Original Research

Characteristics of Preferential Flow Paths and Their Impact on Nitrate Nitrogen Transport on Agricultural Land

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Received: 5 November 2013
Accepted: 24 June 2014

Abstract

Preferential flow is important for solute transport in soil. This study aims to investigate distribution characteristics of preferential flow paths in agricultural land and to determine the effects of preferential flow on nitrate nitrogen transport. Dye tracer experiments were conducted on two farmland plots in Changping County, Beijing. Two undisturbed soil columns (with preferential flow) and two packed soil columns (without preferential flow) were used to determine the influence of preferential flow on nitrate nitrogen transport. The results showed greater nitrate nitrogen movement with a relatively higher velocity in the undisturbed soil columns, which is on average 2.31 times of that in the packed soil column. The breakthrough time of undisturbed soil columns was 12 h with 43% reduction compared with that of the packed soil columns. The preferential transport of NO_3^- in the undisturbed soil columns accounted for 43.83% of the total flux and resulted in a 97.60% accumulative leached mass for NO_3^- of the total mass. These results indicated that the preferential flow with a limited total flux ratio could lead to a large proportion of NO_3^- transport. Tailing phenomenon was observed and found to be a unique feature in the preferential flow's breakthrough curve. Tailing might be caused by discrepancies between the preferential flow, matrix flow, and penetration rate during infiltration.

Keywords: farmland, preferential flow, nitrate nitrogen, solute transport

Introduction

Preferential flow is a common form of soil water movement and is defined as non-equilibrium flow that occurs under various environmental conditions. Studies have shown that soil macropores and preferential flow are widespread in nature [1]. Preferential flow has a great effect on soil water and solute transport, which could account for a significant increased risk of soil and groundwater contamination [2, 3]. Experiments have shown that when the ratio of soil macropores is about 0.32% of total void, they can transmit up to 90% of the total soil water [4]. This property caused a large amount of water and solutes to be transported quickly and move to deep soil during irrigation and rainfall. This action will reduce the effects of pesticides and fertilizers on the soil, but lead to groundwater pollution [5]. Thus, the mechanism of preferential flow and solute transport in farmlands should be studied to meet the requirements of water resource utilization and agricultural management.

Several studies have reported that solute transport in soils is significantly affected by fast flow through preferential flow paths [6]. The Brilliant blue FCF dye-stain method was used to detect preferential flow paths, and on the basis of classification the dye coverage can be computed by

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image processing [7, 8]. Forrer et al. considered this method as a semi-quantitative way because of the unavoidably inaccurate estimations of concentration, and then developed a simple and cheap method to quantify the concentration of brilliant blue from digital photographs of soil profiles [9]. Rosqvist and Destouni studied and quantified water and solute transport through preferential flow paths in biodegraded solid waste by model interpretation of experimental breakthrough curves (BTCs) [10]. Allaire-Leung et al. used the approach with artificial macropore design and discussed the influence of soil marcropore connectivity and bending conditions on water and solutes transport [11]. Öhrström investigated the effects of preferential flow on solute transport by combing the bromide and dye tracers, and the time domain reflectometry technique [12]. The influence of preferential flow on solute transport in forest soil was also investigated in the Gongga Mountains by artificial rainfall, and demonstrated that the preferential flow increases the speed and the total amount of transported solute whether pond water was present or not [13, 14]. Chen et al. analyzed the vertical profile of nitrate nitrogen movement in farmland soil in Taihu Lake, and found that the preferential transport of nitrate nitrogen is not obvious under unsaturated conditions [15].

A real challenge of groundwater security was presented because of the pollution caused by increasingly intensive agricultural activities in the outskirts of Beijing, China. Knowing how to control soil pollution, protect soil resources, and improve land productivity is crucial for people. Nitrate nitrogen is an important water pollution source in agricultural environments. Therefore, studying the transport of nitrate nitrogen in farmland soil is very important for agricultural environmental management. In Beijing, the effect of preferential flow on nitrate nitrogen was seldom considered. The objective of this paper was to get the impact of preferential flow on nitrate nitrogen transport in the farmland in Changping County, Beijing, to provide necessary knowledge that can serve as references for regional water resource protection and agricultural management.

Methods and Materials

Field Site Description

The study site is located in Tingzi Village of Machikou Town, changping County, Beijing (Fig. 1). The site is in the Wenyu river flood plain near Yanshan Mountain. The study area belongs to the temperate monsoon region and has a semi-humid continental monsoon climate. The annual average sunshine hours are 2,684, and the annual average temperature is 11.8ºC. Rain is concentrated from June to September, with an average annual rainfall of 550.3 mm. The soil is Quaternary alluvial soil, which is suitable for planting various crops.

Preferential Flow Paths Detection and Characteristics Analysis

Image analysis using dye tracers is the most widely used method to describe preferential flow path distribution. This method was employed in this study.

The tracer experiments were conducted in October 2011. The experimental process in this study followed that of the study by Cheng et al. [16]. The application of breakthrough curve (BTC) took 1.1 h for the plots, and the experimental plots were dug up in four horizontal cross sections, each with a depth of 10 cm.

Horizontal cross sections of each layer were captured using a digital camera (2,560 pixels×1,920 pixels). The perspective effect of the digital images between the camera lens and the soil layer surface was corrected using Adobe Photoshop CS3. The dye-stained areas were colored black and gray, whereas the unstained areas were colored white. For each horizontal cross-section, the average dye coverage was calculated using Image-Pro Plus 6.0 [17]. In the Image-Pro Plus software, different colors represent different numerical information, for example black represents 0 and white represents 255. The numerical information of each soil profile can be acquired from Image-Pro Plus software.

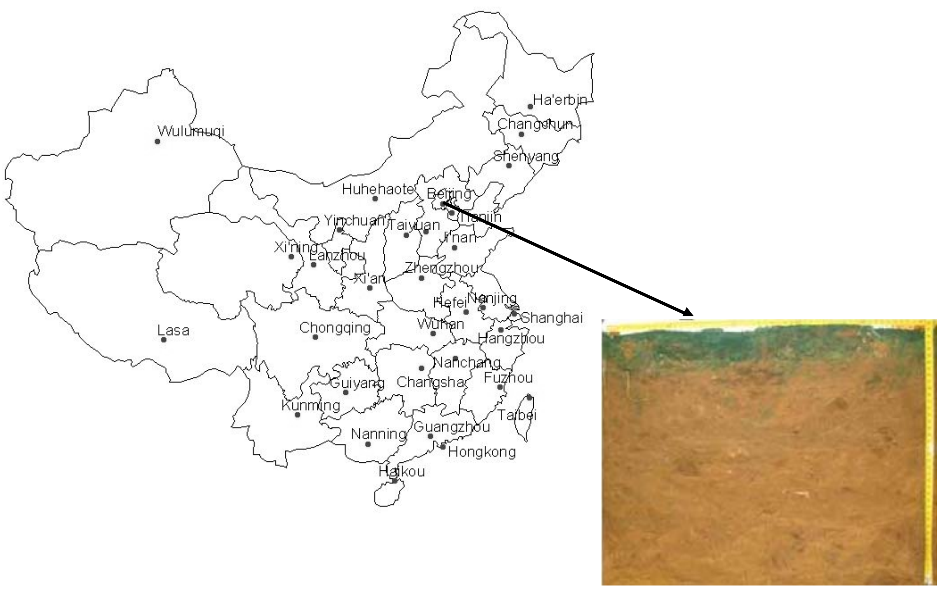

Fig. 1. Field site location.

Table 1. Soil bulk density and soil texture of the field sites.

	Soil depth (cm)	Soil bulk density (g·cm^{-3})	Sand (%)	Silt (%)	Clay (%)
Farmland 1	0~10	1.4314	46.53	39.79	13.67
	10~20	1.4076	44.49	41.84	13.67
	20~30	1.4328	36.34	47.96	15.69
	30~40	1.4453	42.97	44.88	12.15
Farmland 2	0~10	1.4579	43.99	42.84	13.17
	10~20	1.4504	36.40	45.59	18.01
	20~30	1.4558	32.860	51.19	15.95
	30~40	1.4698	40.47	47.8	11.65

The dye-stained areas were thought to be with preferential flow paths, and there were no preferential flow paths in the unstained area. Then the percentage of preferential flow paths can be acquired.

Soil Sample Collecting

Two pieces of farmland planted with corn were selected as experimental plots. In October 2011 soil samples of the 0-40 cm soil layer were collected from the two plots by each 10 cm layer. Soil bulk density and soil texture are shown in Table 1.

Two undisturbed soil columns were collected into a PVC tube with a 50-cm-high and a 20-cm-diameter in each plot. Two packed soil columns were made by filling soil into the same size tube layer by layer. The soil was air-dried and the particle diameters are less than 2 mm. The undisturbed soil columns were thought to have macropores and there was preferential flow. The packed soil columns were thought not to have macropores and there was no preferential flow.

Field Infiltration Experiment and BTC

Prior to the infiltration experiment the soil columns were saturated with deionized water. The volume of deionized water was assumed to be equal to that of soil porosity in the soil column, namely V_0. The V_0 values of the two soil columns were consistent, which were both 4.5 l.

After saturation, each soil column surface was covered with a sand layer to prevent the disturbance of the soil solution. After 24 h of leaching, each soil column was placed on a tripod. The design of the infiltration experiment is shown in Fig. 2.

During the experiment a 1g/L KNO_3 solution was continuously poured into the soil columns from a Markov bottle with a 4 cm head. The initial concentration of NO_3^-, C_0, in the solution is 1 g/L. The concentration of NO_3^-, C, from the collected solution was recorded every 2 hours for the undisturbed soil columns and every 4 hours for the packed soil columns. C was measured continuously, and the solute volume was recorded, then the accumulative solute volume (V) was calculated. The experiment ended when the value of C/C_0 was less than 0.05. NO_3^- concentration was detected by using a sensION + EC5 conductivity meter [18].

The BTC was drawn with pore volume (PV) as the horizontal axis and the relative liquid concentration (C/C_0) as the vertical axis. The pore volume (PV) was equal to V/V_0.

Results and Discussion

Soil Preferential flow Path Distribution in the Field

Based on the theory of two-flow region by Weiler et al. [19], in addition to the dye tracer experiment results, distribution characteristics of preferential flow paths were determined, which are shown in Fig 3.

The perecentage of soil preferential flow paths in different soil layers calculated by Image-Pro Plus 6.0 was shown in Table 2.

According to Fig. 3 and Table 2, the 30 cm to 40 cm soil layer has the fewest preferential flow paths, which denotes a few paths for water and solute transport. This result is consistent with the findings of Kodešová et al. [20], which

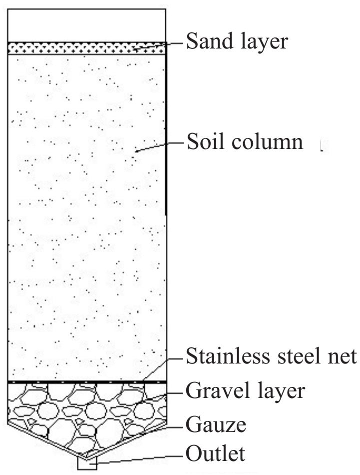

Fig. 2. Experimental design of soil column.

Table 2. Soil macroporosity in different layers.

Soil Depth (cm)	0~10	10~20	20~30	30~40
Macroporosity (%)	18.83	22.06	15.48	12.35

shows that more preferential flow paths are present in the shallow layer than in the deep layer. This also confirmed the results of Cheng et al. that preferential flow paths decreased with soil depth in southern China.

Soil Preferential Flow in Soil Columns

Initial penetration is the important basis for assessing whether preferential flow exists in soil water. When the relative concentration of solute C/C_0 is about 0.5, and PV < 1, preferential flow exists [21]. The results of the soil column infiltration experiment are shown in Fig. 4.

We used the judgment of Mon et al. to tell whether there was preferential flow in the soil columns. According to Fig. 4, when the C/C_0 value from the undisturbed soil column was equal to 0.50 the PV was 0.92. While in the packed soil column the PV is 2.94 when the C/C_0 was 0.50. Notably, when the C/C_0 was 0.50, the PV values for the undisturbed soil column were less than 1 and the packed soil column was much greater than 1. According to the judgment of Mon et al., preferential flow is observed in the undisturbed soil column and not in the packed soil column.

According to Fig. 4, the solute in the undisturbed soil column reached the peak value 0.94 after 120 h while the peak value of that in the packed soil column was 0.96 after 430 h. That means the solute was transported much more quickly in the undisturbed soil column than that in the packed soil column. This also confirmed that there was preferential flow in the undisturbed soil column.

Influences of Preferential Flow on Soil Water Transport Velocity

The observed soil water transport velocity in the undisturbed and packed soil columns exhibit quite different characteristics, as shown in Fig. 5. The average transport velocity of soil water in the undisturbed soil columns is 132.79 ml/h, which is significantly higher than that of the packed soil columns at 57.37 ml/h. The average soil transport velocity in the undisturbed soil column is 2.31 times that of the packed soil column, and the biggest transport velocity is 2.69 times that of the packed soil columns. The velocity curve of the undisturbed soil columns showed a big fluctuation, while the curve of the packed soil columns was relatively flat. Water transport velocity in the undisturbed soil columns varies throughout the experiment, and its value cannot be steady even by the end of the experiment (PV=6.0). By contrast, only a little fluctuation in soil water transport velocity was observed at the beginning of the experiment in the packed soil columns. The soil water transport velocity decreased with time and became consistent at PV=4.0.

The possible reasons for these trends in soil water transport velocity were as follows: first of all, preferential flow paths provided paths for water's quick transport, which was probably why soil water transport velocity in the undisturbed soil columns was significantly higher than that in the packed soil columns. When water flows too fast, water flow might scour the sidewalls of macropores [22], which can result in fragmentation of soil particles and changes in macropores, and eventually lead to water flow velocity fluctuations in the undisturbed soil columns. By contrast, no preferential flow exists in the packed soil columns, so the soil micropores undergo minimal changes. Hence, water transport velocity does not fluctuate significantly [23].

Influences of Preferential Flow on Solute Transport

The effects of preferential flow on solute transport were mainly at two aspects, namely solute transport time and the amount of solute transport.

Solute transport time is defined as the time from adding solute to the soil column until solute concentrations reach the detection limit (C/C_0 > 0.05). According to this definition, the solute transport time in the undisturbed soil columns and in the packed soil columns are about 12 h and 28 h, respectively. NO_3^- is a non-adsorption ion, which means that it does not react with chemicals in the soil and cannot be absorbed by clay and organic matter on the soil surface [24]. NO_3^- in soil can be transported rapidly by preferential flow in the undisturbed soil column, bypassing the

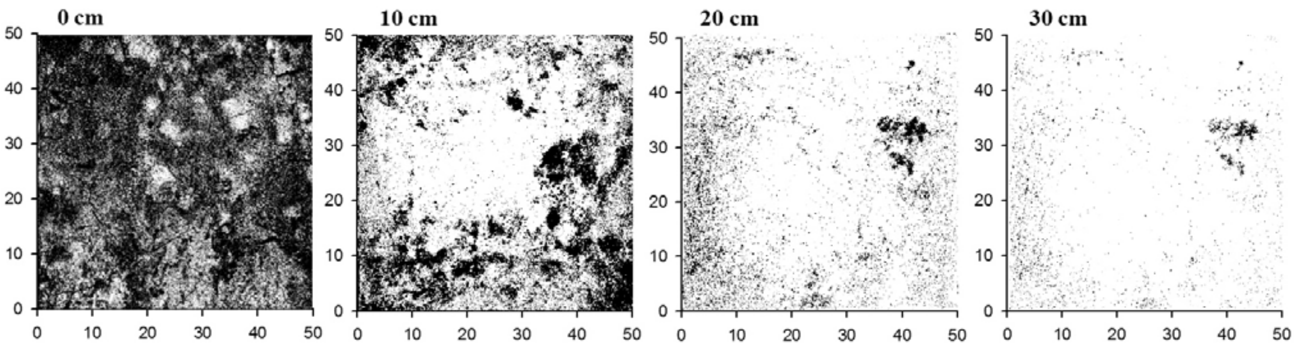

Fig. 3. Image of preferential pathways distribution in horizontal direction.

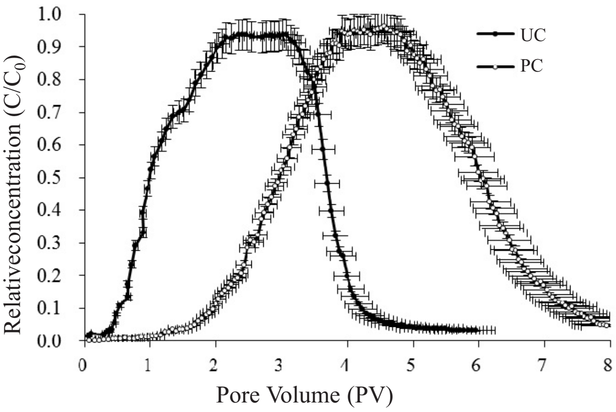

Fig. 4. The BTCs of NO_3^- from undisturbed and packed soil columns.
UC – undisturbed soil column, PC – packed soil column.
The bar means the standard error.

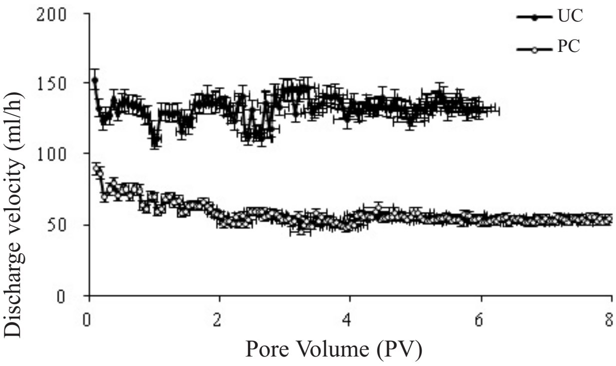

Fig. 5. Water transport velocity in the undisturbed and packed soil columns.
UC – undisturbed soil column, PC – packed soil column

soil matrix [25]. In the packed soil columns without preferential flow, however, the water flow velocity is almost constant, which means that the NO_3^- was transported much more slowly. Thus preferential flow can induce faster movement of NO_3^- in soil, which may lead to groundwater contamination.

The accumulative solute discharge against the change of pore volume for the two types of soil columns is shown in Fig. 6. Fig. 6 showed that the curve of undisturbed soil

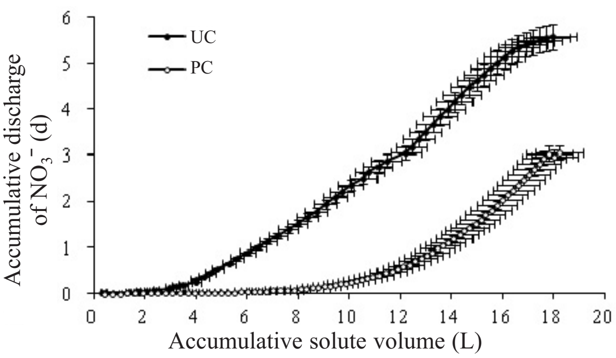

Fig. 6. Cumulative amount of NO_3^- from the undisturbed and packed soil columns.
UC – undisturbed soil column, PC – packed soil column.
The bar means the standard error

column displayed an almost steady increase, and the curve of packed soil column displayed a roughly exponential increase. The accumulative discharge of NO_3^- in the undisturbed soil column was much bigger than that in the packed soil column from beginning to end. The accumulative amount of NO_3^- was 2,350.27 mg in the undisturbed soil columns and 56.47 mg in the packed soil columns. While preferential flow accounted for 43.83% of the total water flow, the accumulative NO_3^- accounted for 97.60% of total NO_3^-; that is to say, most NO_3^- was transported as a result of preferential flow. These results suggested that preferential flow could improve the quantity and speed of nitrate nitrogen transport, which is consistent with the findings of Subramanian et al. [26] and Anaya et al. [27].

Tailing Phenomenon of Preferential Flow

As seen in Fig. 4, the solute BTC becomes smoother, with solute concentration declining more slowly after 3.5 PV in the undisturbed soil columns, and exhibits tailing. Tailing is a special phenomenon in soil water movement in the presence of preferential flow and may be primarily caused by unequal flow velocity.

According to the Chezy formula, with a constant frictional coefficient, water flow velocity will be higher if the pore radius is bigger. Hence water flow velocity is much higher in macropores than in the soil matrix, and unequal flow exists between the macropore region and the soil matrix. Based on the two-flow region theory by Weiler et al., two flow regions are present in the undisturbed soil columns. The solute moves quickly in the macropore region, whereas solute transport is slow in the matrix region, with the solute reaching the bottom of the soil column after a long period of time. Thus, the solute BTC in the undisturbed column occurred over a long duration. The undisturbed soil columns were saturated before the experiment, and little horizontal movement between the macropore region and the soil matrix region occurred. Therefore, the unequal flow velocity induced tailing in water and solute transport.

Conclusions

In the undisturbed soil columns, solute transport exhibited a higher velocity as well as fluctuation throughout the experiment. The average soil transport velocity in the undisturbed soil column is 2.31 times of that in the packed soil column, and the biggest transport velocity is 2.69 times that of the packed soil columns. Moreover, the preferential flow could scour the macropore sidewalls.

The preferential flow can improve the velocity and volume of nitrate nitrogen transport. The transport duration of NO_3^- in the undisturbed soil columns was 12 h and the pore volume was 0.36, which are 43% and 27% less than the transport duration and pore volume of the packed soil columns, respectively. This finding suggests that preferential flow can improve the transport velocity of NO_3^- in the soil. The accumulative NO_3^- transported by preferential flow accounted for 97.60% of the total NO_3^-, which meant that preferential flow can increase the nitrate nitrogen transport volume.

The preferential flow caused the tailing of the BTC. The quick solute transport by preferential flow caused the rapid decline of NO_3^- in the macropore region. However, in the soil matrix region the decline of NO_3^- was slow, which resulted in a long duration for the solute BTC. Therefore, the unequal flow velocity in the macropore region and soil matrix region induced tailing in solute transport.

Acknowledgements

We gratefully acknowledge the editor and reviewers. This research was jointly funded by Beijing Higher Education Young Elite Teacher Project (No. YETP0750), the National "twelve-fifth" technological support project (2011BAD38B0403), and the National Natural Science Foundation of China (Contract No. 41271300 and No. 30900866).

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