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Effects of Tillage Management on Infiltration and Preferential Flow in a Black Soil, Northeast China

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Abstract: The impacts of no-tillage (NT) and moldboard plough (MP) managements on infiltration rate and preferential flow were characterized using a combined technique of double-ring device and dye tracer on a black soil (Mollisols) in Northeast China. The objective of this study is to evaluate how tillage practices enhance soil water infiltration and preferential flow in favor of soil erosion control in the study area. The steady infiltration rates under NT management are 1.6 and 2.1 times as high as those under MP management in the 6th and 8th years of the tillage management in place, while the infiltrated water amounts under NT management are 1.4 and 2.0 times as high as those under MP management, respectively. The depth of methylene blue penetrated into NT soil increases from 43 cm in the 6th year to 57 cm in the 8th year, which are 16 cm and 19 cm deeper than those in MP soil, respectively. The results of morphologic image show that more biological macro-pores occur in NT soil than in MP soil. These macro-pores play a key role in enhancing preferential flow in NT soil, which in turn promotes water infiltration through preferential pathways in NT soil. The results are helpful to policy-making in popularizing NT and have the implications for tillage management in regard to soil erosion control in black soil region of China.

Keywords: no-tillage; moldboard plough; dye tracer; macro-pore; black soil; Northeast China

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1 Introduction

Infiltrability is one of the most important soil physical properties, which affects soil water availability for plant use and groundwater recharge, and is related to soil erosion and water runoff (Lipiec *et al*., 2006). As a crucial form of water movement in fine-textured soils, preferential flow is closely related to soil water infiltration and the quality of surface- and ground-water (Armstrong *et al*., 1999). Five types of preferential flow have been recognized, including macro-pore flow, gravity-driven unstable flow, heterogeneity-driven flow, oscillatory flow, and depression-focused recharge. Among these, macro-pore flow is the most important and extensively studied one (Cullum, 2009). Soil macro-pores play a key role in the rapid transmission of water, known as preferential or bypass flow (Hendrix *et al*., 2007), and have a great impact on soil water infiltration which has the potential to reduce runoff and soil erosion (Arshad *et al*., 1999; Perkins *et al*., 2012).

Dye tracers, visual counting of stained macro-pores in the field, and photographic images of soil macro-

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pores are usually used for characterizing preferential flow and the macro-pore network in soils (Allaire *et al*., 2009). Among these methods, dye tracer techniques are most valuable in gaining information on water movement processes in soils (Kasteel *et al*., 2007). In addition, infiltrated water amount can be assessed by *in situ* measurements using pressure infiltrometers (Reynolds and Elrick, 1990) or tension infiltrometers (Wahl *et al*., 2004). Recently, dye tracer and infiltrometer were usually combined to measure soil pore morphology and water infiltration in deeper soil profiles (Kasteel *et al*., 2007; Cey *et al*., 2009; Holden and Gell, 2009; Homolak *et al*., 2009).

Tillage practices could greatly affect soil macroporosity and infiltration characteristics, which consequently affect water runoff and soil erosion (Kemper *et al*., 2012). These influences varied with many factors such as soil type, location, residue management, and soil measurement method used. Kay and Vanden Bygaart (2002) reported that converting conventional tillage (CT) management to no-tillage (NT) generally increased the volume fraction of > 500 μm bio-pores and 100–500 μm macro-pores and decreased the volume fraction of 30–100 μm macro-pores. It has also been reported that NT management could result in a greater continuity and connectivity of the macro-pore system (Wahl *et al*., 2004) and a higher infiltration rate (Alvarez and Steinbach, 2009; Kahlon *et al*., 2013; Roper *et al*., 2013) compared with CT management. However, some studies found that conservation tillage did not bring detectable increases in macro-porosity or infiltrability compared with CT (Sasal *et al*., 2006; Capowiez *et al*., 2009). Other studies even inferred higher infiltration rate in tilled soils than in NT soils (Lipiec *et al*., 2006; Schwartz *et al*., 2010; Celik and Erahin, 2011; Melero *et al*., 2011).

The tillage-induced changes in soil porosity, preferential flow and infiltration characteristics have been a major focus of soil erosion study, including the studies in Australia (McGarry *et al*., 2000), North and South America (Govaerts *et al*., 2007; Alvarez and Steinbach, 2009; Cullum, 2009), Europe (Hangen *et al*., 2002; Wahl *et al*., 2004; Lipiec *et al*., 2006), Africa (Moroke *et al*., 2009), India (Sharma *et al*., 2009), and China (Xu and Mermoud, 2001; He *et al*., 2009). However, little information is available on black soil in Northeast China. Northeast China is a key base for commercial grain production in China where the fertile and productive black soil (Mollisols) was primarily distributed (Kravchenko *et al*., 2011). However, years of conventional tillage has resulted in increasingly serious soil erosion and degradation problems (Liu *et al*., 2010), and there is an urgent need for identifying suitable tillage practices to maintain and restore farmland soil at present, in response to the sustainable development demand of the nation. It has been reported that NT management can restore organic matter level and reduce soil degradation for the same type of soil in South America (Durán *et al*., 2011). Conservation tillage practices, especially NT, are just starting in the study area. Little is known about how NT affects the macro-pore network or hydraulic behavior of black soil.

Accordingly, the objective of this study is to determine the influence of NT and moldboard plough (MP) tillage practices on infiltration and preferential flow patterns of black soil. The results can be helpful to propose strategies for erosion control in the context of agricultural sustainability for Northeast China and other areas with similar soil degradation problems.

2 Materials and Methods

2.1 Study site

This study was conducted on a tillage trail, including no-tillage (NT), moldboard plough (MP), ridge tillage and zone tillage, initiated in the fall of 2001 at the Experimental Station (44°12′N, 125°33′E) of Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, in Dehui County, Jilin Province, China. The study site is located in a temperate zone with a continental monsoon climate. The mean annual temperature is 4.4℃, and the mean annual precipitation is 520 mm with more than 70% occurring in the warm months of June, July and August. The soil is a clay loam (Mollisols) and soil properties are summarized in Table 1. Prior to establishment of the tillage experiment, the land had been used for continuous maize production under MP management for more than ten years.

2.2 Tillage experiments

Two tillage practices, NT and MP, were used in this study. The NT and MP plots were arranged in a randomized complete block design with four replicates. Each tillage plot was split into two sub-plots (5.2 m × 20.0 m), one sub-plot for maize and the other sub-plot for soybean production, which were under a maize-soybean

Table 1 Properties of studied soil

Depth (cm)	Water content (%)				Bulk density (g/cm^3)		Clay (%)	Silt (%)	Sand (%)
	NT		MP		NT	MP			
0–5	16.1[a]	17.6[b]	14.8[a]	16.0[b]	1.16	1.12	36.0	24.0	40.0
5–10	16.4	20.0	16.2	18.0	1.40A	1.28B	35.8	23.8	40.4
10–20	17.6	18.3	17.0	18.3	1.32	1.32	35.7	24.4	40.0
20–30	17.6	18.3	17.7	18.5	1.30B	1.34A	36.6	25.0	38.7

Notes: a, data in 2007; b, data in 2009; clay, silt and sand data from 2001; bulk density data from 2009. NT, no-tillage; MP, moldboard plow. Different uppercase letters indicate significant difference between NT and MP managements at 0.05 level

rotation with both crops present each year. For NT plots, no soil disturbance was practiced except for planting in spring. Planting operations, including seeding and fertilizer application, were completed at the same time for both NT and MP with a KINZE-3000 NT planter (Williamsburg, Iowa). Herbicides were applied before and after sowing to control weeds for NT management. The soil under MP management was moldboard ploughed to a depth of 18–20 cm in fall; seed beds were prepared in spring by disking (7.5–10.0 cm) and harrowing, and ridges (16 cm high) were formed during the cultivation; weeds were controlled by manual hoeing. Row width was 75 cm in both tillage systems.

2.3 Infiltration measurements and dye tracer experiments

Dye tracer experiments were carried out in conjunction with infiltration measurements in soybean plots immediately after harvest in 2007 and 2009 (the 6th and 8th years after the tillage experiment started). The dye tracer was used for demonstrating the infiltration depth as well as for illustrating water flow pathways. Infiltration measurements and dye tracer experiments were done with four replicates in both NT and MP treatments in 2009 and no replicate was carried out in the 2007 trial.

Infiltration tests were performed at no traffic lane to ensure limited mechanical compaction. A stainless steel double-ring device with inner and outer ring diameters of 30 cm and 60 cm was inserted into the soil, where no evidenced traffic pressure traces, to a depth of 10 cm. A Mariotte bottle (Bagarello *et al.*, 2009) consisting of a 70 cm high reservoir of water with an inner diameter of 17 cm was used to control water head. The Mariotte reservoir was filled with methylene blue ($C_{16}H_{18}ClN_3S{\cdot}2H_2O$) solution (0.5 g/L) which was directly transported to the inner ring when the outlet was opened at time of zero. The reservoir maintained a constant solution height of 5 cm above the soil surface in the inner ring. The fall rate of the solution level in the reservoir was recorded. When the solution in the reservoir dropped to a predetermined amount, the outlet was closed and the reservoir was refilled. During the refilling of the Mariotte reservoir, dye solution was added to the inner ring from a second reservoir to maintain the ponding height. This procedure was repeated until apparent steady state was reached (Braud *et al.*, 2005). To eliminate lateral movement of solution in the soil, the height of water head in the outer ring was also maintained at 5 cm. The amount of infiltrated water was the volume of water infiltrated in the inner ring divided by the area of the inner ring.

Once the infiltration experiment was terminated, the stained sites were covered with plastic sheets to prevent the influence of rain or evaporation. Two weeks later, excavations were performed to expose the stain patterns and photographic images were taken. Half of each site was firstly excavated near the ring diameter to expose a vertical profile to reveal the depth of stain penetration. Successive layers of soil were then removed from the remaining half to expose semicircle-shaped horizontal surfaces at 1 cm step in the top 10 cm, 2 cm step for the 10–20 cm depths, and 5 cm step below 20 cm to the place where no stain was visible. Loose soil was removed from each horizontal surface with a vacuum dust collector and then the surfaces were photographed for subsequent investigation of stained soil. After taking photographs, a soil slice (20.0 cm × 10.0 cm × 0.5 cm) was collected at each layer from the center of the semi-ring for the measurement of soil methylene blue content distributions. The soil slice sample were air-dried and then put into suspension with deionized water (4∶1 water-soil ratio). A series of methylene blue solution of different concentrations were prepared as standard solutions. The absorbance of the standard solutions was determined using spectrophotometer with the wavelength at 665 nm, and then a standard curve was obtained. The concentration of methylene blue in soil suspension after centrifugation (5000 r/min, 20 min) was determined by using the standard curve (Soukos *et al*., 2006).

2.4 Earthworm sampling

Earthworms were collected from NT and MP plots by using the formalin extraction method (Raw, 1959). Briefly, a 60 cm × 60 cm × 15 cm steel frame was inserted in each plot to a depth of 10 cm. Then the formalin solution (12 L, 0.55%) was added to each frame and allowed to stand for 2 h. Earthworms moving out of the soil surface in the frame were collected. After that, the top 10 cm soil inside the frame was dug out for earthworm collection. All earthworms collected were taken to the lab and cleaned with alcohol. The numbers and fresh weight of the earthworms were then recorded.

2.5 Data analysis

Statistical analysis was conducted by using the SPSS 11.5 (SPSS Inc., Chicago, IL) and the charting was conducted by using the Origin 7.5 software package (OriginLab Corp., Northampton, MA). The difference between the tillage treatments was determined by using paired *t*-test at 5% significance level.

3 Results

3.1 Water infiltration rate and infiltration amount

In both NT and MP soils, infiltration rates in both 2007 and 2009 trials were high at the beginning, declined gradually, and then approached a steady stage (Fig. 1). The time reaching the steady stage was 140 min for both NT and MP soils in 2007 and 160 min for both soils in 2009. There is a decreasing trend of infiltration rates and infiltration amount with increasing tillage intensity: 8-year NT (2009) > 6-year NT (2007) > MP (Fig. 1; Fig. 2). The amount of water infiltrated in NT soil is 1.4–2.7 times as high as in MP soil in 2007, and correspondingly, 2.0–2.4 times in 2009. The highest infiltration rates appeared during the transient stage at 12.3 mm/min (NT) vs. 7.7 mm/min (MP) in 2007 and 14.4 mm/min (NT) vs. 12.5 mm/min (MP) in 2009. The infiltration rates at steady stage were 3.9 mm/min and 5.2 mm/min for NT soil in 2007 and 2009, respectively, which were 1.6 and 2.1 times as high as for MP soil.

3.2 Preferential flow characteristics

Preferential flow patterns in the soil were evident in the dye-stained soil profiles (Fig. 3). In 2007, dye-staining was dominant in the surface 0–10 cm of the MP soil and was extremely faint below 27 cm depth. However, dye-staining was clearly shown as deep as 47 cm in the NT soil. In 2009, dye-staining reached a depth of 49 cm under MP management and a depth of 61 cm under NT management through macro-pores or cracks, and evidently larger stained area was shown in NT soil than in MP soil.

The distribution of water-conducting bio-pores in the soil was recorded in the photos taken from 12 cm and 20 cm depth of the NT and MP sites (Fig. 4). There were

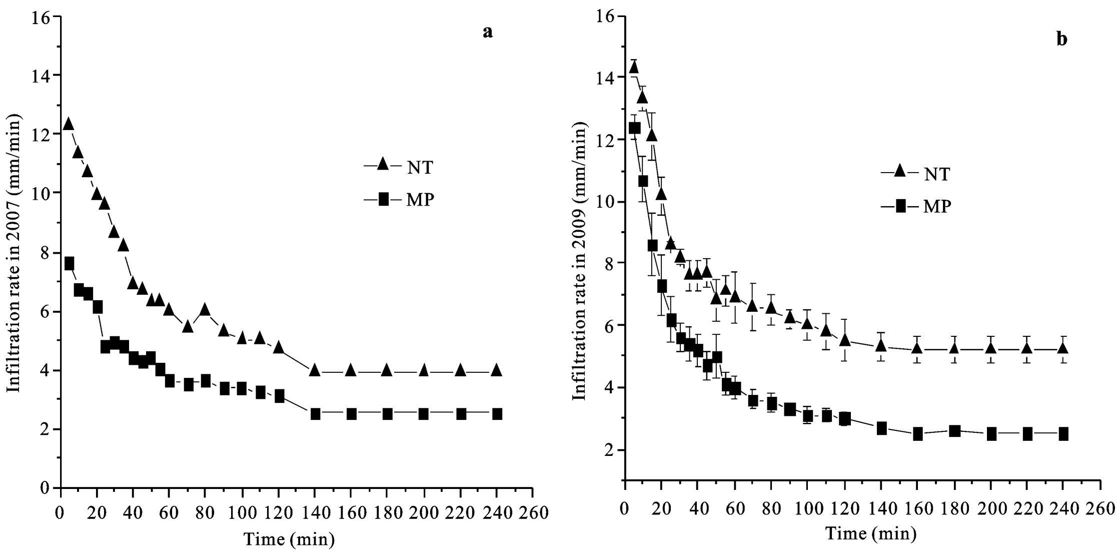

Fig. 1 Infiltration rate for a black soil under no-till (NT) and moldboard plough (MP) managements in Northeast China. Single measurement in 2007 (a) and four replicates in 2009 (b). Bars in b indicate standard deviation (*n* = 4)

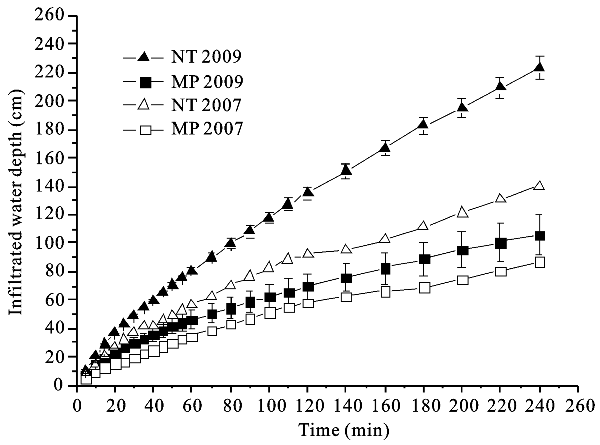

Fig. 2 Infiltration amount for a black soil under no-tillage (NT) and moldboard plough (MP) managements in Northeast China. Bars indicate standard deviation (n = 4)

six and eight bio-pores at the 12 and 20 cm depths in NT soil, whereas no macro-pore was found at the same depths in MP soil in 2007. The results of the photos also clearly showed that dye stained area, either stained cracks or poroid voids, were larger in all depths of NT soil in 2009 compared with MP soil (Fig. 4). The concentration of methylene blue was relatively high at 0–5 cm depth and decreased rapidly with increasing depth in both NT and MP soils. It was significantly higher in NT soil than in MP soil in the top 5 cm for both years and showed the opposite pattern down to the 25 cm depth ($P < 0.05$). The concentration of dye in MP soil was extremely low or was not detectable below 25 cm in 2007 and below 40 cm in 2009, while the concentration in NT

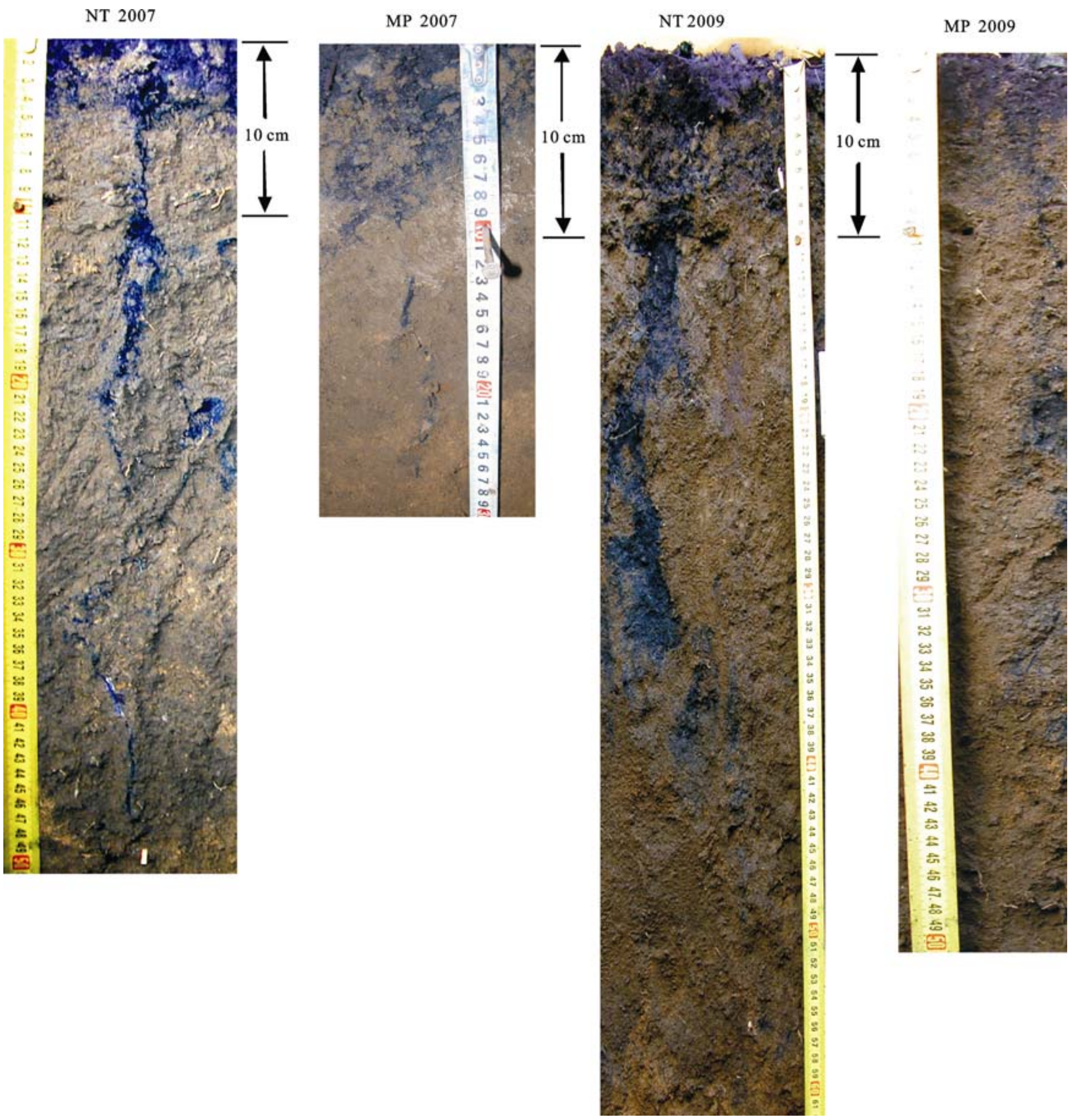

Fig. 3 Stained images of vertical sections under no-till (NT) and moldboard plough (MP) managements on a black soil in Northeast China

soil was higher and extended to lower soil depth in both years (Fig. 5).

3.3 Earthworm abundance and biomass

Significantly more earthworms were collected from NT plots than from MP plots in both studied years (P < 0.05). In 2007, the earthworm abundance and biomass under NT management were 29.86 n/m^2 and 4.60 g/m^2, respectively, which were 4.3 and 3.9 times as high as those under MP management. In 2009, earthworm abundance and biomass in NT soils were 4.5 and 3.0 times as high as those under MP, respectively (Table 2).

4 Discussion

Soil water infiltration is reported to be directly affected by the soil tillage management (Moret and Arrúe, 2007). In this study, the infiltration rate and infiltration amount

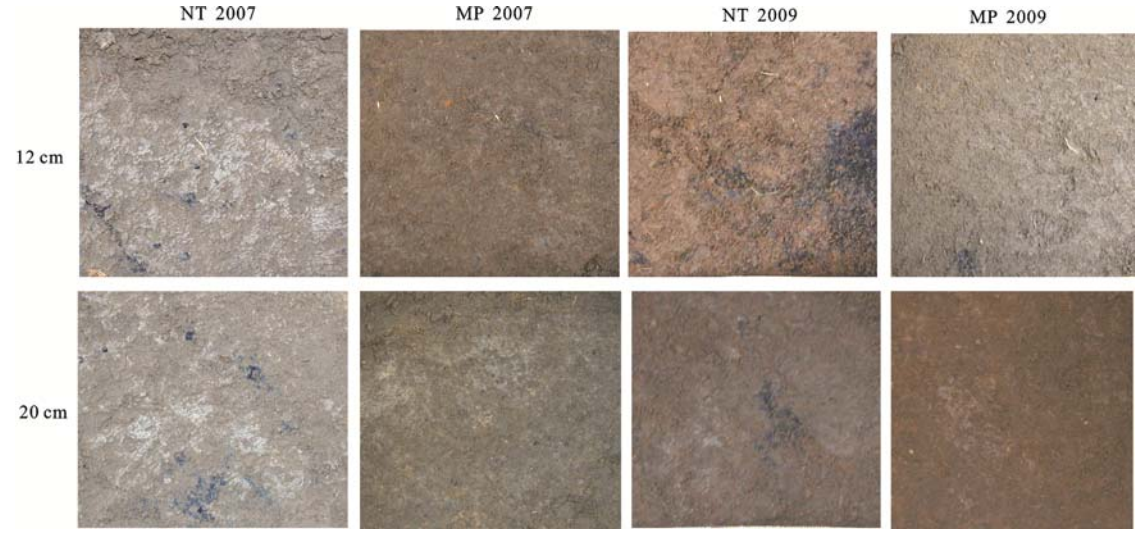

Fig. 4 Bio-pores of soil sections at depths of 12 cm and 20 cm under no-till (NT) and moldboard plough (MP) managements on a black soil in Northeast China

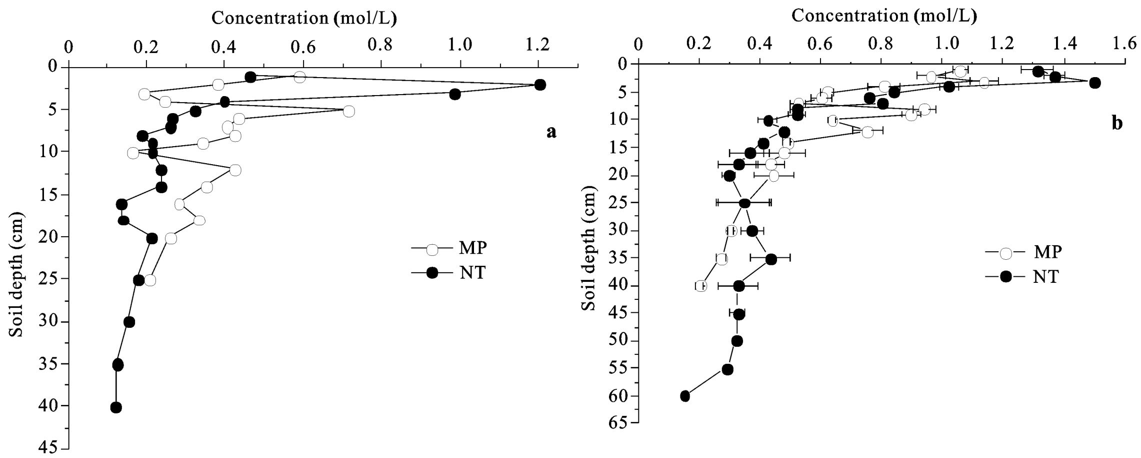

Fig. 5 Concentration of methylene blue under no-tillage (NT) and moldboard plough (MP) managements in 2007 (a) and 2009 (b) on a black soil in Northeast China. Bars indicate standard deviation (n = 4)

Table 2 Earthworm abundance and biomass under no-tillage and moldboard plough managements in 2007 and 2009

Year	No-tillage		Moldboard plow	
	Number (n/m^2)	Biomass (g/m^2)	Number (n/m^2)	Biomass (g/m^2)
2007	29.86^a	4.60^A	6.94^b	1.17^B
2009	30.90^a	8.15^A	6.94^b	2.75^B

Notes: different lowercase or uppercase letters in the same row indicate significant difference of earthworm number or biomass at 0.05 level were significantly higher under the NT management compared with those under the MP management. These results are in agreement with those of many studies (Govaerts *et al*., 2007; Alvarez and Steinbach, 2009; Presley *et al*., 2012; Kahlon *et al*., 2013), but disagree with those of other studies which showed evidently higher infiltrability in tilled soils than in NT soils (Lipiec *et al*., 2006; Schwarts *et al*., 2010; Celik and Ersahin, 2011). There are many factors influencing soil water infiltration, such as soil structure, aggregation, soil bulk density, soil moisture, organic matter content, macropore quantity and continuity, soil texture, dye application methods, *etc*. (Hangen *et al*., 2002; Cullum, 2009; Truman *et al*., 2011), most of which are greatly sensitive to tillage practices. Increased organic matter content, reduced bulk density below the plow layer, and higher macro-aggregate contents and macroporosity in NT soils are reported in our previous studies as well as in other published literatures (Liang *et al*., 2009; Zhou *et al*., 2009; Liang *et al*., 2011). These may all contribute to the improved water infiltrability when the soils were converted from CT to conservation tillage. The higher infiltration rate and infiltration amount are important for reducing soil surface runoff, and have great potential for reducing the soil erosion in the studied region.

Biotic factors, such as earthworm burrowing and root decomposition can greatly affect numbers and continuity of macro-pores for preferential transport (Jarvis *et al*., 2008; Cey *et al*., 2009; Kramers *et al*., 2009). It has been widely reported that the earthworm abundance and activity and root developments could be greatly affected by tillage practices (Chan, 2001; Imhoff *et al*., 2010). In NT plots, root channels functioned as continuous macropores which connected the soil surface to the subsoil, while in MP plots, these continuous macro-pores were disrupted and the pathways for water infiltration were reduced (Larsbo *et al*., 2009). In an infiltration study by using dye-stained technique, Gish *et al*. (1998) found greater deethylatrazine concentrations in deeper soil of NT soil compared with tilled soils due to the formation of stable root channels. Capowiez *et al*. (2009) found that the higher abundance of the ecological type of earthworms in soils under reduced tillage was associated with large macro-pores and thus might enhance infiltration compared with that in MP soil. It agreed with our result that the earthworm population was significantly higher under NT than under MP management, and this partly explained why there were more macro-pores in NT than in MP plots in the studied site.

Dye-stained technique is one of the most commonly used methods for preferential flow determination because it is inexpensive, easy to implement, and makes flow pathways visible. Luo *et al*. (2006) successfully quantitatively described the channeling flow in saline rice soil and alkaline soil in Northeast China by using bromide as a tracer. The results of this study showed higher methylene blue concentrations in topsoil than in subsoil for both NT and MP managements. This could result from the heavy absorption of dye to the solid phase, which led to limited amount of dye being transported to deeper depths through limited macro-pore structures in subsoil. The discontinuity of macro-pores in the plough layers could prolong the stay of dye tracer solution in soil, which might contribute to the concentrated methylene blue in the 5–25 cm depth of the MP soil. In contrast, dye-stained solution would be transported constantly along macro-pore pathways down to deeper depth in NT soil (> 25 cm). The higher soil organic matter content in topsoil than in subsoil also played a role in the higher dye concentration in upper layers (Liang *et al*., 2009).

In preliminary tests, we followed the method of Wahl *et al*. (2004) and sprayed the dye solution on the soil surface. This method only resulted in dye penetration to the top 20 cm, possibly because it was adsorbed on the soil particles and organic matter. When the dye method was combined with the double-ring infiltration experiment, the dye tracer penetrated much deeper into the soil profile under continual and constant supply of fresh dye solution to the soils from the Marriot reservoir and follows the infiltrate. It suggests that the combined technique of dye tracer with a double-ring device is an appropriate method exploring soil water infiltration and preferential flow characteristic in the studied clay loam soil. The fact of dye tracer reached a deeper depth in NT soil compared with MP soil also implies enhanced preferential flow and infiltration capacity for the NT soil. The results indicate that the implication of NT could contribute to the reduction of soil runoff in the black soil studied.

5 Conclusions

Infiltration rate and preferential flow were characterized by using dye tracer (methylene blue) combined with double-ring technique on a black soil in Northeast China in the 6th and 8th year of no-tillage (NT) and moldboard plough (MP) managements. The results suggested that application of the newly introduced NT management to the black soil (Mollisols) in Northeast China notably improved soil quality in terms of macro-pores and soil water infiltrability compared with the pervasive conventional tillage. The higher amount of infiltrated water and deeper penetration depth in NT soils suggests that NT has the potential for reducing runoff and soil erosion in black soil region in Northeast China. The results may be helpful in informing the decision-making process towards no-tillage popularization in the black soil region of China.

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