Assessing the Impact of Organic-Inorganic Nitrogen Application on Maize Yield and Nitrogen Leaching Using the DNDC Model

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Abstract. In order to optimize maize yield and minimize nitrogen leaching, field experiments and DNDC model simulations assessed various organic-inorganic nitrogen application treatments. Trials were conducted in the Hetao irrigation area of Inner Mongolia, comparing six treatments: no nitrogen (CK), solely inorganic nitrogen (U1), and combinations where 25%, 50%, 75%, and 100% of inorganic nitrogen was replaced with organic nitrogen (U3O1, U1O1, U1O3, O1). The DNDC model was calibrated using the U1 treatment data from 2018-2020 and validated with other treatments. Results indicated the model accurately simulated maize yield (NRMSE < 5%) and nitrate nitrogen leaching (NRMSE < 15%). Simulation outcomes demonstrated that increasing inorganic nitrogen application reduced crop yield and significantly increased nitrate leaching. Conversely, higher proportions of organic nitrogen, along with adjusted irrigation and frequency of inorganic nitrogen fertilization, increased maize yield while reducing nitrate leaching. At a fixed nitrogen application rate of 240 kg hm^{-2}, maize yield initially rose and then declined with increasing organic nitrogen ratios, while nitrate nitrogen leaching decreased consistently. Optimal results were achieved with a 3:2 ratio of organic to inorganic nitrogen, yielding 12578 kg hm^{-2} with nitrate nitrogen leaching at 15.7 kg NO_{-}^{3}-N hm^{-2}, indicating this ratio as the preferred method for combined nitrogen application in the region.

1.Introduction

The application of nitrogen fertilizer is crucial for increasing crop yields. According to statistics, the world's annual consumption of nitrogen fertilizer is about 1.09×10^8 t, of which 1/3 is used by China [1-3]. While increasing crop yields, the application of fertilizer will also cause a series of negative environmental problems. Studies have shown that only 55% of the global nitrogen application rate is absorbed and utilized by crops , and surplus nitrogen is easily lost through leaching, ammonia volatilization, and denitrification. Therefore, agricultural production must comprehensively consider the sustainability of crop yields and the ecological environment, and transform from a single goal to multiple goals.

One of the keys to controlling nitrate leaching is to formulate a reasonable plan to suppress the accumulation of nitrate nitrogen in the soil profile [4], so that the space and time nitrogen supply can be better synchronized with plant demand [5-7], so as to achieve improvement nitrogen use efficiency and reduce the risk of nitrogen loss. Based on the perspective of agricultural ecology, organic agriculture is considered a model of sustainable agricultural culture. Studies have shown that the application of organic fertilizers has good benefits in increasing soil fertility and alleviating environmental degradation. Previous comprehensive research indicates that combining organic and inorganic fertilizers stabilizes or enhances crop yields more effectively than using synthetic nitrogen fertilizer alone. However, there are different reports on the effect of applying organic materials on soil nitrogen leaching. However, some studies have found that when organic nitrogen is used as a nitrogen source, it will cause a higher nitrogen leaching rate [8]. This may be caused by differences in the level of farmland fertility, climatic conditions, fertilization levels, and types of organic fertilizers in various regions. For example, the amount of organic fertilizer applied will affect the content of soil active organic carbon and related soil properties [9], and affect the soil nitrogen conversion process, which in turn affects the soil nitrate leaching rate.

Field experiments play an important role in monitoring crop yield and nitrate leaching, but there are limitations in space and time, and predicting yield or nitrogen leaching on a larger scale must rely on some mathematical models . The DNDC model is a process-based biogeochemical model, which is considered a useful tool to assess the impact of management practices on nitrogen loss in agricultural ecosystems, and has been applied to different countries and ecosystems around the world. The DNDC model can combine nitrogen conversion with hydrological processes in detail, and can be used to simulate crop yields, nitrogen leaching, and greenhouse gas emissions. A large number of studies based on the DNDC model have extensively evaluated the

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nitrogen loss of different cropping systems [45, 48-50], but there are few reports from agronomic (yield) and environmental perspectives (nitrogen leaching loss) to determine the optimal ratio of organic nitrogen to inorganic nitrogen.

Agricultural non-point source pollution has become a serious problem in many agricultural fields in the world [6]. Nitrate leaching is one of the most common non-point source pollution, which has been widely confirmed worldwide [7-8]. The loss of a large amount of nitrogen leads to ecological problems, system eutrophication and water quality degradation [9] will also increase the risk of human cancer, water hypoxia, and biodiversity loss [2]. Some scholars surveyed in 14 provinces in northern China and found that the amount of nitrogen fertilizer applied in most counties exceeded 500 kg N ha-1, and the nitrate content in groundwater in about half of the areas exceeded 11.3 mg NO_3^--N (WHO or European standards for nitrate limits in drinking water).Our study area is located in the Hetao Plain, and the lateral runoff of groundwater is very small. It is a typical irrigation (rainfall) replenishment and evaporative consumption irrigation area. The local groundwater depth is relatively shallow, and drinking water basically comes from groundwater. Therefore, controlling the concentration of nitrates at a limited pollution level is very important for human health. In addition, farmers in irrigated areas usually apply large amounts of chemical fertilizers to increase crop productivity. The current amount of chemical fertilizers in farmland has exceeded 600,000 $t{\cdot}a^{-1}$ [5]. When the supply of nitrogen fertilizer exceeds demand, nitrate will accumulate in the soil.

A 3-year field experiment was conducted in the Hetao Irrigation District of Inner Mongolia to assess the impacts of varying organic-inorganic nitrogen application ratios on spring maize yield, nitrate leaching, and soil environmental variables including soil temperature, soil humidity, and top soil nitrate nitrogen content. Due to the limited number of experimental treatments, it is difficult to accurately determine the nitrogen fertilizer management measures that reduce nitrogen leaching loss and maintain the best corn yield. Therefore, this study integrated the results of field experiments and the DNDC model to evaluate the effects of combined application of organic and inorganic fertilizers on corn yield and nitrate leaching. It also evaluated the applicability of the DNDC model under complex conditions in the Hetao irrigation area. And through a variety of scenario simulations to determine the optimal ratio of organic-inorganic fertilizer nitrogen based on agronomic and environmental perspectives.

2.Results

2.1. Yield

The DNDC model simulation was validated by comparing measured and simulated crop yields across various fertilization treatments and the control (CK) treatment (Fig. 1). Statistical analysis indicated that the R2 values for each treatment exceeded 0.97, while the Mean Bias Error (MBE) ranged from -97.17 to 352.10 and Root Mean Square Error (RMSE) varied between 289.56 and 367.53. Additionally, the Normalized Root Mean Square Error (NRMSE) values were all below 5%. These evaluation indicators consistently fell within the "good" to "excellent" range, demonstrating the model's ability to accurately simulate crop yields under different treatment conditions. This confirms the validity of the model's parameter settings for effectively predicting crop yields in varied treatments.

The observed and simulated maize yield values both demonstrate significant increases with fertilization. Over three years, each fertilization treatment showed an average maize yield 31.19% to 57.28% higher than the untreated CK control, with simulated yields showing an increase of 37.42% to 62.05%. Specifically, maize yield initially increased and then decreased with higher proportions of organic fertilizer. The U1O1 treatment showed the greatest yield enhancement, with measured and simulated average increases of 17.92% and 19.89% over the U1 treatment, respectively.

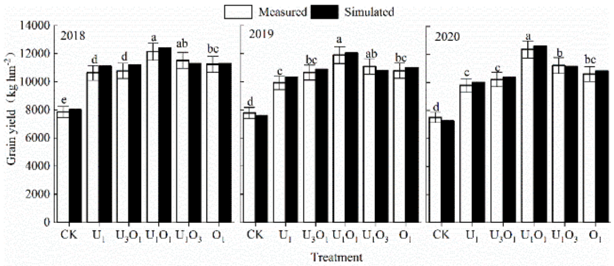

Fig.1 Simulated and measured Grain yield, Vertical bars in the panels b and c indicate standard deviations of three replicated measurements.

2.2. The nitrate nitrogen content in the surface soil

Based on Figure 2, the DNDC model effectively simulates the temporal changes and levels of nitrate nitrogen in surface soil (0-20 cm) during the growth period. However, its accuracy is lower compared to its simulation of soil temperature and humidity. Statistical analysis reveals that the R^2 values for different treatments range from 0.69 to 0.72. The DNDC model tends to underestimate nitrate nitrogen levels, with Mean Bias Error (MBE) ranging from -4.55 to -0.91, Root Mean Square Error (RMSE) between 12.19 and 13.80, and Normalized Root Mean Square Error (NRMSE) varying from 18.82% to 22.58%. Overall, the model's performance is assessed as "medium". These findings indicate that the DNDC model shows relatively poor simulation performance in capturing the spatial and temporal dynamics of soil nitrate nitrogen content.

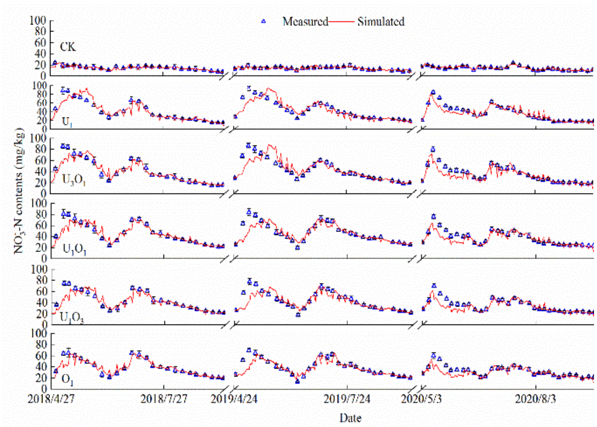

Fig.2 simulated and measured soil NO^{-}_{3}-N contents (0~20 cm)

2.3. Surface soil nitrate nitrogen content

Both measured and simulated data indicate that nitrogen application significantly increases soil nitrate nitrogen leaching loss (Fig. 3). Over a three-year average, different fertilization treatments showed 1.4-3.1 times and 1.2-2.6 times higher nitrate-nitrogen leaching loss compared to the CK treatment, respectively. There was a trend of decreasing nitrate nitrogen leaching with higher proportions of organic nitrogen. Specifically, compared to the U1 treatment, the O1 treatment demonstrated a decrease in measured and simulated nitrate nitrogen leaching of 42.6% and 39.6%, respectively.

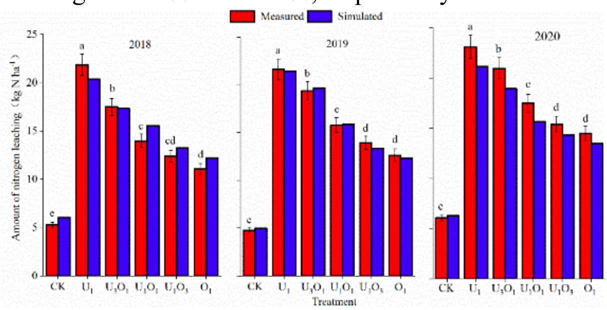

Fig.3 Comparisons of simulations and measurements of amount of nitrate leaching

2.4. The impact of various management practices on corn yield and nitrate nitrogen leaching

It can be seen from Table 1 that different management methods will affect corn yield and nitrate nitrogen leaching loss. Increasing application of inorganic nitrogen fertilizer has no obvious effect on crop yield, but it will significantly increase the nitrate nitrogen leaching loss. When the application rate of inorganic nitrogen is changed from 240 kg N hm^{-2} to 180 and 300 kg N hm-2 the nitrate Nitrogen leaching loss decreased by 25.83% and increased by 31.67%, respectively. Increasing or reducing the amount of soil irrigation does not have a significant impact on crop yield, but has a greater impact on the amount of soil nitrogen leaching. When the irrigation amount is changed from 50 mm to 40 and 60 mm, soil nitrate nitrogen leaching loss the amount decreased by 13.75% and increased by 15.83% respectively. On the contrary, increasing the amount of organic nitrogen will significantly increase the yield of maize, while the increase in the amount of nitrogen leaching is small. When the amount of organic nitrogen is increased from 0 to 60 and 120 kg N hm-2, the crop yield will increase by 10.96% and 24.54%, respectively. In addition, when the number of inorganic nitrogen fertilization increased from 2 to 3 times, the corn yield increased by 2.67%, and the nitrate nitrogen leaching loss increased by 7.08%. When the number of inorganic nitrogen fertilization was changed from 2 to 1, yield and nitrate nitrogen leaching loss decreased by 4.13% and 13.75%, respectively.

The sensitivity index shows (Table 1) that among the four alternative management measures, the amount of inorganic nitrogen (S=1.27) and the amount of irrigation (S=0.84) have a greater impact on soil nitrogen leaching, while the increase organic nitrogen application (S=0.13) and increasing the splits of inorganic nitrogen fertilization (S=0.22) had relatively little effect on the amount of nitrogen leaching. In terms of yield, the amount of irrigation (S=0.12), the amount of organic nitrogen application (S=0.11), the inorganic nitrogen application frequency (S=0.10) and the amount of inorganic nitrogen application (S=0.09) all have a greater impact on crop yield. According to the results of comprehensive sensitivity index analysis, different management measures have a positive effect on nitrogen leaching and corn yield, and a single factor change cannot achieve the goal of a win-win situation for both economic and environmental benefits. In this study, reducing the amount of inorganic nitrogen application will significantly reduce the amount of soil nitrogen leached, but it will also reduce crop yields, while increasing the amount of organic fertilizer application will not cause a large amount of nitrogen leaching, and can achieve the effect of increasing production. Therefore, from the perspective of farmers' management practices, the combined application of organic and inorganic nitrogen is an effective management measure for seeking high yield and low nitrate.

Table.1 Impacts of Nitrate Leaching Amounts and Yield under Different Management Practices: Sensitivity Analysis.

Management practice	Basel	management	nitrate leaching (kg N hm^{-2})	Yield (kg hm^{-2})	Sensitivity index (S)	
Inorganic N input (kg N hm^{-2})	240	180	17.2	10126	1.27	0.09
		240	18.7	10639		
		300	21	10596		
organic N input kg N hm^{-2})	0	0	14.8	11805	0.13	0.11
		60	21	11241		
		120	28.6	13250		
inorganic Fertilizer split	2	1	21	10200	0.22	0.10
		2	24.1	10639		
		3	27.2	11320		
Irrigation (mm)	50	40	18.2	10262	0.84	0.12
		50	21	10639		
		60	22.7	10761		

2.5. Determination of optimal management measures based on agronomic and environmental perspectives

The simulation results show (**Fig.4**) that when the proportion of organic nitrogen is in the range of 0-60%, the 3-year average yield increases as the proportion of organic nitrogen increases, if continue to increase the proportion of organic fertilizer, the yield will decrease, but even when the proportion of organic nitrogen application reaches 100%, the yield is still 5.44% higher than that of inorganic nitrogen alone. It can be seen that the combined application of organic nitrogen can make the yield reach an acceptable level. When the ratio of organic nitrogen is 60%, the yield is the best, which is 20.10% higher than the baseline scenario. From the point of view of nitrogen leaching loss, as the proportion of organic nitrogen application increases, the nitrate nitrogen leaching loss gradually decreases, and the nitrate nitrogen leaching loss of the only application of organic nitrogen is reduced by 39.52% compared with the baseline scenario. When the organic fertilizer application rate is 50%~100%, the nitrogen leaching loss is reduced to an acceptable level of 15.7 kg NO^{-}_{3}-N hm^{-2} or less. Combining the actual conditions of the experimental area and considering the comprehensive maize yield and nitrogen leaching loss, the acceptable fertilization mode is that the proportion of organic nitrogen is more than 50%, and the best fertilization mode is 40% inorganic nitrogen add 60% organic nitrogen.

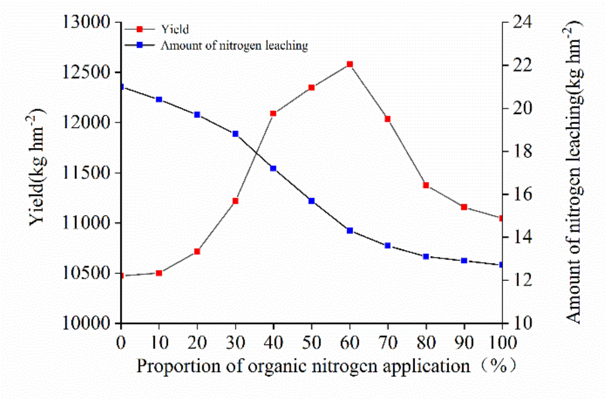

Fig. 4. Response curves depicting simulated grain yield and nitrate leaching across various treatments, with each data point representing the mean value derived from continuous weather data spanning three years (2018-2020).

3.Conclusion

The DNDC model, validated against field observations, effectively simulates the impacts of various management practices on corn yield and nitrate leaching. Sensitivity analysis indicates that types of nitrogen application, nitrogen amount, irrigation volume, and frequency of nitrogen application positively influence both maize yield and nitrate nitrogen leaching. For instance, under a nitrogen application rate of 240 kg N hm^{-2}, optimizing the ratio of organic to inorganic nitrogen application ensures optimal maize yield while maintaining nitrate nitrogen leaching within acceptable limits. When the amount of organic nitrogen is 144 kg N hm^{-2} and the amount of inorganic nitrogen is 96 kg N hm^{-2}, the corn yield can reach 12578 kg ha^{-1}, and the nitrate nitrogen leaching loss is relatively low (15.7 kg NO^{-}_{3}-N hm^{-2}). This study has certain reference value for the determination of organic and inorganic nitrogen application models in other crop systems and regions in my country.

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