

Modeling Soil Salt and Nitrogen Transport under Different Fertigation Practices with Hydrus-1D

Zeng Wen-zhi, Huang Jie-sheng, Wu Jing-wei and Xu Chi
State Key Laboratory of Water Resources and Hydropower Engineering
Science, Wuhan University, Wuhan 430072, China

Abstract: In this study the effects of different fertigation practices on salt and nitrogen dynamics were analyzed in the Hetao District, China by using the Hydrus-1D model. The results indicated that the soil electrical conductivity increased gradually with depth after irrigation and the electrical conductivity of 0~60 cm depth changed faster than that of 60~100 cm depth. However, the soil ammonium nitrogen concentration decreased with depth and high irrigation intensity could promote the increase of ammonium nitrogen while reducing the differences of their distributions in soil profile. In addition, when the initial urea application was in a small amount (10 g), the nitrate nitrogen concentration increased with soil depth while decreased with irrigation intensity after irrigation. Furthermore, both ammonium and nitrate nitrogen content of soil profile rose with increasing initial urea application amount, which played a more important role in the changes of soil ammonium (0~100 cm) and nitrate (0~80 cm) nitrogen content than irrigation intensity.

Keywords: Irrigation, leaching, salinity, simulation, transport

INTRODUCTION

As one of the most active elements in nature, nitrogen transforms and migrates in the heterogeneous system of soil. Meanwhile, nitrogen is an essential element for the growth of crops and the demand of it is the largest. Recently, it has become a major method to apply nitrogen fertilizer to improve grain production and to cope with the nitrogen deficiency in many farmlands of China, especially in arid districts of north China. However, improper fertilization or excessive nitrogen application will not be beneficial to production improvement or resource conservation and may cause serious environmental problems (Bagges and Watson, 2000). Among different forms of nitrogen, nitrate nitrogen is known as one of the major forms that are prone to lose nitrogen since it is not easy to be absorbed by soil particles (Hosen and Yagi, 2011). Transport of nitrate nitrogen in soil profiles may cause pollution to groundwater: researches have indicated that 30 to 50% of fertilizer in soil was lost and leached into groundwater and obvious correlation has been found between the application of nitrogen and the concentration of nitrate nitrogen in shallow groundwater. At the same time, the transport of some nitrate nitrogen along the soil profile to the root zones results in the loss of nitrogen and in turn reduces the effectiveness of the fertilizer. As a result, increasing attention has been drawn to the transport of nitrogen in soil and its impact on agricultural environment (Fu *et al.*, 2006).

As one of the major food production districts of China, the Hetao Irrigation District in Inner-Mongolia covers an area of 11900 km², with the irrigated area of 5743 km². In fact, the soil in the district suffers from high salinity. To suppress the accumulation of salt to the surface of the soil in spring and ensure a sound environment for crop growth, the practice of salt-leaching with flooding is usually adopted in the earlier autumn. However, nitrogen can lose easily in this way (Wang and Gao, 2006). In general, research on the transport of nitrogen and salt under different irrigation conditions plays a vital role in improving fertilizer management and reducing agricultural pollution.

Hydrus-1D is a one dimensional finite element model of water, heat and solute transport in unsaturated media developed by the salinity laboratory of USDA (the United States Department of Agriculture). It takes into consideration the water uptake by roots and the hysteresis of soil water suction and can be applied into constant and inconstant boundaries. The model is widely used to simulate the transport of moisture, salts, heavy metals and organic matters with the advantage of flexible input and output functions (Šimůnek and Suarez, 1994; Šimůnek *et al.*, 1998). Nevertheless, previous researches mainly aimed at the movement of moisture or solutes from a single aspect and there was little research on the coupling of water and fertilizer. The purpose of this study is to calibrate and verify the Hydrus-1D model with the parameters obtained by soil column experiment; and to simulate the salt and nitrogen transport in soil to disclose the relationship

Table 1: Soil properties of the Yonglian experimental station

Soil texture	Particle size distribution (%)			Organic carbon (g/kg)	EC _{1.5} (ds/m)	pH*	Saturated moisture content (cm ³ /cm ³)
	<2 um	2~20 um	>20 um				
Sandy loam	6.61	20.13	73.26	5.51	2.50	8.43	43.40

*: Soil: water = 1:1

between irrigation, fertilization and the changes in salt and nitrogen.

MATERIALS AND METHODS

Column experiment: Soil samples were taken from Yonglian Experimental Station, Hetao Irrigation District, China and they were pretreated by crushing, smoothing and air-drying. Then the pretreated samples were put through 1 mm sieve and set aside for use. Both sieving and hydrometer method were used to analyze soil particles while the sodium hexametaphosphate (AR) was selected as dispersant. According to the international soil texture triangle, the soil samples were classified as sandy loam. Oil bath heating capacity method of potassium dichromate was used to determine the content of organic matter in soil and the basic physical and chemical properties of the soil samples were shown in Table 1.

One-dimensional salinity and nitrogen transport experiment was carried out in 20 cm inner diameter by 100 cm long cylindrical organic glass columns which were assembled from the prepared soil with the designed soil dry bulk density (1.5 g/cm³). The columns contained a 60 cm long soil core that was divided into 12 layers to fill and specially made the layers become rough to have a good connection between soil layers. Furthermore, 5 cm filter layer was set at the end of columns and 2~3 mm quartz sand was tiled on the soil surface to prevent the occurrence of edge effects.

For the sake of simulating the actual irrigation and fertilization practices, we slowly moistened the soil columns from top to bottom with pure water after assembling the soil columns to achieve the designed soil water content (22.5, m³/m³). After the water completely penetrated into the soil, about 6300 mL (20 cm) solution with 10 and 20 g urea dissolved was applied evenly and slowly to the surface of each column, respectively. Soil samples of 6 columns were taken from different soil layers (interval of 10 cm) when filling the soil columns and 24 and 48 h after irrigation, respectively.

The nitrate and ammonium nitrogen in soil samples were analyzed by using a Cleverchem 200 auto analyzer (Dechem-Tect, Germany). In addition, the electrical conductivity of soil extract was measured by a conductivity meter (DDSJ-318, China) and the experiment was repeated 3 times.

Model description: The Hydrus-1D model (Šimůnek *et al.*, 2005) simulates one-dimensional water flow and solute transport in incompressible, porous, variably

saturated media, in steady or transient regime, for a known metric system and various time steps.

One-dimensional uniform water movement in a partially saturated rigid porous medium is described by a modified form of the classical Richards equation using the assumptions that the air phase plays an insignificant role in the liquid flow process and that water flow due to root uptake can be neglected, the mathematical expression is as follows:

$$C(h) \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} [K(h) \frac{\partial h}{\partial z} - K(h)] \quad (1)$$

where,

C (h) = The specific moisture capacity (cm⁻¹)

C (h) = dθ/dh

θ = The volumetric water content (cm³/cm³)

h = The total water head (cm)

K(h) = The unsaturated hydraulic conductivity (cm/h)

t = The time (h)

Z = The spatial coordinate (cm)

Traditional convection diffusion equation is used to describe the transport process of nitrogen in soil (Šimůnek *et al.*, 1998).

For ammonium nitrogen:

$$\left\{ \begin{aligned} \frac{\partial c_1 \theta}{\partial t} + \frac{\partial c_1 \rho s}{\partial t} &= \frac{\partial}{\partial z} [\theta D(\theta, q) \frac{\partial c_1}{\partial z}] - \frac{\partial (qc_1)}{\partial z} + S_N(t, z) \quad (2) \\ S_N &= k_1 \theta C_0 - k_2 \theta c_1 \end{aligned} \right.$$

where,

C₁ : The ammonium nitrogen concentration in soil solution (mg/L)

s : The linear equilibrium adsorption constant which reflects the amount of soil particles on the nitrogen adsorption

ρ : The soil dry bulk density (g/cm³)

q : The vertical water flux (cm/h)

D (θ, q): The integrated diffusion coefficient that presents the effective molecular diffusion and mechanical dispersion of soil solution

S_N : The sink term and only different forms of nitrogen transformation are considered here (cm³/cm³/d)

k₁, k₂ : The first-order rate constant for the mineralization of organic nitrogen and ammonium nitrification, respectively (d⁻¹)

C₀ : The soil organic nitrogen content (mg/cm³)

For nitrate nitrogen:

Table 2: Calibrated parameters

θ_r cm ³ /cm ³	θ_s cm ³ /cm ³	α cm ⁻¹	n	k_s cm/d	l	Disp cm	Difus.W cm ² /d	k_1 mg/kg/d	k_2 d ⁻¹	k_3 d ⁻¹
0.065	0.430	0.013	3.067	50.400	0.500	7.000	4.000	1.000	0.150	0.012

Table 3: The RMSE and N of EC_{1:5} and nitrogen for the calibration and validation periods

Urea mass (g)	EC _{1:5} (ds/m)				Ammonium nitrogen (mg/L)				Nitrate nitrogen (mg/L)			
	Calibration		Validation		Calibration		Validation		Calibration		Validation	
	N	RMSE	N	RMSE	N	RMSE	N	RMSE	N	RMSE	N	RMSE
10	6	0.3103	6	0.4078	6	0.0028	6	0.0066	6	0.0200	6	0.0320
20	6	0.3103	6	0.4078	6	0.0057	6	0.0182	6	0.0298	6	0.0315

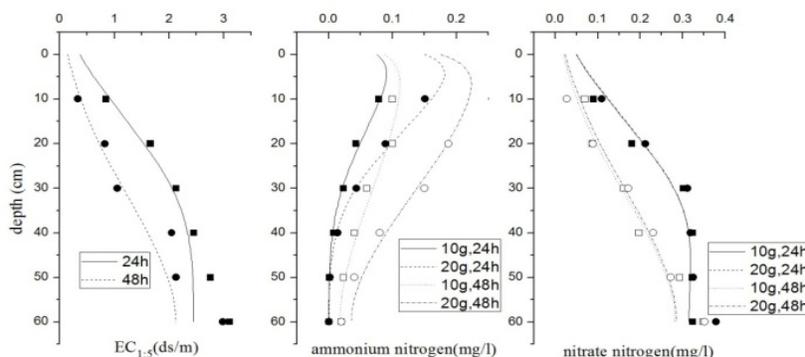


Fig. 1: Comparison of simulated value with measured values

$$\begin{cases} \frac{\partial c_2}{\partial t} = \frac{\partial}{\partial z} [\theta D(\theta, q) \frac{\partial c_2}{\partial z}] - \frac{\partial (qc_2)}{\partial z} + S_N(t, z) \\ S_N = k_2 \theta c_1 - k_3 \theta c_2 \end{cases} \quad (3)$$

where,

c_2 : The nitrate nitrogen concentration in soil solution (mg/L)

k_3 : The first-order rate constant for the denitrification of nitrate nitrogen (d⁻¹)

The remaining symbols are the same as in Formula 2.

Since there was water building up on the surface during the experiment, atmospheric boundary condition with surface layer was used to describe the upper boundary condition of water flow while the lower boundary condition was free drainage. In addition, the maximum surface layer was 30 cm in this research.

For nitrogen transport, the urea concentration of irrigation water was chosen as the upper boundary condition. Furthermore, since free drainage was selected for water flow, zero concentration gradient was used to define the lower boundary condition for nitrogen transport.

Calibration and validation of the model: The Hydrus-1D model was calibrated based on the electrical conductivity of the soil extract (1:5), EC_{1:5}, ammonium and nitrate nitrogen were measured from soil profiles in the two observation columns, with 10 g urea and 20 g urea dissolved in irrigation water, respectively. The calibration period was from 0 to 24 h after irrigation and the verification period was from 24 to 48 h after irrigation.

The soil hydraulic properties, residual and saturated water contents (θ_r and θ_s) were measured in the laboratory from soil samples that were extracted from the study area with Hyprop System (UGT German) and SW-PF soil pF curve system (KOKUSAN Japan). The saturated hydraulic conductivity (K_s) and the empirical shape parameters, α and n , were optimized by using the Levenberg-Marquardt method which was incorporated in the model code (Šimůnek *et al.*, 2005). During the inverse process, the K_s range was settled as 2-10 cm/h and θ_s and θ_r were fixed according to the measured values. Each inverse process was restarted several times and the run with the lowest objective function value was assumed to represent the global minimum. The calibrated parameters are shown in Table 2.

The model was evaluated in two ways: graphically and statistically. In the graphical approach, the measured and simulated results were plotted as a function of soil depth (Fig. 1). The statistical approach involved the calculation of the root mean square error (RMSE):

$$RMSE = \left[\frac{\sum_{i=1}^N (O_i - P_i)^2}{N} \right]^{0.5} \quad (4)$$

where,

P_i : The predicted values

O_i : The observed values

N : The number of observations

Table 4: Simulation program

Treatment	Irrigation/ (cm/h)	Fertilizer/ (g)
1	I _{0.25} F ₅	5
2	I _{0.25} F ₁₀	10
3	I _{0.25} F ₂₀	20
4	I _{0.25} F ₅₀	50
5	I _{0.5} F ₅	5
6	I _{0.5} F ₁₀	10
7	I _{0.5} F ₂₀	20
8	I _{0.5} F ₅₀	50
9	I ₁ F ₅	5
10	I ₁ F ₁₀	10
11	I ₁ F ₂₀	20
12	I ₁ F ₅₀	50
13	I ₂ F ₅	5
14	I ₂ F ₁₀	10
15	I ₂ F ₂₀	20
16	I ₂ F ₅₀	50

The RMSE of EC_{1.5} and nitrogen concentration for both the calibration and validation periods are shown in Table 3. During the calibration period, the RMSE of EC_{1.5} was 0.3103 ds/m, the ammonium nitrogen and nitrate nitrogen ranged from 0.0028 to 0.0057 mg/L and 0.02 to 0.0298 mg/L, respectively. During the validation period, the RMSE of EC_{1.5} was 0.4078 ds/m, the ammonium nitrogen and nitrate nitrogen ranged from 0.0066 to 0.0128 mg/L and 0.0315 to 0.0320 mg/L, respectively. The values of RMSE indicated the model could relatively correctly predict the observed EC_{1.5} and soil nitrogen concentration.

Simulation program: Simulation factors included irrigation intensity and urea application and irrigation intensity was equivalent to rainfall in 24 h. According to Complete Cross Design (Table 4), we set 4 levels of irrigation intensity from 0.25 to 2 cm/h and 4 levels of urea applications from 5 to 50 g dissolved in irrigation water respectively to simulate the transport of soil salt and nitrogen 48 h after irrigation.

RESULTS AND DISCUSSION

Impact of different irrigation intensity on soil salt changes: Figure 2 indicated the changes of soil electrical conductivity 48 h after irrigation when irrigation intensity increased from 0.25 to 2 cm/h in turn under the same application rate of urea (20 g). We found that soil electrical conductivity (EC_{1.5}) increased with soil depth in each treatment regardless of the irrigation intensity. Furthermore, previous studies have shown that there was a sound correlation between EC_{1.5} and soil salt content (Liu *et al.*, 2006). So we considered that soil salt content increased with soil depth in condition of infiltration, which reflected the role of irrigation on salt leaching.

What's more, after irrigation, the soil salt content changed rapidly at 0~60 cm depth while tended to be slow and steady at 60~100 cm depth. The reason might be that soil salinity transported quickly from shallow soil to the deep soil in the irrigation water infiltration and then constantly discharged from soil. In addition, salt content at each depth of soil profile gradually reduced with the increase of the irrigation intensity. To

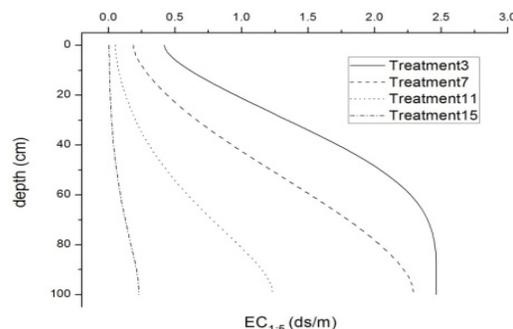


Fig. 2: Impact of irrigation intensity on soil salt changes

be more specific, when treatment 15 (I₂F₂₀) was compared to treatment 3 (I_{0.25}F₂₀), the soil salt content diminished by 98.40% at the depth of 20 cm while this value was 90.67% at the depth of 100 cm. This phenomenon indicated that the salt leaching is increasing with the strengthening of the irrigation intensity.

Impact of different irrigation intensity on soil nitrogen changes: Figure 3a and 3b represented the effect of different irrigation intensity on the changes of soil ammonium nitrogen. For the initial ammonium nitrogen content was so low that might be ignored in the analysis. Forty eight hours after irrigation, the amount of ammonium nitrogen was significantly increased, indicating that the urea applied in irrigation water had been partly transformed into ammonium. Researches have shown that the proportion of urea transforming into ammonium is 28.9% in 3~7 h after urea applied to soil and 63.85~76.50% in 24 h, 79.99~85.02% in 48 h (Nkrumah *et al.*, 1989), illustrating that urea can be rapidly decomposed in soil. Because the increase of ammonium nitrogen in the soil was mainly from the transaction of applied urea nitrogen, we could obtain the effect of irrigation intensity on the transaction of urea nitrogen by analyzing changes of ammonium nitrogen content. In addition, Fig. 3 showed that the ammonium nitrogen content, on the whole, decreased with soil depth in condition of irrigation, which manifested the role of irrigation in the leaching of both urea and ammonium nitrogen. However, when irrigation intensity was low, the amount of ammonium nitrogen at 0~40 cm depth was obviously larger than that at 60~100 cm depth; More exactly, the ammonium nitrogen content at 20 cm depth was nearly 1500 times the depth of 100 cm in treatment 2 (I_{0.25}F₁₀). What's more, this difference was not significant at high levels of irrigation intensity, for ammonium nitrogen content at 20 cm depth only increased by 7.24% than that at the depth of 100 cm in treatment 14 (I₂F₁₀). This was mainly because irrigation water had relatively weak influence on the leaching of urea nitrogen when the level of irrigation intensity was low. Therefore, the applied urea mostly remained in the upper layer of soil and gradually transformed into ammonium in the role of urease, which raised the

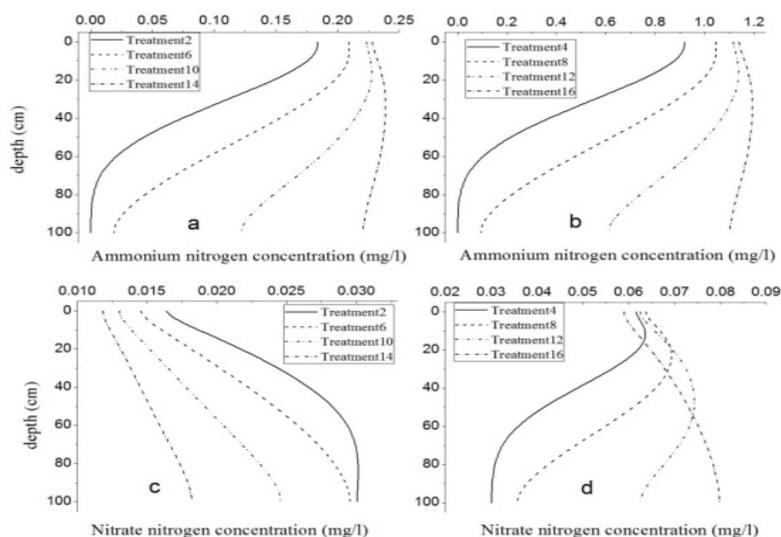


Fig. 3: Impact of irrigation intensity on soil nitrogen changes

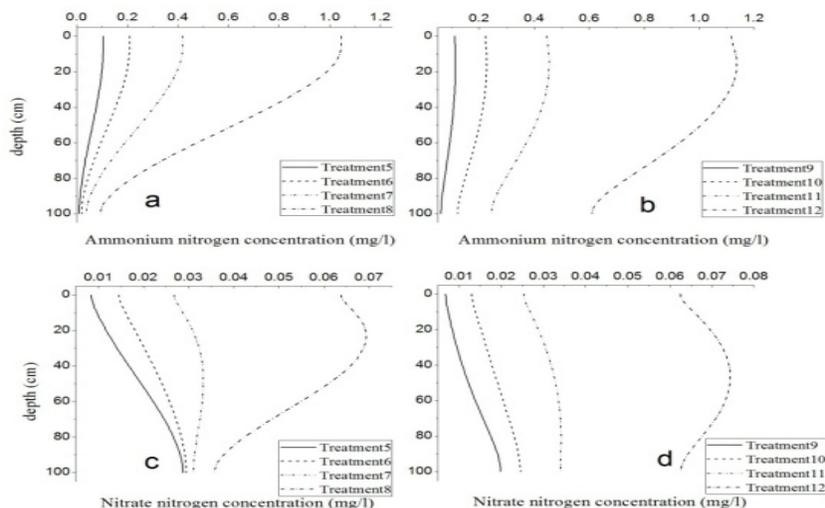


Fig. 4: Impact of urea applications on soil nitrogen changes

amount of ammonium nitrogen in soil. Furthermore, the leaching role of irrigation water enhanced with the increase of irrigation intensity, which weakened the difference of ammonium nitrogen distribution in the soil profile. That is to say, high irrigation intensity could increase the amount of ammonium nitrogen while reduce the differences of their distribution in soil profile. Meanwhile, comparing Fig. 3a and 3b also indicated that increasing urea application (from 10 to 50 g) could raise the soil ammonium nitrogen content.

Figure 3c and 3d depicted the impact of different irrigation intensity on the change of soil nitrate nitrogen. It can be seen from Fig. 3c that the soil nitrate nitrogen content increased with soil depth 48 h after irrigation when 10 g urea dissolved in the irrigation water. In addition, the nitrate nitrogen content gradually decreased in each treatment with the increase of

irrigation intensity; however, the differences of nitrate nitrogen content between the upper and lower soil layers declined. To be more exact, nitrate nitrogen content at 60 cm depth was 1.35 times larger than that at the depth of 60 cm in treatment 2 ($I_{0.25}F_{10}$) while this value was only 1.21 times in treatment 14 (I_2F_{10}). The possible reason might be that there was more nitrate nitrogen leaching from the soil with the increase of irrigation intensity. Moreover, only nitrate nitrogen in treatment 16 (I_2F_{50}) was in accordance with the law of increasing with soil depth while the nitrate nitrogen in other treatments were shown firstly increased and then decreased with soil depth when the amount of urea increased from 10 to 50 g (Fig. 3d). The reason for this case might be the irrigation intensity of treatment 4 ($I_{0.25}F_{50}$) treatment 8 ($I_{0.5}F_{50}$) and treatment 12 (I_1F_{50})

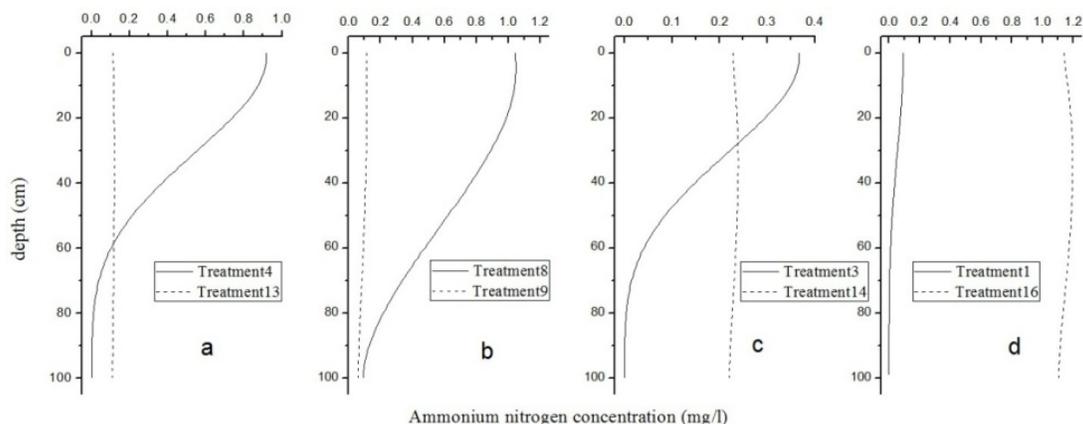


Fig. 5: Interactions of irrigation and urea applications for ammonium nitrogen

was lower than that of treatment 16 (I_2F_{50}) and in this way, the leaching effect on large amount of applied urea was not significant.

Impact of different urea applications on soil nitrogen changes:

In Fig. 4a and 4b, the changes of ammonium nitrogen in soil profiles as a result of different urea applications under the same irrigation level were presented. The amount of ammonium nitrogen decreased with the depth of the profile, as shown in Fig. 4a, which was in accordance with the results indicated in Fig. 3a. While in Fig. 3, the amount of ammonium nitrogen on the surface of the soil had little differences, the differences were obvious at the depth of 100 cm, which was contrary to the results illustrated in Fig. 4a. This was perhaps due to the significant difference of the application of initial amount of ammonium nitrogen. Besides, from the figures, we could also find out that the amount of ammonium nitrogen increased as the urea application increased, especially at the depths from 0 to 40 cm. Comparing Fig. 4a with Fig. 4b, we can easily figure out that larger amount of irrigation could increase the ammonium nitrogen in large quantity in soil profile 48 h after irrigation. This might be due to the contribution of increased irrigation to the leach of urea nitrogen.

As to nitrate nitrogen, the amount increased with the depth of soil profile at lower urea application treatments (Treatment 5, 6, 9 and 10), while at higher urea levels (Treatment 7, 8, 11 and 12), it increased at first, then decreased and finally reached a peak at the depths of 20 to 40 cm. It demonstrated that ammonium nitrogen accumulated under higher urea applications (Fig. 4a and b) and could be transformed into nitrate nitrogen by microorganisms. Moreover, it can be noted that higher irrigation had more influence on the depth of 60 to 100 cm than that of 0 to 40 cm under the same urea applications.

Interactions of irrigation and urea applications: As shown in Fig. 5a, at the depth of 0 to 60 cm of soil profile, the amount of ammonium nitrogen in treatment 4 ($I_{0.25}F_{50}$) was larger than that in treatment 13 (I_2F_5). While at the depth of 60 to 100 cm, it presented the opposite results. This was mainly due to the lower irrigation level but higher urea application in treatment 4 ($I_{0.25}F_{50}$) compared with treatment 13 (I_2F_5); as analyzed above, the increase of irrigation and urea application could contribute to the increase of ammonium nitrogen in soil profile. Comparing treatment 8 ($I_{0.5}F_{50}$) with treatment 9 (I_1F_5), we can find that the amount of ammonium nitrogen at the same depth was higher than that of treatment 9 (I_1F_5), resulting from the higher urea application of treatment 8 ($I_{0.5}F_{50}$) than that of treatment 9 (I_1F_5) by 10 times while the irrigation amount half that of treatment 9 (I_1F_5). It can be seen from Fig. 5c that the ammonium nitrogen of treatment 3 ($I_{0.25}F_{20}$) and treatment 14 (I_2F_{10}) came to be equal at the depth of 30 cm and this might be because the amount of urea in treatment 3 ($I_{0.25}F_{20}$) was only 2 times of that in treatment 14 (I_2F_{10}), but the irrigation amount in treatment 14 (I_2F_{10}) was 14 times as much as that of treatment 3 ($I_{0.25}F_{20}$). Besides, in Fig. 5d, we can also discover the phenomena that the ammonium nitrogen in treatment 16 (I_2F_{50}) was nearly 14 times the size of treatment 1 ($I_{0.25}F_5$) as the irrigation and urea application in treatment 16 (I_2F_{50}) was 8 and 10 times as much as that of treatment 1 ($I_{0.25}F_5$), respectively. The results indicated that, the initial urea application amount had obvious influence on the surface of soil (e.g., 0~30 cm) and high urea application and irrigation amount could promote the amount of ammonium nitrogen in soil profile effectively (Fig. 5).

In Fig. 6, the interactions of irrigation and urea applications on nitrate nitrogen transport in soil were depicted. As known from the results described before, when urea application was low (10 g), the nitrate nitrogen content in soil profile decreased as the amount of irrigation water increased after 48 h; and at the same

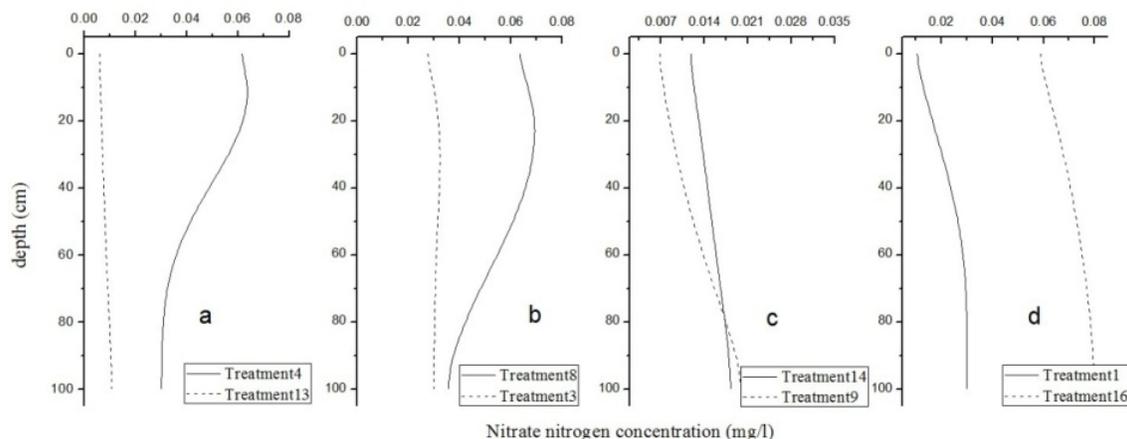


Fig. 6: Interactions of irrigation and urea applications for nitrate nitrogen

irrigation level, the nitrate nitrogen increased as the urea application increased. In comparison of treatment 8 ($I_{0.5}F_{50}$) with treatment 3 ($I_{0.25}F_{20}$) and treatment 1 ($I_{0.25}F_5$) with treatment 16 (I_2F_{50}), it could be found out that increase in the application of urea could increase the amount of nitrate nitrogen in soil profile. Furthermore, in Fig. 6c we could see that the influence of initial urea application on nitrate nitrogen at the depth of 0 to 80 cm of soil profile were more significant than that of irrigation. It could be explained with the phenomena that in treatment 14 (I_2F_{10}), the initial urea application and irrigation amount were both twice more than that of treatment 9 (I_1F_5), but the amount of nitrate nitrogen increased only by 25%. Moreover, Fig. 6a indicated that more urea application and less irrigation would be a good way to improve the nitrate nitrogen stored in the soil.

CONCLUSION

After calibration and validation of Hydrus-1D model based on the data of column experiments, different schemes of fertigation practices were simulated by Hydrus-1D. By analyzing the simulation results of soil salt and nitrogen content, we obtained the following results:

- The soil electrical conductivity increased gradually with depth after irrigation and the electrical conductivity at 0~60 cm depth changed faster than that at 60~100 cm depth.
- The soil ammonium nitrogen concentration decreased with depth and high irrigation intensity could increase the amount of ammonium nitrogen while reduce the differences of their distribution in soil profile.
- When the amount of initial urea application is small (10 g), the nitrate nitrogen concentration

increased with soil depth while decreased with irrigation intensity after irrigation.

- Both ammonium and nitrate nitrogen content of soil profile increased with increasing initial urea application amount, which played a more important role in the changes of soil ammonium (0~100 cm) and nitrate (0~80 cm) nitrogen content than irrigation intensity.

ACKNOWLEDGMENT

This study was made possible with the support provided by the National "Twelfth Five-Year" Plan for Science & Technology Support Program (Technology integration of agricultural water saving, research No. 2011BAD25B07 and "the Fundamental Research Fund for the Central Universities" by Ministry of Science and Technology, China, No. 2012206020206.

REFERENCES

- Bagges, E.M. and C.A. Watson, 2000. The fate of nitrogen from incorporated cover crop and green manure. *Nutrient Cycling Agroecosystem*, 56: 153-163.
- Fu, Y., Y. Lei, L. Zheng and L. Zhang, 2006. Characteristics of nitrate distribution in deep unsaturated zone in farmland [J]. *Agric. Res. Arid Areas*, 24(1): 73-77 (In Chinese with English Abstract).
- Hosen, Y. and K. Yagi, 2011. Recovery and leaching of ^{15}N -labeled coated urea in a lysimeter system in the north china plain [J]. *Pedosphere*, 2011(06): 763-772.
- Liu, Y., L.S. Pereira and R.M. Fernando, 2006. Fluxes through the bottom boundary of the root zone in salty soils: Parametric approaches to estimate ground-water contribution and percolation. *Agric. Water Manag.*, 84: 27-40.

- Nkrumah, M., S.M. Griffith and N., Ahmad, 1989. Lysimeter and field studies on ^{15}N in a tropical soil, II. Transformation of $(\text{NH}_2)_2\text{CO}-^{15}\text{N}$ in a tropical loam in a lysimeter and field plots. *Plant Soil*, 114: 613-620.
- Šimůnek, J. and D.L. Suarez, 1994. Major ion chemistry model for variably saturated porous media. *Water Resour. Res.*, 30(4): 1115-1133.
- Šimůnek, J.M., T. Sejna and G.M.T. van, 1998. The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat and Multiple Solutes in Variably-Saturated Media (Version 2.0) [M]. Colorado School of Mines Publishers, Riverside, California, pp: 125-132.
- Šimůnek, J., M.Th., van Genuchten and M. Sejna, 2005. The HYDRUS-1D Software Package for Simulating the Movement of Water, Heat and Multiple Solutes in Variably Saturated Media. Version 3.0. HYDRUS Software Series 1. Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, pp: 270.
- Wang, X. and Q. Gao, 2006. Salt-water balance and dry drainage desalting in hetao irrigating area inner mongolia [J]. *Sci. Geogr. Sinica*, 26(4): 455-460 (In Chinese with English Abstract).