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Field study on macropore flow in typical Black soils of northeast China

Xiaojin Jiang[1], Enheng Wang[1,2], Xiangwei Chen[1,2], Xiangyou Xia[1], and Changting Shi[1]

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Jiang, X., Wang, E., Chen, X., Xia, X. and Shi, C. 2012. **Field study on macropore flow in typical Black soils of northeast China**. Can. J. Soil Sci. **92**: xxx–xxx. Macropores are important preferential pathways for the transport of water and contaminants in soil. A series of hood infiltration experiments were conducted using dye tracers (Brilliant Blue FCF) at pressure heads of −5.0 cm, −3.0 cm, and −1.0 cm at a conventional tilled site on Keshan Farm, northeast China. The study objective was to combine the test method of dye tracing with a hood infiltrometer to analyze soil subjected to conventional tillage methods. Dye staining patterns and macroporous networks were analyzed by excavation, mapping, photography, and image analysis. Results showed that macropore flow began very near the soil surface under three pressures heads of −5.0 cm, −3.0 cm and −1.0 cm, and that a pressure head of −1.0 cm resulted in more lateral flow. Soil deeper than 40.0 cm was less disturbed, which resulted in good continuity. At pressure heads of −5.0, −3.0 and −1.0 cm, the dye staining technique resulted in maximum stained depths of 74.3, 60.7 and 64.7 cm, respectively, with maximum stained widths of 41.6, 41.5 and 47.9 cm, respectively (at depths from 14.0 to 28.0 cm). Soil under a pressure head of −1.0 cm had the highest initial and steady infiltration rates of 13.0 and 4.1 mm min^{-1}, respectively. Soil under a pressure head of −5.0 cm showed the most connectivity. To distinguish the macropores from the interaction area of macropore flow and the soil matrix surrounding the macropores, the stained area was separated into different classes based on dye color.

Key words: Macropores, conventional tillage, hood infiltrometers, dye tracers

Jiang, X., Wang, E., Chen, X., Xia, X. et Shi, C. 2012. **Étude sur le terrain du flux des macropores dans les sols noirs typiques du nord-est de la Chine**. Can. J. Soil Sci. **92**: xxx–xxx. Les macropores constituent l'une des principales voies de transport de l'eau et des contaminants dans le sol. Les auteurs ont entrepris une série d'expériences d'infiltration sous hotte en appliquant un colorant traceur (Brilliant Blue FCF) à une hauteur piézométrique de −5,0 cm, −3,0 cm et −1,0 cm dans un champ labouré de manière classique, à la ferme Keshan, dans le nord-est de la Chine. L'étude devait combiner la technique du test de colorant à celle de l'infiltromètre sous hotte pour analyser les sols assujettis aux travaux usuels. La dispersion du colorant et les réseaux de macropores ont été analysés par excavation, cartographie, photographie et analyse d'image. Les résultats indiquent qu'aux trois hauteurs piézométriques de −5,0 cm, −3,0 cm et −1,0 cm, l'écoulement dans les macropores commence très près de la surface et qu'une hauteur piézométrique de −1,0 cm favorise un écoulement plus latéral. À plus de 40,0 cm de profondeur, le sol est moins perturbé, ce qui se traduit par une bonne continuité. Aux hauteurs piézométriques de −5,0 cm, −3,0 cm et −1,0 cm, le test du colorant permet la coloration du sol à une profondeur maximale de 74,3 cm, 60,7 cm et 64,7 cm, respectivement, et sur une largeur maximale de 41,6 cm, 41,5 cm et 47,9 cm (profondeur de 14,0 cm à 28,0 cm). C'est le sol à la hauteur piézométrique de 1,0 cm qui enregistre le plus fort taux d'infiltration initial et le taux d'infiltration le plus stable (13,0 mm par minute et 4,1 mm par minute, respectivement). Le sol présente la meilleure connectivité à la hauteur piézométrique de −5,0 cm. Pour distinguer les macropores de la zone d'interaction avec le flux des macropores et la matrice du sol entourant ces derniers, les auteurs ont réparti le sol coloré en différentes classes selon sa teinte.

Mots clés: Macropores, travail classique du sol, infiltromètre sous hotte, colorant traceur

Preferential flow comprises conditions where uneven and often rapid movement of water and solutes follow pathways while bypassing volume fractions of the porous soil matrix (Allaire et al. 2009). Preferential flow patterns include macropore, fingering/unstable, and funnel. In macropore flow, water and contaminants flow through naturally formed channels such as cracks, plant roots, worm holes, and voids between peds (Beven and Germann 1982). Macropores are a result of a variety of weathering and biological processes, and are a critical feature in hydrologic systems due to their affect on infiltration rates and depths, rainfall-runoff relationships, and contaminant transport to groundwater. To summarize, macropores are important preferential pathways for the transport of water and contaminants in soil (Beven and Germann 1982; Cey and Rudolph 2009).

Preferential flow through macroporous soils has been identified in a considerable number of field studies (Flury et al. 1994). Different methods have been used for evaluating and/or quantifying macropore flow characteristics with the most common being dye tracing with image analysis and tension infiltrometers (Schärzel and Punzel 2007; Allaire et al. 2009). Combining laboratory analysis with in situ irrigation experiments and dye tracing provides a better understanding of the hydrodynamic aspects and spatial patterns of flow processes in soil, although dye and water application methods at the soil surface greatly influence preferential flow (Allaire et al. 2009). Another common indirect technique for determining macropore flow is to measure the unsaturated hydraulic conductivity (K (*h*)) under varying tension (*h*) using infiltrometers (Watson and Luxmoore 1986; Jarvis et al. 1987). By maintaining tension in the instrument, the minimal equivalent pore radius from different infiltration rates between two tensions is calculated along with the number of macropores based on Poiseuille's and Darcy's laws. Dunn and Phillips (1991) modified the approach proposed by Watson and Luxmoore (1986), replacing the minimum pore radius with the mean pre radius in the pressure head range. Bodhinayake et al. (2004a) found that the Dunn and Phillips (1991) could have biased estimation of conducting porosity and presented an improved method for estimations conducting porosity. The instruments used in this approach are less expensive and easy to use. Measurements can be performed directly on intact cores and repeated on the same core under different tensions. However, this technique has its limitations (Timlin et al. 1994; Allaire et al. 2009) and results are frequently supplemented with data from dye tracing experiments (Allaire et al. 2009). Cey and Rudolph (2009) have successfully combined tension infiltration with the use of dye tracers to provide valuable information about the hydraulic behavior of macroporous soils.

The study objective was to combine the test methods of dye tracing techniques with a hood infiltrometer to analyze soil subjected to conventional tillage in northeast China, and to discuss whether the method is a better technique to investigate macropore flow in a soil.

MATERIALS AND METHODS

Experimental Sites

The study area is located in the Black soil (Black Chernozem) region of northeast China on Keshan Farm (lat. 48°12′–48°23′N, long. 125°08′–125°37′E). Conditions at the site are an annual mean temperature of 0.9°C, mean rainfall of 501.7 mm yr^{-1}, mean evaporation rate of 1 329.4 mm yr^{-1}, a frost-free period of 115 d, a soil freezing period from early November to mid-June, and a maximum frozen depth of 2.5 m. Selected soil properties from the study sites are provided in Table 1.

Table 1. Soil properties of the experimental sites

Soil depth (cm)	Bulk density (g cm^{-3})	Soil water content (%)	Capillary porosity (%)
0–10.0	1.09±0.09	31.00±3.30	47.00±2.12
10.0–20.0	1.25±0.11	35.00±3.00	43.34±4.78
30.0–40.0	1.35±0.07	37.00±0.00	41.40±1.69
60.0–70.0	1.47±0.07	39.00±1.00	39.71±1.17

Hood Infiltration Experiments

From 2009 Sep. 10 to Sept. 23, nine dye stained and infiltration tests were conducted on a conventional-tilled field planted with continuous soybeans (*Glycine max* L.). The dye stained test sites were prepared by carefully removing surface vegetation and a thin layer of soil (less than 2.0 cm) to ensure a horizontal surface, even though Bodhinayake and Si (2004) suggested that a slope of <20% had no effect on measured hydraulic properties and conducting porosity. The nine dye stained tests were conducted with the hood infiltrometer (diameter 17.6 cm) at three different locations for each pressure head (−5.0, −3.0, and −1.0 cm) to assess macropore flow under differential pressure heads. Brilliant Blue FCF dye (C.I. Acid Blue 9, 42 090) was added to the test water at a concentration of 4.0 kg m^{-3} (Andreini and Steenhuis 1990; Ghodrati and Jury 1990; Boll et al. 1992; Flury et al. 1994; Flury and Fluhler 1995). Infiltration rates were measured every 2.0 min until steady-state conditions were reached (Bodhinayake et al. 2004b). Following the nine dye stained tests, the infiltrated area was covered with vinyl film to prevent evaporation and dilution by rainfall (Kim et al. 2004).

Excavation and Photographs of Soil Sections

Excavations were conducted to map soil features and examine flow patterns for each of the nine dye stained tests. Parallel longitudinal soil sections of 70.0 cm (width) × 110.0 cm (height) were excavated at distances of 20.0 cm, 14.0 cm, 8.0 cm, 4.0 cm, and 0 cm from the center of each hooded area. Beneath the remaining half of the dye stained area, transverse soil sections of 40.0 cm (width) × 70.0 cm (height) were prepared at 1.0 cm from the surface to a soil depth of 10.0 cm; 2.0 cm from the surface at a soil depth of 10.0 cm to 20.0 cm; and 5.0 cm from the surface at soil depths greater than 20.0 cm thereafter until no further dye staining was observed. Soil sections were carefully cut using hand tools to reduce damage to soil structure. Soil sections were photographed with a digital camera using procedures adapted from Forrer et al. (2000), and an opaque white tarp to diffuse sunlight. Frames for soil transverse sections (30.0 cm × 60.0 cm) and soil longitudinal sections (60.0 cm × 90.0 cm) were placed in the soil profile to assist with subsequent image correction and uneven illumination.

Image Analysis and Index Determination

Image processing was conducted using ERDAS IMAGINE, Version 9.0 geographic software. Image analysis procedures developed by Weiler and Flühler (2004) and Forrer et al. (2000) were used with selected modifications to improve examination of dye stained patterns and to ensure consistency between images. A detailed description of the image analysis procedure is provided in Cey and Rudolph (2009). Images were developed under the following procedures: geometric correction, background subtraction, color adjustment, histogram

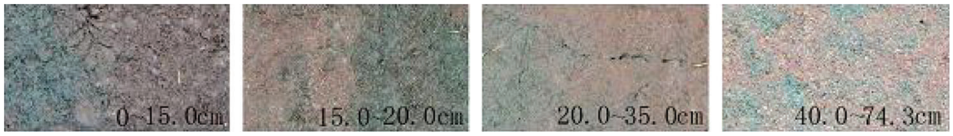

Fig. 1. Photos of soil stained using Brilliant Blue at different depths under pressure head of −3.0 cm.

stretching, dye classification, and a final visual check. This process classified areas as either unstained or stained. Stained areas of the longitudinal (excavated at distances of 0 cm from the center of each hood) and transverse sections were subclassified according to color difference.

The stained area (cm^2) was estimated by counting stained pixel images (60.0 cm × 90.0 cm) for the longitudinal section (20.0, 14.0, 8.0, 4.0 and 0 cm away from the center of the hood), and calculating the dye coverage percentage (%) which is the ratio of actual stained area (cm^2) to image area (60.0 cm × 90.0 cm). For the longitudinal section at the center of the hood, the area of dark blue was calculated at every 10 cm of soil depth starting from the surface. The dye stained width of the longitudinal section was recorded at increments of 2.0 cm from the soil surface to the deepest stained depth where the largest dye stained width (cm) occurred (including unstained areas). For the transverse sections, the stained area was calculated from areas not covered by the hood.

Statistical Analysis

One-way variance analysis (ANOVA) was used to assess the effect of pressure head on infiltration rates and dye stained depth, coverage, width and area based on the average values of three replicates.

RESULTS

Soil Stained by Brilliant Blue

Photos stained with Brilliant Blue at different depths under a pressure head of −3.0 cm were selected to qualitatively explain the soil water flow pattern and the characteristics of soil macropores (Fig. 1). In the 0- to 15.0-cm soil layer, the effect of conventional tillage and other management measures on the soil surface resulted in a loose and porous soil structure. Soil at 15.0 cm to 20.0 cm showed poor permeability and lateral flow occurred most likely being a result of compaction by farm machinery and the presence of plow pan. At a soil depth of 20.0 to 35.0 cm, macropore flow induced by cracks occurred, and between 40.0 and 74.3 cm, the soil was less disturbed when compared with the upper layers, indicating various pore sizes with good continuity. Macropore flow was also shown to be generated in this layer.

Infiltration Rate

Infiltration rates indicated that soil infiltration was not steady under different pressure heads (Fig. 2) until after approximately 30 min. After a steady infiltration rate occurred, there was no significant difference among infiltration rates at the three different pressure heads. The highest initial and steady infiltration rates of 13.0 mm min^{-1} and 4.1 mm min^{-1}, respectively, occurred at a pressure head of −1.0 cm. At a pressure head of −3.0 cm, the lowest initial and steady infiltrations rate occurred, at 8.8 and 2.4 mm min^{-1}, respectively.

Longitudinal Dye Stained Patterns

Dye stained characteristics under different pressure heads are summarized in Table 2. The maximum dye stained depths were 74.3, 60.7 and 64.7 cm below the surface at pressure heads of −5.0, −3.0 and −1.0 cm, respectively, and there was no significant difference between any two maximum stained depths. For the same pressure head, dye coverage of the longitudinal section decreased with increasing distance from the center. At the same distance to the center of the hood, dye coverage of the longitudinal section showed no obvious pattern

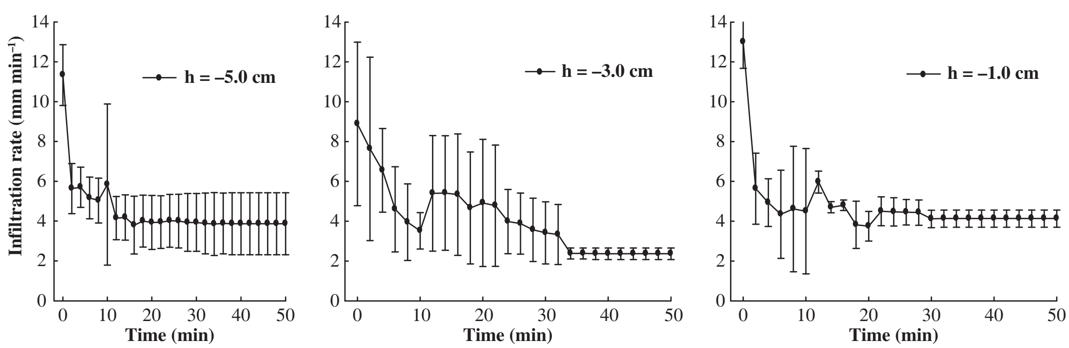

Fig. 2. Variation of infiltration rate with time.

Table 2. Dye stained characteristics for the hood infiltration tests

Pressure heads (cm H_2O)	Time period of application (min)	Depth[z] (cm)	Dye coverage for different longitudinal sections (%)				
			d[y] = 0 cm	d = 4.0 cm	d = 8.0 cm	d = 14.0 cm	d = 20.0 cm
−5.0	43.3 ± 9.3	74.3 ± 15.8	15.2 ± 5.4	14.6 ± 4.7	7.9 ± 6.2	4.1 ± 2.9	0
−3.0	46.7 ± 4.7	60.7 ± 15.5	15.5 ± 4.4	11.5 ± 0.5	8.1 ± 0.7	3.7 ± 0.7	0
−1.0	40.0 ± 4.4	64.7 ± 11.8	21.0 ± 0.4	12.7 ± 4.3	12.2 ± 3.7	6.6 ± 6.3	0

[z]Maximum depth of dye stained.
[y]The distance from the longitudinal section to the center of the hood.

change as the pressure head increased. The variation in dye coverage indicated differential lateral flow in the soil, while coverage under three different pressure heads showed no significant difference.

Three color grading photos of soil longitudinal sections stained with Brilliant Blue under different pressure heads were selected to illustrate macropore flow patterns (Fig. 3). The dark blue area indicates the macropore flow paths, which were heavily stained by Brilliant Blue as water infiltrated the soil. The light blue area indicates the interaction between macropores and the surrounding soil matrix. The dark blue stained area reveals the degree of macropore flow paths and the connectivity of vertical macropore flow paths. At pressure heads of −3.0 and −1.0 cm, the dark blue area varied significantly from depths of 10.0 to 50.0 cm, and resulted in maximum areas of 137.8 cm^2 (−3.0 cm) and 126.8 cm^2 (−1.0 cm) at depths of 10.0 to 20.0 cm (Fig. 4). This pattern may indicate that connectivity of macropore flow paths was disturbed at a soil depth of 20.0 cm. At a pressure head of −5.0 cm, the dark blue area decreased gradually through the soil profile, indicating better connectivity of flow paths. There was no significant difference between any two dark blue areas from different pressure heads.

The distribution of the largest dye stained width as a function of soil depth (Fig. 5) indicates that lateral flow occurred as water infiltrated the soil, which corresponds with visual observation of soil longitudinal sections stained using Brilliant Blue (Fig. 3). The dye stained width initially increases, then gradually decreases with soil depth after reaching its maximum area. Combining the macropore flow patterns of longitudinal soil sections indicates that lateral flow results in the largest dye stained width at a depth of 14.0 to 28.0 cm. The maximum dye stained widths were 41.6, 41.5 and 47.9 cm at pressure heads of −5.0, −3.0, and −1.0 cm, respectively. The dye stained widths were significantly different between pressure heads of −5.0 and −1.0 cm ($P < 0.05$) and −3.0 and −1.0 cm. Additionally, total infiltration was 4.4, 4.0 and 4.5 L at pressure heads of −5.0, −3.0, and −1.0 cm, respectively. While not significantly different, higher infiltration rates resulted in more lateral flow which occurred at a pressure head of −1.0 cm.

Transverse Dye Stained Patterns

Thirty classified patterns of soil transverse sections stained using Brilliant Blue under three pressure heads were selected from the dye infiltration tests and are displayed in Fig. 6. The patterns indicate that macropore

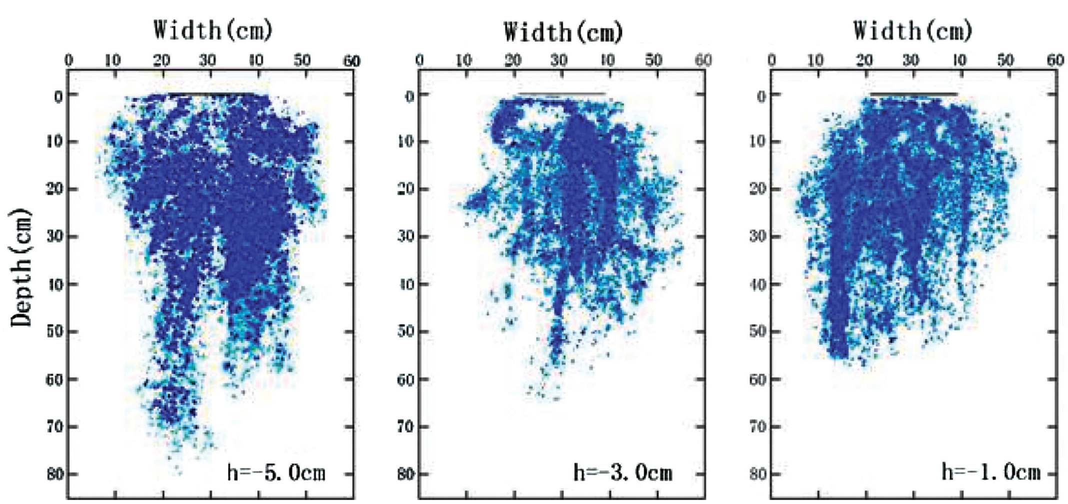

Fig. 3. Unsupervised classified patterns of soil longitudinal sections stained using Brilliant Blue.

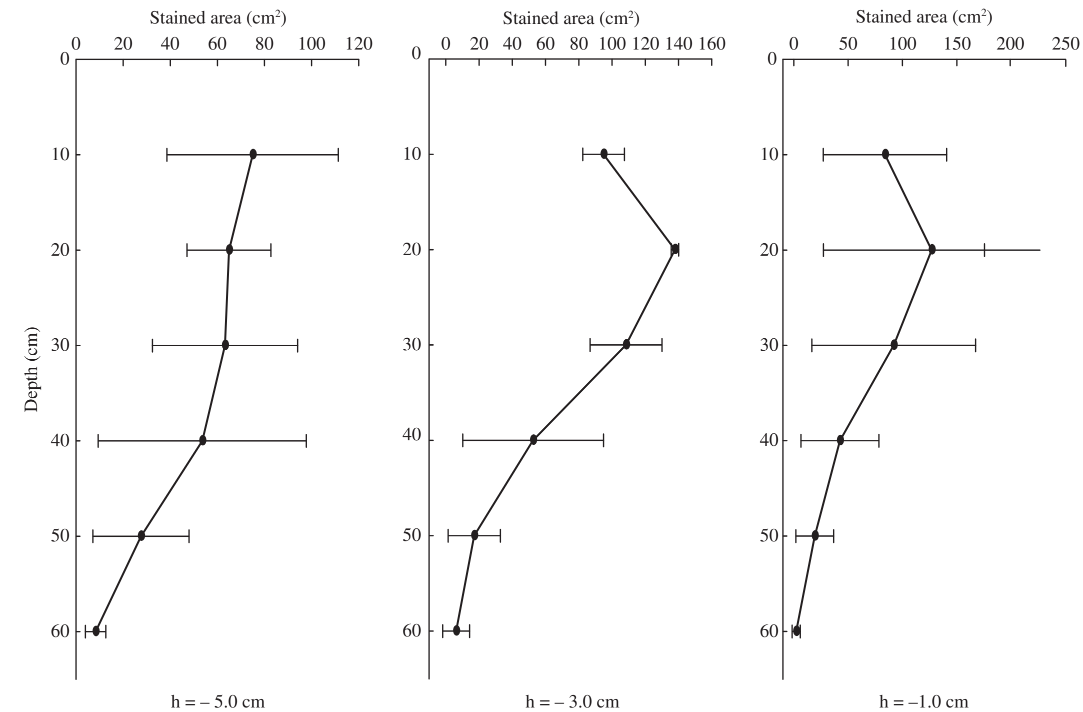

Fig. 4. Stained area of dark blue class in soil longitudinal sections stained using Brilliant Blue.

flow was initiated very near the soil surface, and that a pressure head of -1.0 cm resulted in more lateral flow in the shallower depths of soil.

The stained region which was not covered by a hood resulted from lateral flow as water infiltrated the soil, and therefore was used to relate the extent of lateral flow (Fig. 7). At a pressure head of -1.0 cm, the stained area outside of a hood changed quickly within a soil depth of 10.0 cm. The largest area, equal to 400.6 cm^2, was found at soil depth of 4.0 cm, and then fluctuated with no

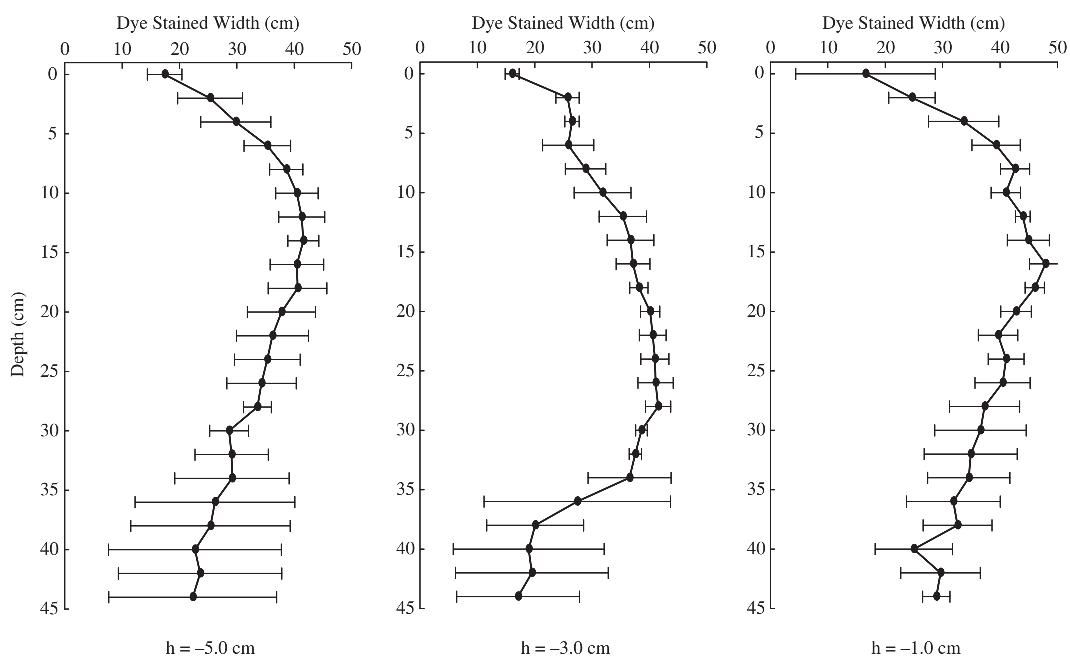

Fig. 5. Dye stained width as a function of soil depth under different pressure heads.

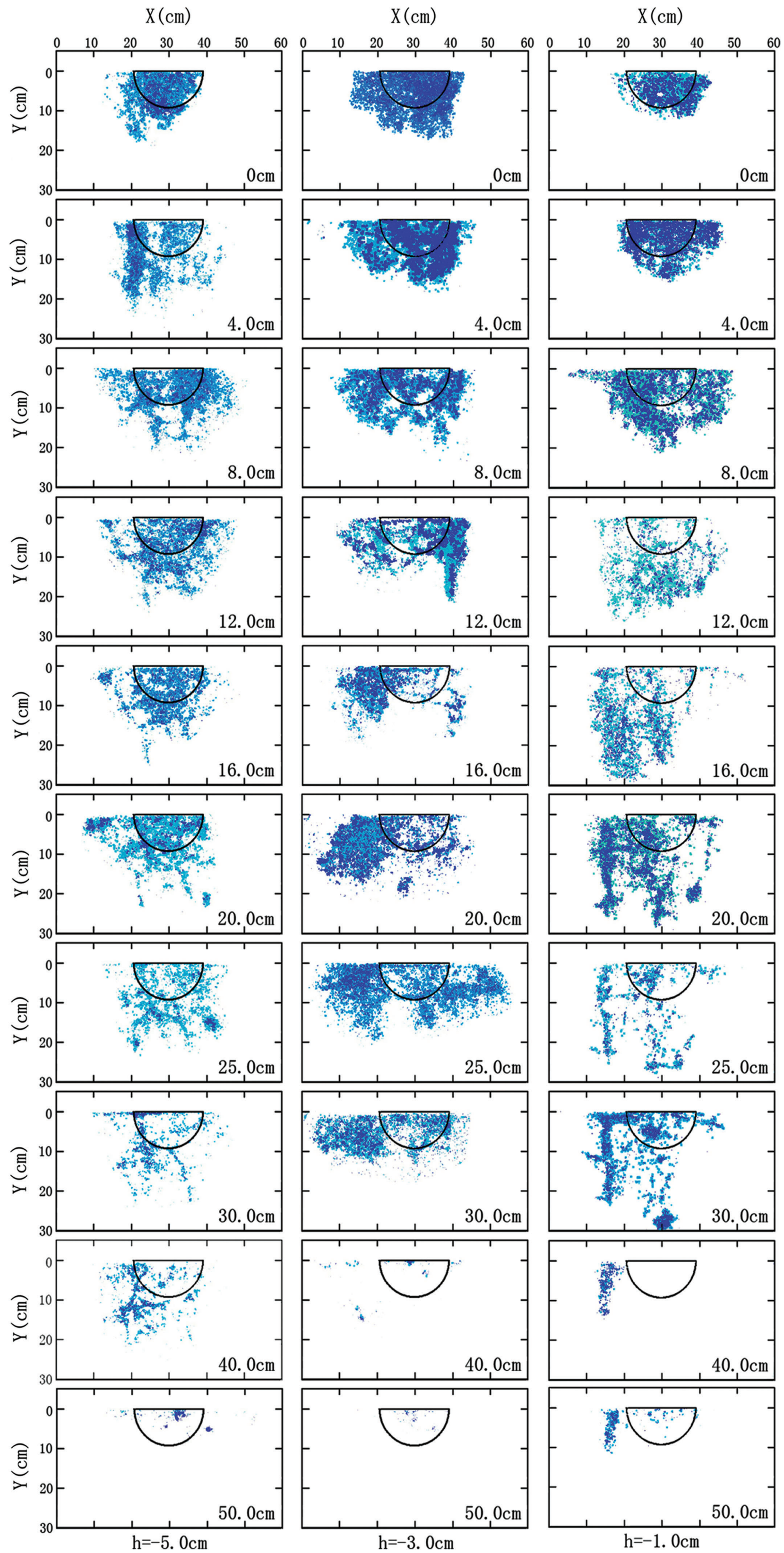

Fig. 6. Unsupervised classified patterns of soil transverse sections stained using Brilliant Blue.

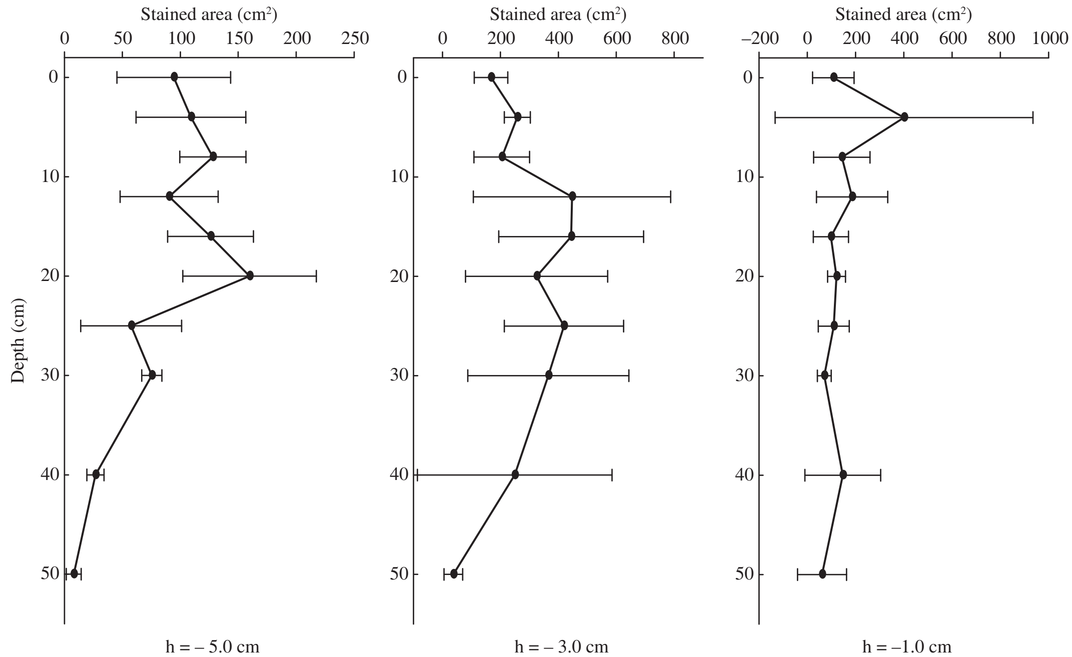

Fig. 7. Stained area outside of hood in soil transverse sections.

distinct pattern as soil depth increased. At a pressure head of -3.0 cm, the stained area outside of a hood initially increased and then decreased as the soil depth increased. A maximum area of 447.2 cm^2 was reached at a depth of 12.0 cm. When compared with pressure heads of -1.0 and -3.0 cm, the extent of stained area at a pressure head of -5.0 cm was smaller and showed a smaller range of variation through the soil profile. The maximum area of 159.8 cm^2 was reached at soil depth of 20.0 cm. The maximum stained areas outside of a hood showed no significant difference among the three pressure heads. The most lateral flow occurred at a pressure head of -3.0 cm, which was followed by -1.0 cm. Lateral flow at a pressure head of -5.0 cm was not evident.

DISCUSSION

The method of combining the dye tracer technique with the tension infiltrometer can both support and broaden the test methods (Allaire et al. 2009). Cey and Rudolph (2009) successfully investigated the macropore flow paths for a conservation-tilled soil by combining the two methods. The study showed that the predominant macropore flow paths occurred through cylindrical macropores and worm burrows, and that there was a clear relationship between the longitudinal extent of dye staining and pressure head. The study also indicated that macropore flow only occurred at pressure heads greater than -3.0 cm in conservation-tilled soil with a good structure of macropores. However, the results of this study were not in agreement with Cey and Rudolph's findings as macropore flow occurred at three pressures heads (-5.0, -3.0 and -1.0 cm). One explanation may be the different soil structures of conservation and conventional tilled soil. In this study, soil structure was not uniform through the soil profile. The upper portions of cultivated soil are typically disturbed, which contributes to poor macropore connectivity thereby making it difficult to distinguish macropore flow from matrix flow. Macropore flow is more easily identified by separating stained areas into different classes of dye color. In deeper soils below the cultivated layer, a stronger plow pan is induced by tractors and other farm machinery (Wang et al. 2008). Subsoil compaction is a critical factor that influences macropore flow, especially lateral flow.

Combining the dye tracer technique with a hood infiltrometer has both advantages and disadvantages. Preferential flow is largely influenced when performing the dye tracer technique (Allaire et al. 2009). For example, under rainfall conditions soil must reach a saturation level such that the rainfall rate exceeds the infiltration rate thereby allowing runoff to occurs and the solute to penetrate surface-opened macropores. In contrast, during flood irrigation water and solute flows directly into large macropores open to the soil surface. Thus, rainfall conditions limit water intake by the macropores when compared with flood irrigation (Allaire et al. 2009). The combining method could decrease the effect of the dye tracer technique on macropore flow by controlling the amount of water. Furthermore the qualitative and quantitative relationship between macropore flow and pressure head can be described by observing macropore flow paths under different pressure heads. This relationship cannot be observed by either the dye tracer or hood infiltrometer techniques when performed separately. Another disadvantage of this method is that the dye affects the flow of water in soil (Cey and Rudolph 2009).

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