and 0.86 for the 60–100 cm soil layer. This variation could be attributed to nitrogen volatilization and internal transformation, discrepancies between model and actual boundary conditions, and the complexity of solute migration parameters (Deb *et al.*, 2015).

Nevertheless, the overall fit is commendable, with all evaluation indices residing within reasonable ranges, illustrating the capability of the model to effectively forecast dynamic changes in soil nitrogen in Qiqihar under varied fertilization treatments. Ding *et al*., (2020) implemented the RZWQM model to simulate the quantity of dry matter under different treatments of winter wheat in Yuzhou, Henan, with the d value of the simulation efficacy evaluation indicator ranging between 0.84 and 0.93. Ren *et al*., (2022) used the WHCNS model to simulate the dry matter quantity of winter wheat and summer maize, with d values ranging between 0.96 and 0.98. In this study, the d value for the dry matter simulation efficacy evaluation indicator ranged between 0.98 and 0.99, representing an elevation in precision compared to the RZWQM model and exhibiting a high degree of concordance with previous simulations. This implies that the weight of crop dry matter can be accurately simulated by the WHCNS model.

In summary, the validated WHCNS model demonstrates strong capabilities in simulating soil water dynamics and crop growth indicators under various fertilization strategies, similar to established models such as RZWQM, APSIM, and HYDRUS-2D. The WHCNS model also improves the precision of these simulations.

**Impact of straw returning on field evapotranspiration, crop yield, and water-nitrogen use efficiency:** By altering the soil's physical properties and nutrient supply levels, different fertilization treatments influence crop growth processes and soil water dynamics. These effects, in turn, impact crop evapotranspiration, yield, and WUE. Rational fertilization promotes the development of soil aggregate structure, enhances overall soil structure, improves soil moisture retention, and boosts cation exchange capacity. In addition, it helps regulate soil pH and increases the effectiveness of nutrient utilization.

Crop straws are rich in nitrogen, phosphorus, potassium, and trace elements. Straw returning to the fields not only recycles its nutrient elements back to the soil, maintaining soil nutrient balance and fertilizing soil fertility but also improves the soil plow layer structure through tillage (Bijay *et al.*, 2008; Yang *et al.*, 2012), promoting the expansion of soil moisture and nutrient storage (Lu *et al.*, 2014; Hong *et al.*, 2018). It effectively boosts agricultural productivity and is an essential agronomic measure for green agricultural development (Chen *et al.*, 2020). Through long-term fixed-point experiments, Chen *et al*., (2017) found that straw returning combined with chemical fertilizers can greatly raise the amount of accessible phosphorus, total nitrogen, and soil organic carbon. As an agricultural country, China is rich in straw resources, with annual production reaching up to 800 million tons (Shi *et al.*, 2019).

After being straw-covered, soil water transmission to the atmosphere is obstructed, reducing soil surface evaporation. This process plays a role in water storage and moisture conservation (Chen *et al.*, 2006), ensuring that more water is available for crops. Wang *et al*., (2010) discovered that returning straw can reduce evaporation from the soil surface. Our study shows that the evapotranspiration of T2 and T3 treatments with straw returning is less than that of CK and T1 treatments without straw returning, which is consistent with previous research.

In this study, the amount of nitrogen absorbed by the crops was between 128 and 191 kg N/ha. Liang (2017) used the WHCNS model to simulate the water-nitrogen balance and its utilization efficiency in spring maize, and based on a yield of 12,209 kg/hm$^2$, the nitrogen absorption of the crop was 256 kg N/ha. Compared with this study, crop yield is directly proportional to the amount of nitrogen absorbed; the higher the yield, the more nitrogen the plants absorb. Nitrogen loss (ammonia volatilization + leaching + denitrification) was between 74.1 and 195.38 kg N/ha. Zhang *et al*., (2021) quantitatively predicted the nitrogen leaching of summer maize in production in the North China Plain, where the average nitrogen leaching in the study was 22.8 kg N/ha, similar to the leaching amounts in the T2 and T3 treatments in this study. Liang (2017) used the WHCNS model to simulate the water–nitrogen balance and its utilization efficiency in spring maize. In their research, nitrogen loss was between 119.6 and 201.9 kg N/ha, and ammonia volatilization was between 17 and 28 kg N/ha, closely resembling the results we found in our study. Moreover, besides the amount of fertilizer applied, the type of fertilizer, timing of fertilization, and method of fertilization all affect nitrogen loss, and future quantitative research should pay attention to these factors (Mote *et al.*, 2020).

The research results of Zhang *et al*., (2020) indicate that the maize yield in straw returning combined with nitrogen fertilizer treatment is consistently higher than in treatments without straw returning. In this study, except for the CK and T1 treatments, the maize yields under the other nitrogen application measures in the straw returning model were higher than those without straw treatment. This is primarily because straw returning enhances water retention by increasing soil water content, reducing bulk density, and limiting soil water evaporation. The lower yield in T3 treatment compared to T2 might be due to the lesser amount of nitrogen applied in T3, and although humic acid can provide nitrogen, plants still require other key nutrients such as phosphorus, potassium, and trace elements to support their growth, or else the plants might exhibit lower efficiency in yield and nitrogen utilization (Zhang *et al*., 2012). The simultaneous application of nitrogen fertilizer with straw returning can maintain an appropriate carbon-to-nitrogen ratio, which not only can replenish the soil nitrogen reservoir, enhancing soil fertility, but can also improve soil structure, elevate the number of microorganisms, and increase soil enzyme activity (Li *et al*., 2019). This approach enriches soil productivity and promotes nutrient uptake by roots, thereby increasing crop yield.

Applying appropriate amounts of nitrogen fertilizer under full straw returning conditions can significantly enhance the WUE of winter wheat/summer maize in areas with irrigation (Xu *et al.*, 2020; Mian *et al.*, 2021; Zhao *et al.*, 2023). Comparable results were found in this study, under rainfed conditions in Qiqihar, applying a moderate amount of nitrogen fertilizer (195 kg/hm$^2$) under the condition of full straw returning (6,000kg/hm$^2$) after shredding can significantly improve the WUE of maize, outperforming other treatments. This was because continuous straw returning could increase soil porosity, enhancing the ability of the soil to retain water during the mid-to-late growth stages of crops and subsequently promoting the contributing factors to maize yield. Furthermore, the appropriate nitrogen fertilizer (195kg/hm$^2$) can regulate the carbon-to-nitrogen ratio in the soil, accelerating straw decomposition and nutrient release, providing a sufficient nutrient supply for the growth of maize, and resulting in a significant increase in maize water-nitrogen use efficiency.

## Conclusion

To obtain key soil parameters from the experimental fields in Meilisi Daur District, Qiqihar, and to simulate water movement, nitrogen transport, and maize growth in soil profiles under different fertilization strategies in the semiarid region of Northeast China, the WHCNS model was employed in this study. Field-measured maize data from Meilisi Daur District were then used to validate the model. The results showed that the simulated values of aboveground dry matter mass, nitrate nitrogen content, and soil water storage for each treatment had a relative root mean square error of less than 32% when compared to measured values. The consistency index was ≥0.68 for the 0–60 cm soil layer and ≥0.30 for the 60–100 cm layer, with Nash–Sutcliffe efficiency coefficients falling within acceptable ranges. Compared to the T1 treatment, which involved only compound fertilizer application, the T2 treatment (conventional fertilization combined with straw returning) reduced evaporation and improved water and nitrogen use efficiency, with a higher yield than that of T3. Nitrogen availability was identified as the limiting factor for yield under straw returning conditions, indicating that the WHCNS model is capable of simulating field-scale water movement, crop yield, and water and nitrogen use efficiency under straw returning scenarios in this region. This study offers a technical framework and empirical support for enhancing fertilizer and water management in the Chernozem region of Qiqihar, thereby contributing to the advancement of sustainable agricultural practices in the area.

## Acknowledgments

We thank the reviewers and issue editor of the journal for the valuable comments and suggestions that led to significant improvements in this manuscript.

This research was funded by the National Key Research and Development Program of China(2022YFD1500200，2023YFD1500500), Strategic Priority Research Program of the Chinese Academy of Sciences (XDA28130200), Innovation Capacity Building Project of Beijing Academy of Agriculture and Forestry (KJCX20240506), Special project for scientific and technological innovation capacity building of Beijing Academy of Agricultural and Forestry Sciences (KJCX20200801), UNDP (cpr/21/401), Beijing Academy of Agricultural and Forestry Sciences Youth Scientific Research Fund (QNJJ202132), Beijing scholars program municipal financial support, National soybean industry technology system(CARS-04).

### References

Bijay, S., Y.H. Shan and S.E. Johnson. 2008. Chapter 3 crop residue management for lowland rice-based cropping systems in Asia. *Adv. Agron. Amst.*, 98: 117-199.

Chen, S.L., S.Y. Chen, H.Y. Sun, X.Y. Zhang and D. Pei. 2006. Effects of tillage methods on evaporation and water use efficiency of winter wheat. *Soil Bull.*, 37(4): 817-820.

Chen, Y.F., X.G. Xia and L. Yang. 2020. Straw returning to the field is a realistic way for straw resource utilization. *China Soil Fertil.*, (6): 299–307.

Chen, Y.L., L. Xin, J.T. Liu and M.Z. Yuan. 2017. Changes in bacterial community of soil induced by long-term straw returning. *Scientia Agricola*, 74(5): 349-356.

Cui, H.Z., Q.Y. Zhou, N.N. Han and B.Z. Zhang. 2023. Dynamic simulation of soil water and nitrogen under drip irrigation based on HYDRUS-2D model. *J. Irrig. Drain.*, 42(4): 57-66.

Deb, S.K., P. Sharma and M.K. Shukla. 2015. Numerical evaluation of nitrate distributions in the onion root zone under conventional furrow fertigation. *J. Hydrol. Engin.*, 21(2): 211-223.

Ding, J.L., W. Hu, J.C. Wu, Y.H. Yang and H. Feng. 2020. Simulating the effects of conventional versus conservation tillage on soil water, nitrogen dynamics, and yield of winter wheat with RZWQM2. *Agri. Water Manag.*, 230: 105956.

Driessen, P.M. and N.T. Konijn. 1992. Land Use System Analysis. *Wageningen Agricultural University*.

Fu, X.P. 2008. China's water resources and the middle route project of south-to-north water transfer. *Henan Water Conser. South-North Water Transfer*, (1): 1-2.

Hong, C., Y. Su and S.G. Lu. 2018. Phosphorus availability changes in acidic soils amended with biochar, fly ash, and lime determined by diffusive gradients in thin films (DGT) technique. *Environ. Sci. Poll. Res.*, 25(30): 30547-30556.

Jia, S.F., C.Q. Zhou, H.Y. Yan, H.F. Zhou, Q.C. Tang and J.B. Zhang. 2004. Estimation of water resources availability and carrying capacity in Northwest China. *Adv. Water. Sci.*, 15(6): 801-807.

Jumadi, O., Y. Hala and R.N. Iriany. 2020. Combined effects of nitrification inhibitor and zeolite on greenhouse gas fluxes and corn growth. *Environ. Sci. Poll. Res.*, 27(2): 2087-2095.

Li, H.D., X.T. Dong and Q.L. Li. 2023. Dynamic simulation of soil moisture near the dam area based on HYDRUS-1D model. *J. Yangtze River Sci. Res. Inst.*, 41(07): 34-40.

Li, R., X.Q. Hou, P.N. Wu, P.F. Li and X.N. Wang. 2019. Effects of straw returning with nitrogen fertilizer on soil properties and water use efficiency. *J. Agri. Machin.*, 50(8): 289-298.

Li, Y., R. White and D. Chen. 2007. A spatially referenced water and nitrogen management model (WNMM) for (irrigated) intensive cropping systems in the North China Plain. *Ecol. Mod.*, 203(34): 395-378.

Li, Y.H. 2021. Effect of water and nitrogen management on summer maize yield and water and nitrogen use efficiency of automatic irrigation with canal. *Shandong Agri. Uni.*, (01):73.

Li, Z. J., K.L. Hu, B.G. Li, M.R. He and J.W. Zhang. 2015. Evaluation of water and nitrogen use efficiencies in a double cropping system under different integrated management practices based on a model approach. *Agri. Water Manag.*, 159: 19-34.

Liang, H. 2017. Construction of coupling model of water, carbon and nitrogen processes in soil-crop system and its application in water and nitrogen management. *China Agri. Uni.*, (08): 124.

Liang, H., K. Hu, W.D. Batchelor, Z.M. Qi and B.G. Li. 2016. An integrated soil-cropsystem model for water and nitrogen management in north China. *Sci. Rep.,* 6(1): 25755.

Liang, H., Z.H. Hu, S.H. Yang, J.Z. Xu, Z. Gu and K.L. Hu. 2021. Dynamic simulation of water and nitrogen in paddy field-gully pond system and construction of irrigation and drainage regulation model. *J. Agri. Eng.*, 37(22): 49-57.

Lin, L., K.L. Hu, G.D. Li and H.Y. Wang. 2011. Analysis on the ways of nitrogen loss in maize season under different fertilization modes in high-yield grain areas, *Environ. Sci.*, 32(09): 2617-2624.

Liu, M., Z.X. Zhang, E.N. Zheng, P. Chen, S.H. Chen and W.B. Shang. 2018. Experimental study on photosynthetic characteristics and water and nitrogen use efficiency of maize under different water and nitrogen management modes. *J. Irrig. Drain.*, 37(12): 27-34.

Lu, S.G., F.F. Sun and Y.T. Zong. 2014. Effect of rice husk biochar and coal fly ash on some physical properties of expansive clayey soil (Vertisol). *Catena*, 114: 37-44.

Luis, S.P., L.U. Ramón and O.F. Samuel. 2024. Editorial to the special issue on contributions to update the FAO56 guidelines for computing crop water requirements. *Irrig. Sci.*, 1-5.

Ma, R.L., G. Li, Y. Wang and Y. Yao. 2022. Yield simulation and climate sensitivity analysis of spring maize under different fertilization treatments based on APSIM model. *J. Maize Sci.*, 30(5): 116-121.

Mian, Y.M., F.F. Miao, P.N. Wu, Y.N. Wang and X.Q. Hou. 2021. Effects of nitrogen application rate on soil moisture, temperature, carbon and nitrogen and corn yield in Yanghuang irrigation area. *J. Irrig. Drain. Mach. Engin.*, 39: 950-958.

Mote, K., J. Manickam and G. Nagaraj. 2020. Humic acid as foliar and soil application improve the growth, yield and quality of coffee (cv. C×R) in Western Ghats of India. *J. Food Agri. Sci.,* 101(6): 2273-2283

Qu, W.K., X.X. Xu, T.J. Hao, S. Liu, J.K. Zhao, F.G. Meng and C.X. Zhao. 2022. Effect of nitrogen application rate on annual yield and nitrogen use efficiency of drip irrigation winter wheat-summer maize. *J. Plant Nutr. Fertil.*, 28(7): 1271-1282.

Ren, J., T.C. Wang, H. Liang, X.K. Guan and K.L. Hu. 2022. Improving WHCNS model to simulate the effects of farming methods on crop growth and water use efficiency. *J. Agri. Engin.*, 38(14): 117-126.

Richter, G.M., M. Acutis and P. Trevisiol. 2010. Sensitivity analysis for a complex crop model applied to Durum wheat in the Mediterranean. *J. Europ. Agron.*, 32: 127-136.

Shi, Z.L., F. Wang, J.C. Wang, X. Li, R.H. Sun and C.J. Song. 2019. Utilization characteristics, technical models and development suggestions of crop straw resources in China. *China Agri. Sci. Technol. Herald*, 21(5): 8-16.

Sun, M., X.L. Zhang, S.Y. Feng and Z.L. Huo. 2014. Parameter optimization and verification of RZWQM2 model based on PEST. *J. Agri. Machin.*, 45(11): 146-153.

Wang, X.J., G.B. Huang and Q.P. Li. 2010. Evaporation and transpiration characteristics and yield effect of spring wheat field and pea field in dryland under different tillage measures. *Resour. Environ. Arid Area*, 24(5): 172-177.

Xie, W.Y., H.P. Zhou, Z.X. Yang, Z.P. Liu, Y.L. Du, J. Guo and Q.Q. Lv. 2020. Effects of combined application of controlled-release urea and common urea on yield, nitrogen utilization and economic benefits of spring maize. *Agri. Res. Arid Area*s, 38(05): 31-38.

Xu, Y., L.J. Sun, L.Y. Du, M.H. Jiang, S.W. Niu, K. Guo and Z. Meng. 2020. Research progress on influencing factors of nitrogen leaching in dryland soil under conventional field management. *Soil Bull.*, 51(5): 1246-1254.

Yang, F., Y. Dong and M.G. Xu. 2012. Effect of straw returning to field on comprehensive soil fertility and crop yield in southern China. *Acta Appl. Ecol.*, 23(11): 3040-3044.

Zhang, H.J., S.J. Wang, S.S. Luo and C.J. Tian. 2020. Research progress on the effects of different straw returning methods on soil microorganisms. *Soil & Crops*, 9(2): 150-158.

Zhang, K.Z. 2023. Measures to save water in farmland irrigation. *Management*, (4): 91.

Zhang, L., T.M. Huang, X.F. Zheng, C.M. Gu and C.H. Wang. 2012. Effect of nitrogen application on winter wheat yield and water use efficiency after straw returning. *J. Northwest A & F Uni.*, 41(1): 49-54.

Zhang, Y. F., Y.Y. Sui, Y.M. Chen, H. Yu and X.G. Jiao. 2021. Effects of different nitrogen application levels on maize yield and nitrogen use efficiency under the condition of straw returning to field. *Soil & Crops*, 10(4): 395-403.

Zhao, X.Y., N.T. Wang, B. Cui, S.L. Yin, X. Yang and F.Q. Meng. 2023. Quantitative prediction of nitrogen leaching in summer maize production in North China. *J. China Eco. Agri.*, 31(09): 1439-1448

Zheng, W.K., Y.S. Wan, Y.C. Li and Z.G. Liu. 2020. Developing water and nitrogen budgets of a wheat-maize rotation system using auto-weighing lysimeters: Effects of blended application of controlled-release and un-coated urea. *Environ. Poll.*, 263: 114383.

(Received for publication 15 June 2024)