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Effects of different management practices on vertical soil water flow patterns in the Loess Plateau

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ABSTRACT

Different management practices are adopted to ensure sustainable development in agriculture and to maintain ecological environment security. However, the soil water infiltration types under different management practices were still unclear. This study was designed to assess the effect of different management practices on the water flow behavior of soil. Four management practices were carefully selected. Plot 1 was uncultivated field, Plot 2 contained alfalfa (*Medicago sativa L.*) and was untilled for two years (alfalfa field), Plot 3 contained maize (*Zea mays L.*) with conventional tillage from 2008 to 2015 (conventional tillage field), and Plot 4 contained maize with conservation tillage from 2008 to 2015 (conservation tillage field). Soil physical properties (e.g., gravimetric water content, soil bulk density, total porosity, and saturated water content) in the top 50 cm layer were measured following conventional methods A dye tracer was introduced to these plots, and the different types of water flows were visualized using classified dye-stained patterns. In the uncultivated field, preferential flow was triggered by wetting front instabilities and generally confined to the upper 15 cm of the soil profile. The presence of preferential paths (alfalfa taproot) in the alfalfa field resulted in high and continuous preferential flow. The macropore flow bypassed the compacted soil and was confined into two isolated patches, making it the dominant flow behavior in the conventional tillage field. Conservation tillage systems enhanced the continuity and connectivity of the macropore system and converted the shape of the preferential flow to an inverted triangular distribution. The order of continuity and connectivity degree for the macropore system from highest to lowest was alfalfa field, conservation tillage field, uncultivated field, and conventional tillage field. Above mentioned results that were newly achieved from this study highlighted a significant change in soil water storage and flow behaviors with different management practices compared with those of uncultivated land. The present study suggests that local governments and farmers would prefer alfalfa field and conservation tillage field to other management measures.

1. Introduction

The continuous expansion of uncultivated land areas is a result of the unreasonable use and exploitation of land, and this phenomenon has resulted in the reduction of farmland areas and the destruction of the ecological environment of the Loess Plateau in Northwestern Shanxi Province, China (Qiao et al., 2000; Yuan et al., 2004). The local climate in the Loess Plateau is characterized by highly concentrated rainfall from July to August, and the soil is classified as sandy-loam chestnut loessal soil (Xue et al., 2013). Heavy rainfall and erodible soil make soil erosion and surface runoff highly likely, causing solutes (e.g., residual pesticides and nitrate nitrogen) to migrate and leach in the soil profile. Consequently, water flow and solute migration influence the utilization efficiency of agricultural resources. To ensure sustainable agricultural development and secure the ecological environment, local farmers have been adopting different management practices to utilize and develop uncultivated land (Li et al., 2015; Yuan et al., 2016).

Management practices involve different crops (e.g., corn and alfalfa) and different tillage systems (e.g., conventional tillage involves moldboard ploughing and harrowing; conservation tillage refers to management practice with low soil disturbance, shallow tillage depth, and lack of topsoil inversion), all of which has different influences on the physical and hydraulic properties of soil

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(Andreini and Steenhuis, 1990; Marshall et al., 2014). With regard to different crops and root systems, old root channels, which have openings at the soil surface (Wang et al., 1996) and decaying roots at a large penetration depth in a vertical direction (Mitchell et al., 1995) are generally considered as soil macropores. Jabro et al. (2009) reported that conventional tillage is one of the most important practices in conventional tillage systems. On the one hand, this practice affects the physical and hydraulic properties of soil (e.g., pore size, porosity, and infiltration), destroys most of the preferential paths at the soil surface, and reduces the number of pathways for water to move through gravity into the soil profile (Cullum, 2009). Moreover, conventional tillage increases soil erosion and surface runoff. On the other hand, conservation tillage has shown advantages in the modification of numerous physical properties, such as aggregate stability (Angers and Mehuys, 1988), soil structure (Gibbs and Reid, 1988), soil infiltration rate (Meek et al., 1990), total porosity, and continuous macropores (Cullum, 2009). Such tillage practices leave the structure of surface soils largely intact, yield large amounts of continuous macropores, reduce soil erosion and surface runoff, and increase infiltration. Simply put, different management practices would influence soil water flow behavior differently because of the variations in soil structure and porosity.

The soil water infiltration process generally includes matrix flow and preferential flow. The former is a relatively slow and even movement of water and solutes through the bulk soil (Allaire et al., 2009; Stamm et al., 1998). Preferential flow describes the physical phenomenon of rapid water and solute transfer in the soil. It occurs in most soils and is often attributed to macropore flow through cracks, fissures, or voids and between peds or through biopores, such as earthworm burrows and root channels (Beven and Germann, 1982; Flury and Flühler, 1995). However, preferential flow in soils is not restricted to macropore flow. Non-homogeneous infiltration and wetting front instabilities can also lead to preferential flow (Bundt et al., 2001). According to Beven and Clarke (1986), the macropore-matrix transfer process refers to the absorption of water into the surrounding matrix through the macropore walls with the help of capillary forces. Lateral flow refers to the infiltration of laterally moving water (Ritsema et al., 1995; Oostindie et al., 2013; Wine et al., 2012).

Although Sasal et al. (2006) noted that the infiltration rate was influenced by no-till management, the soil water infiltration types under different management practices were still unclear. Different management practices can be used to develop and utilize uncultivated land. It would be of great importance to obtain a better understanding of how soil water flow behaves under different management practices. In this study, an uncultivated land served as the reference, and three soil plots with different tillage regimes were selected as the management practices. A traditional method involving a dye tracer was conducted on these four soil plots. The study was divided into two parts: one, the water losing capacity and associated soil physical properties was analyzed among the four plots; and two, the soil water flow behaviors were interpreted from the classified dye-stained patterns. This study aimed to assess the effect of different management practices on the water flow behaviors based on a comparative analysis of water content variation and flow type in the soil profiles of four land-management systems.

2. Materials and methods

2.1. Experimental site

The study area was located in the Shi Zuitou county of Shanxi Province, North China. Its specific geographic position is between 111°28′–113°E and 38°44′–39°17′N, which covers the semi-arid and sandy area of the Loess Plateau in North China. The area has an arid continental climate with an annual average temperature of 5.0 °C, −14 °C in January and 19 °C in July, and annual sunshine of 2870 h. Annual average precipitation in the area is between 450 and 500 mm yr^{-1}. Rainfall is concentrated in July and August and accounts for approximately 44% of the total annual precipitation. In accordance with the Chinese Soil Classification System (Gansu Provincial Soil Survey Office, 1992), the soil in the study area was classified as sandy-loam chestnut loessal soil, which is similar to Anthropic Camborthids according to Soil Taxonomy (Soil Survey Staff, 1998). The resulting soil has loose texture, high porosity, strong permeability and ventilation, low fertility, and low soil organic matter.

2.2. Experimental design

2.2.1. Plots and soil physical properties

A wide field covering 100 m (length) × 80 m (width) of land that has been uncultivated and undisturbed for 50 years was used in this study. To utilize the uncultivated field, it was divided into four plots. One plot was planted with alfalfa (*Medicago sativa* L.) without tillage from 2013 to 2015 (alfalfa field), another was planted with maize (*Zea mays* L.) with conventional tillage from 2008 to 2015 (conventional tillage field), another was planted with maize (*Zea mays* L.) with conservation tillage from 2008 to 2015 (conservation tillage field), and the last plot remained uncultivated (uncultivated field). Our experiments were conducted in these four plots. Soil particle size distributions of the four plots are provided in Table 1.

Table 1
Soil particle size (mean ± SE, n = 3) of the experimental sites.

Soil depth (cm)	Particle size	Treatments			
		Uncultivated field	Alfalfa field	Conventional tillage field	Conservation tillage field
0–10	Clay (%)	0.70 ± 0.11	2.38 ± 0.03	1.90 ± 0.04	3.06 ± 0.19
	Silt (%)	1.97 ± 0.05	6.97 ± 0.62	12.99 ± 0.14	15.44 ± 0.65
	Sand (%)	97.33 ± 1.03	90.65 ± 0.20	85.11 ± 0.14	81.50 ± 2.48
10–20	Clay (%)	0.62 ± 0.31	2.39 ± 0.02	2.05 ± 0.05	2.78 ± 0.24
	Silt (%)	2.79 ± 0.99	14.18 ± 0.22	15.11 ± 0.13	13.98 ± 0.61
	Sand (%)	96.59 ± 1.30	83.43 ± 0.58	87.53 ± 0.54	83.24 ± 0.84
20–30	Clay (%)	1.02 ± 0.29	1.60 ± 0.11	1.33 ± 0.04	0.85 ± 0.12
	Silt (%)	2.19 ± 0.60	8.35 ± 1.29	8.48 ± 0.03	3.77 ± 0.49
	Sand (%)	96.79 ± 1.33	90.05 ± 1.45	90.24 ± 0.57	95.38 ± 0.59
30–40	Clay (%)	0.85 ± 0.01	1.27 ± 0.06	1.14 ± 0.07	1.49 ± 0.13
	Silt (%)	1.99 ± 0.22	6.79±0.40	7.92 ± 0.28	5.74 ± 0.72
	Sand (%)	97.16 ± 0.28	91.94 ± 0.46	90.13 ± 0.42	92.77 ± 0.80
40–50	Clay (%)	1.03 ± 0.19	2.86 ± 0.15	0.41 ± 0.43	0.98 ± 0.17
	Silt (%)	2.71 ± 1.21	3.56 ± 0.32	6.49 ± 0.38	5.39 ± 0.75
	Sand (%)	96.26 ± 1.38	93.58 ± 0.45	95.61 ± 0.06	93.63 ± 0.92

Soil physical properties (e.g., gravimetric water content, soil bulk density, total porosity, and saturated water content) in the top 50 cm layer of the four plots were measured following the methods described by Chen (2005). The soil gravimetric water content and other properties for four plots were measured one time at the depth of 5,15,25,35 and 45 cm with three replicates. Bulk soil samples were taken using cutting rings (inner diameter = 50.46 mm, height = 50.00 mm). Considering the change of soil physical properties, bulk soil samples were collected at the same day and at the four plots where there had been no rain for half a month.

In the present study, water losing capacity (%) was a new terminology. Considering that for a case the value of water losing capacity (%) added to the value of water holding capacity (%) was equal to 100% and the lack of a very clear contrast in a figure when using the water holding capacity (%), the water losing capacity (%) was adopted to show the water holding capacity (%) from the opposite angle. The water losing capacity indicated the capability of soil to lose water for 2 h. The more water was lost, the higher the water losing capacity became. The ratio of the volume of drained water to the volume of saturated water was adopted to express the water losing capacity (%). The measurements were conducted as follows. In a laboratory, the samples were saturated from below by placing them in distilled water. The water was nearly at the level of the soil surface, and it was made sure that there no water entered the samples from above. The volume of saturated water was measured after the soil core cylinders were ponding for 24 h. Then the soil core cylinders were placed on the sand layer, the volume of water drained by gravity from the saturated samples for 2 h was measured. The gravitational water is the amount of water held in the soil between the saturation and field capacity.

2.2.2. Dye tracer

Twelve dye tracer experiments were also conducted on four plots from September 15 to 25, 2015. To ensure a horizontal surface, dye-stained test sites were prepared by carefully removing a thin layer (less than 2 cm) of the soil (e.g., a surface vegetation layer for the uncultivated and alfalfa plots, and loose top soil for the conventional and conservation plots). In each plot, three points (3 m away from each other) were randomly selected as replicates. Tests 1, 2 and 3 referred to replicates 1, 2 and 3 respectively. Each replicate plot was surrounded by a 0.3 m-high quadrat made of PVC (edge length = 0.2 m). The bottom edges of the PVC quadrats were inserted 0.05 m into the soil, and the side walls and edges were water tight. Tap water was dyed with Brilliant Blue FCF at a concentration of 3.0 g L^{-1} (Flury and Flühler, 1995). A total of 6.3 L of dyed water was poured into each PVC quadrat of all 12 plots, and the plot areas were immediately covered with big plastic sheets to prevent soil evaporation and dilution by rainfall (Jiang et al., 2012).

Twenty-four hours after the end of infiltration, the plastic sheets and PVC quadrats were carefully removed, and the 60 cm (length) × 50 cm (width) dye-stained soil vertical sections were carefully excavated at the center of the ring using a spatula (Weiler and Flühler, 2004). Notice that the size of dye-stained soil vertical sections were large enough to contain all the dye-stained soil in vertical sections. Beneath the remaining half of the dye-stained area, 60 cm (length) × 40 cm (width) soil horizontal sections were prepared at 5 cm from the surface to the deep layer until no further dye staining was observed. Calibrated frames for soil vertical and horizontal sections were placed in the soil profile to assist with subsequent image correction. To provide a soft light condition, all areas of the pit were covered with a black umbrella. All the soil sections were photographed using a digital camera (Canon EOS Rebel T3, Japan) under daylight conditions. The distance from the camera to the center of the vertical and horizontal sections was 40 cm. Then, 12 dye-stained soil vertical sections and 84 horizontal sections were photographed.

To define concentration categories for the dye-stained soil regions during image analysis, dye-stained calibration patches were prepared and photographed for the soil horizons as described by Weiler and Flühler (2004). On soil horizontal sections adjacent to the infiltration tests, five 5 cm (width) × 5 cm (length) patches of soil were excavated approximately 10 mm deep. Approximately 100 mL of Brilliant Blue FCF dye solution with concentrations of 3.0, 2.0, 1.0, 0.5, and 0.05 g L^{-1} were poured onto the patches and allowed to infiltrate and fully drain. The dye-stained soil was then photographed using the methods described earlier.

2.3. Image analysis, parameter determination, and statistical analysis

Image processing was conducted using ERDAS IMAGINE version 9.0, following the procedures developed by Forrer et al. (2000) and described in detail by Cey and Rudolph (2009). Images were developed under the following procedures: geometric correction, background subtraction, color adjustment, histogram stretching, dye classification, and final visual check. The resulting images were separated into dyed and non-dyed regions, with the dyed regions further divided into three relative classes (dark blue, light blue and green) based on the intensity of dye staining. Dye-stained soil calibration patches were used to determine concentration categories for the three dye-stained soil classes (0.05–0.5 g L^{-1}, 0.5–2.0 g L^{-1}, and >2.0 g L^{-1}).

The maximum dye-stained depth (cm) and width (cm) of soil vertical sections were measured using a tapeline. The real area (cm^2) of each concentration category was estimated by counting stained pixel images from the dye-stained patterns (Jiang et al., 2012). Proportion (%) was calculated as the percentage of each concentration category over that of the entire stained region in the longitudinal dye-stained patterns.

One-way analysis of variance (ANOVA) was used to assess the effect of different plots on the measured parameters (e.g., maximum dye-stained depth and area) in photographed soil vertical sections. One-way ANOVA was also applied to assess the effects of different plots on the physical properties of the soil. Significant differences between means were detected using the least significant difference at $P < 0.05$. All statistical procedures were performed in SPSS 15.0.

3. Results

3.1. Soil physical properties

Soil physical properties (Fig. 1), such as initial soil water content (%), bulk density (g cm^{-3}), and total porosity (%), determine the type of soil water flow and distribution. The difference of bulk density was significant between any two treatments. The smallest value of bulk density at 5 cm soil depth was 1.20 (g cm^{-3}), which was found in the conventional tillage field. The bulk density from soil surface to depth of 25 cm was always smaller in conventional tillage field than in uncultivated field. In addition, the highest total porosities at 5 and 25 cm soil depth were 53.44% and 49.19% respectively, which were also observed in the conventional tillage field. Therefore, several years of conventional tillage and the plough pan resulted in the lowest bulk density and the highest total porosity from the soil's surface to a depth of 25 cm. Compared with the uncultivated field, more agricultural management measures were conducted in the conservation tillage and alfalfa fields, thus the conservation tillage and alfalfa fields had higher bulk density and lower total porosity from the soil's surface to deeper soil levels (i.e., 25 cm).Compared with other treatments, the water losing capacity in the uncultivated field was 31.36% at 5 cm and 24.55% at 15 cm, which were the highest values. Thus, the capacity of soil to store water on the shallow soil (i.e., 0–15 cm) was

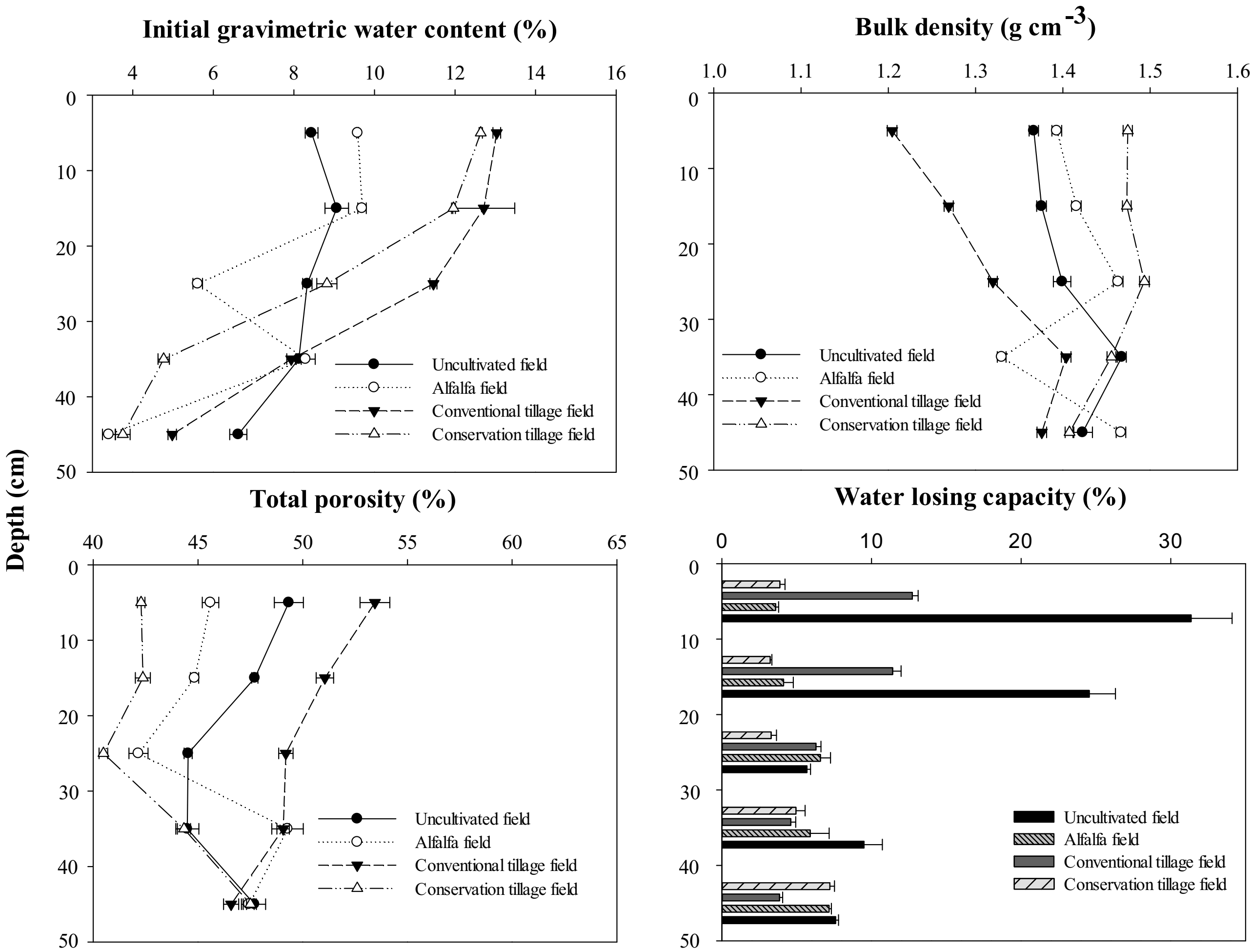

Fig. 1. Soil physical properties (mean ± SE, n = 3) of the four sites. In the present study, water losing capacity (%) was a new terminology. Considering that for a case the value of water losing capacity (%) added to the value of water holding capacity (%) was equal to 100% and the lack of a very clear contrast in a figure when using the water holding capacity (%), the water losing capacity (%) was adopted to show the water holding capacity (%) from the opposite angle.The water losing capacity indicated the capability of soil to lose water for 2 h. The more water was lost, the higher the water losing capacity became. The ratio of the volume of drained water to the volume of saturated water was adopted to express the water losing capacity (%).

better in the three other management practices than in the uncultivated field.

3.2. Vertical dye-stained patterns

The types of preferential flow paths were interpreted directly from the vertically classified dye-stained patterns (Fig. 2).The quantitative information of infiltration behavior, as shown in Fig. 3, illustrates the variations of the stain area (cm^2) (i.e., different concentration distributions of the Brilliant Blue FCF dye) in relation to the soil depth. Fig. 2 shows the 12 classified dye-stained patterns for the soil vertical sections cut along the center line of the PVC ring for the four sites. The number, distribution characters, and connectivity of the vertical macropore flow paths were directly illustrated from the soil vertical sections. In the same plot, the dye-stained patterns were more or less different from any two tests, but they exhibited common features when the mean values of tests 1–3 were considered. In a similar 60 cm (length) × 40 cm (depth) soil section, the uneven wetting region and non-uniform distribution of dye in the four sites indicated that the infiltration of water into the soil followed preferred pathways and bypassed other parts of the soil matrix. However, the detailed water distribution patterns were different among the four sites. The mean value of dye areas exhibited different features between any two treatments when the mean values of tests 1–3 were considered (Fig. 3). In the uncultivated field, the dye spread less uniformly, as evidenced by an unstained fraction within the staining area (Fig. 2). The large proportion of dark blue areas was generally confined to the upper 15 cm of the soil profile, and the mean light blue areas increased with soil depth (Figs. 2 and 3). In the conventional tillage field, two dominant dark blue patches were distributed separately; the larger proportion of mean dark blue areas were generally confined to the upper 10 cm of the soil profile. The mean light blue areas along the soil depth initially increased from the soil surface to 10 cm of soil depth and then decreased.

The uncultivated field and the conventional tillage field seemed to exhibit common variation trend of the dye areas along soil depth. The dark blue area in the uncultivated field was sharply increased from 32.94 cm^2 to 59.23 cm^2 and rapidly decreased to 0.32 cm^2, however, the dark blue area in the conventional tillage field showed a form looking like a contrarotated capital letter of "W". In the alfalfa field, the dark blue regions exhibited belt distribution (Fig. 2). The mean value of dye area in the alfalfa field revealed a gradual change (Fig. 3), and the range of dark blue area from soil surface to soil depth of 22 cm was between 20.08 cm^2 and 35.52 cm^2. Therefore, the presence of preferential paths (i.e., alfalfa taproot) in the alfalfa field resulted in highly continuous preferential flow. In the conservation tillage field, one interesting

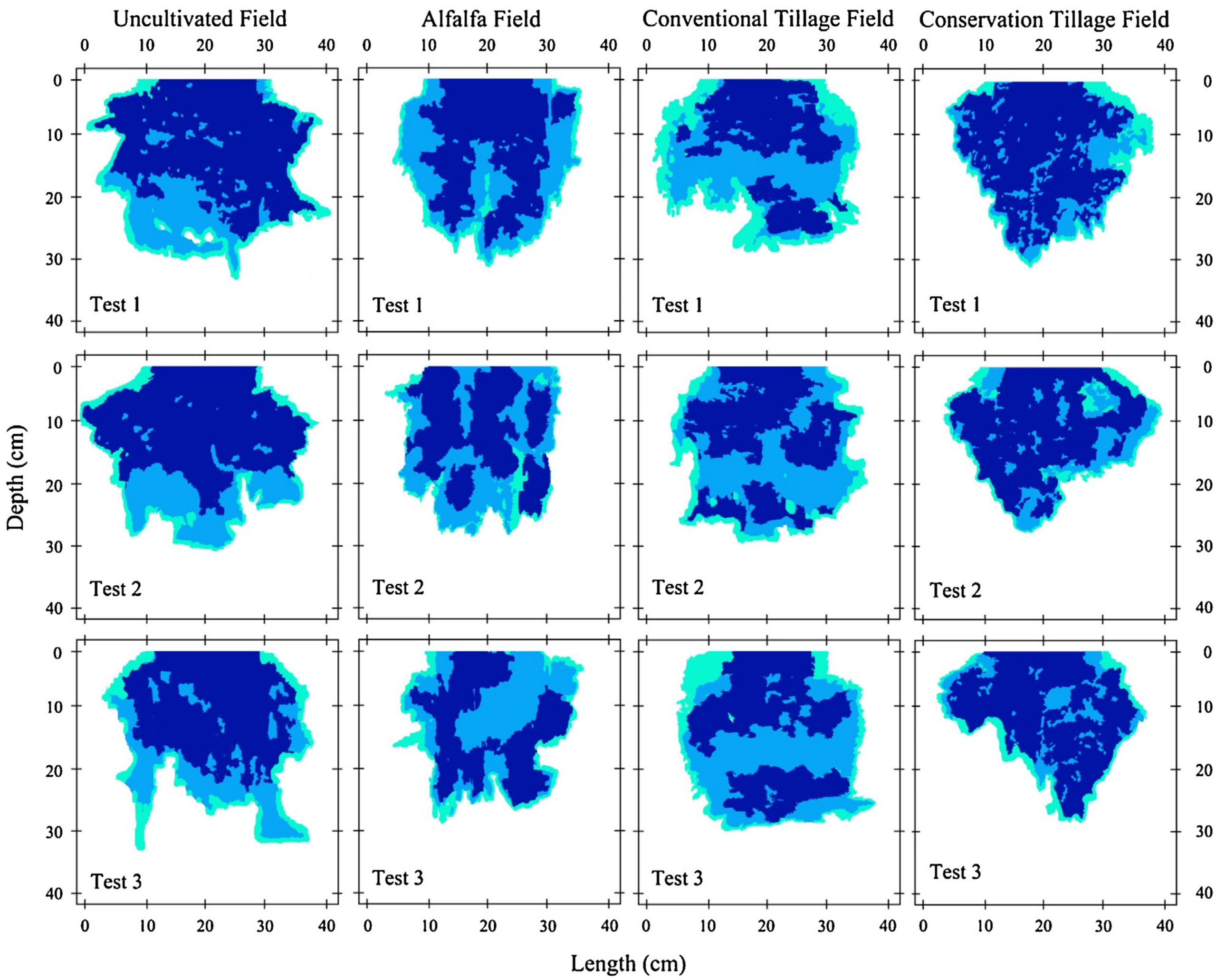

Fig. 2. Classified dye patterns for soil vertical sections in the four plots. The three profile sections in each sample plot are shown by tests 1, 2, and 3. The dark blue areas indicate the macropore flow paths were heavily stained with Brilliant Blue FCF dye as water infiltrated the soil; the concentration was > 2.0 g L^{-1}. The light blue and green areas were slightly stained with Brilliant Blue FCF dye; the concentration was from 0.5 to 2.0 g L^{-1} and from 0.05 to 0.5 g L^{-1}, respectively. The light blue and green areas indicate the strong and weak exchanges between the macropore and the surrounding soil matrix, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

phenomena was the inverted triangular distribution of dye-stained regions (Fig. 2). The mean value of the dark blue area in the conservation tillage field was sharply increased from 31.65 cm^2 to 52.81 cm^2 and slowly decreased to 0.17 cm^2 (Fig. 3), which implied that the conservation tillage systems promote the formation of greater continuity and connectivity of the macropore system. It is worth noting that the light blue area in the uncultivated field was increased from 1.25 cm^2 at soil surface to 33.75 cm^2 at 22 cm soil depth, meantime the light blue area in the conservation tillage field was decreased from 9.30 cm^2 at soil surface to 1.44 cm^2 at 28 cm soil depth.

The corresponding stain characteristics (e.g., dye-stained depths, widths, and areas) are summarized in Table 2. The proportion of dark blue region over that of the entire stained area increased from the least value of 45% in the conservation tillage field to the largest value of 68% in the conventional tillage field. This result indicated that macropore flow was the dominant flow behavior in the four fields, and the macropore transport was greater in the uncultivated field and in the conservation field since the dark blue areas are larger in those treatments compared with the others. Compared with uncultivated fields, the dark blue area was significantly smaller in the alfalfa and conservation tillage fields but was slightly smaller in the conventional tillage field. The light blue region decreased as the dark blue region increased. The highest value of the light blue region was 274.52 cm^2 in the conservation tillage field, which means that such field had the highest degree of exchange between macropore and soil matrix. The green region had the lowest proportion (12–18%); however, the weak exchange between the macropore and the surrounding soil matrix in the conservation tillage and uncultivated fields reached a considerable part.

3.3. Horizontal dye-stained patterns

Water flows into soil through pores in every direction in three-dimensional space. A total of 72 horizontal dye-stained patterns for four sites were completed from 0 cm to 25 cm of soil depth. One dye-stained pattern was randomly selected from three patterns for one site at the same depth. Thus, 24 horizontal classified dye-stained patterns for four sites are shown in Fig. 4. The horizontal distribution characters of macropore flow paths could interpret the soil horizontal section. Similar to the vertical dye-stained patterns, the dark blue region of horizontal patterns indicates that macropore flow was initiated near the soil surface, bypassed other parts

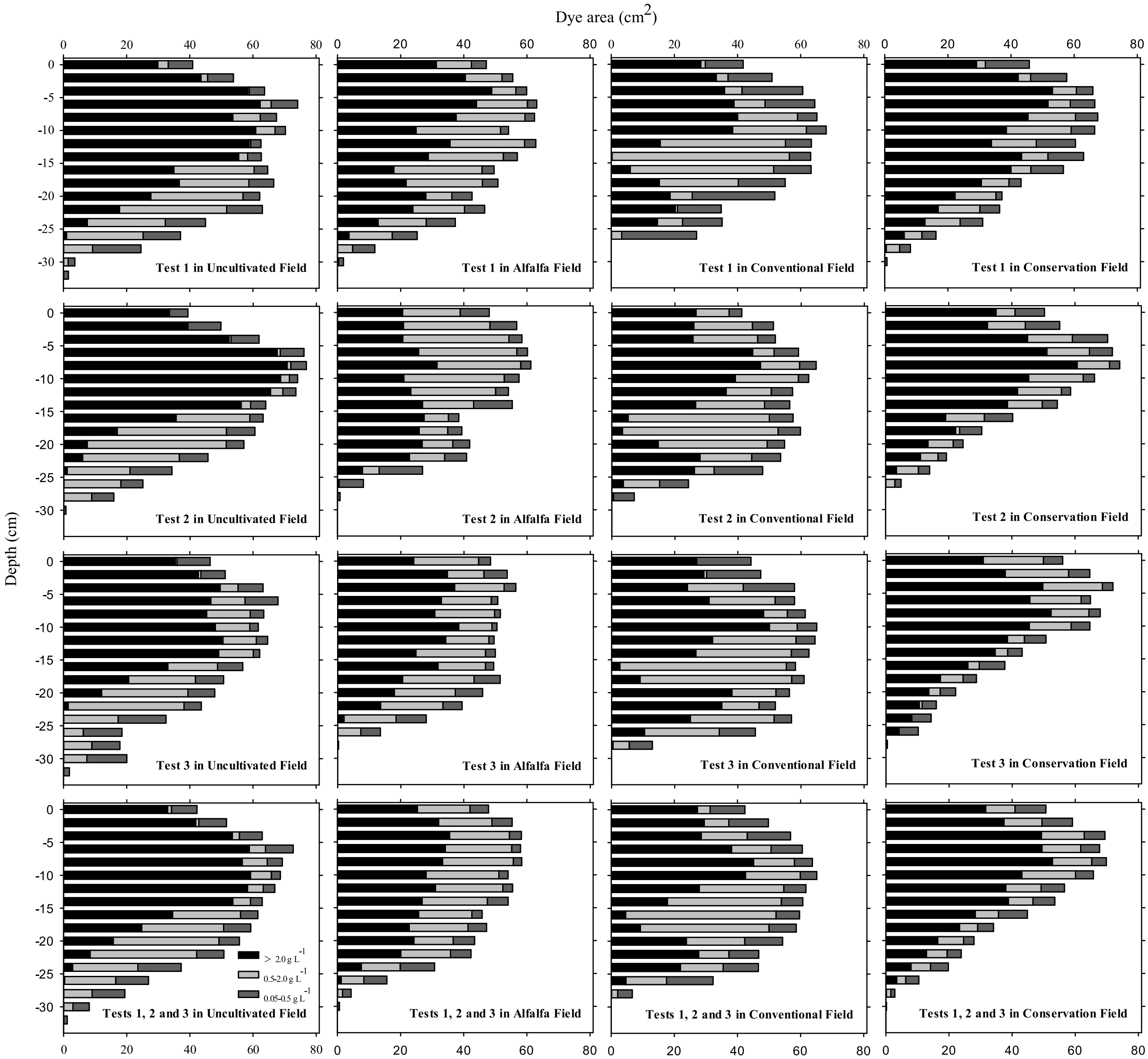

Fig. 3. Real area (cm^2) of the Brilliant Blue FCF dye vs. depth in the four sites. The real area (cm^2) of each concentration category was estimated at 2.0 cm intervals from the soil surface to the deep layer, unless the soil was not stained by dye. The three profile sections in each sample plot are shown by tests 1, 2, and 3. The mean value of the three experiments is denoted by tests 1, 2, and 3 in each sample plot.

Table 2
Dye stain characteristics (mean ± SE, n = 3) in the vertical classified dye patterns for the four sample plots.

Treatments	Dark blue region		Light blue region		Green region		Entire dye-stained area (cm^2)	Dye-stained width (cm)	Maximum dye −stained depth (cm)
	Area (cm^2)	Portion (%)[m]	Area (cm^2)	Portion (%)	Area (cm^2)	Portion (%)			
Uncultivated field	483.58 ± 31.07a	61.31	190.57 ± 3.95b	24.26	113.26 ± 8.10ab	14.43	787.42 ± 25.80a	37.95 ± 1.67a	32.59 ± 0.77a
Alfalfa field	321.86 ± 19.24b	50.39	234.69 ± 8.41a	36.75	74.31 ± 6.77b	11.64	638.44 ± 16.63b	29.08 ± 0.44c	30.40 ± 1.21ab
Conventional tillage field	330.79 ± 17.37b	44.57	274.52 ± 17.13a	36.97	136.41 ± 25.13a	18.46	741.73 ± 15.75a	32.21 ± 0.91b	29.75 ± 0.15ab
Conservation tillage field	418.81 ± 15.77a	67.87	119.10 ± 15.10c	19.12	80.66 ± 6.59b	13.01	618.57 ± 34.73b	34.30 ± 0.83b	29.56 ± 1.00b

The a, b, and c averages in small letters within a column indicate a significant difference at the 0.05 level.
[m] Portion (%) was calculated as the percentage of each concentration category in the entire stained area in the longitudinal dye-stained patterns.

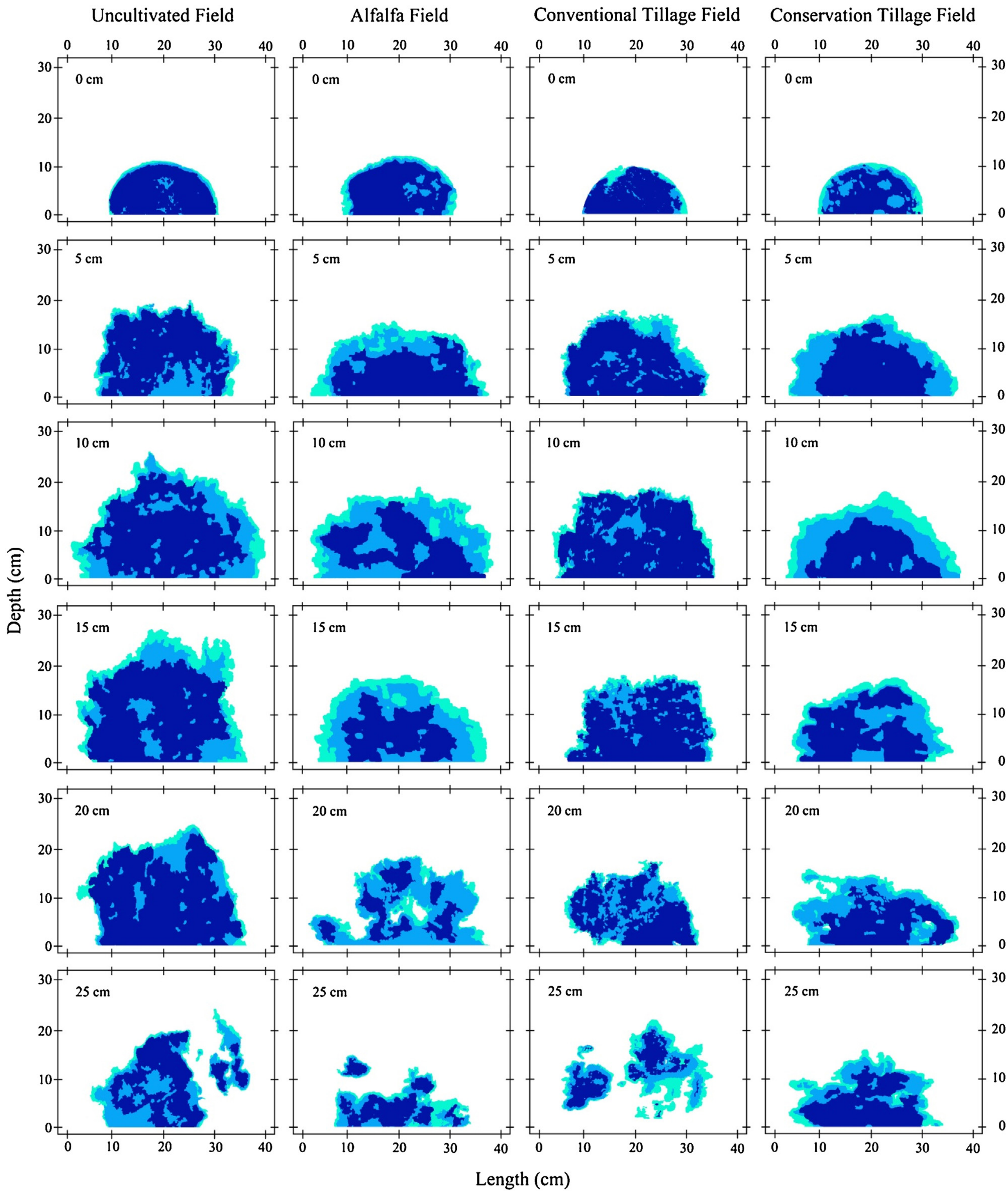

Fig. 4. Classified dye patterns for soil horizontal sections in the four sites. The three profile sections in each sample plot are shown by tests 1, 2, and 3. The dark blue areas indicate the macropore flow paths were heavily stained with Brilliant Blue FCF dye as water infiltrated the soil; the concentration was > 2.0 g L^{-1}. The light blue and green areas were slightly stained with Brilliant Blue FCF dye; the concentration was from 0.5 to 2.0 g L^{-1} and from 0.05 to 0.5 g L^{-1}, respectively. The light blue and green areas indicate the strong and weak exchanges between the macropore and the surrounding soil matrix, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the soil matrix, and became separated at the deeper layer. The different distribution characteristics of the dark blue region also revealed the varied trend of macropore flow across soil depth. For instance, the dye patterns in four fields showed that the macropores increased from the soil surface to 15 cm of soil depth.

The single flow pattern showed more irregularity as a result of different flow types. However, the mean stain area (cm^2) of different concentration distributions for Brilliant Blue FCF dye across soil depth could reveal the degree of flow behaviors (Fig. 5). The greatest degree of macropore flow, exchange between

Fig. 5. Real area (cm^2) of the Brilliant Blue FCF dye vs. depth in the four sites. The real area (cm^2) of each concentration category was estimated at every 5 cm of soil depth starting from the surface. The three profile sections in each sample plot are shown by tests 1, 2, and 3. The mean value of the three experiments is denoted by tests 1, 2, and 3 in each sample plot.

macropore and soil matrix for different fields appeared at different soil depths. For example, the maximum dark blue area for the uncultivated field was 380.23 cm^2, which appeared at 15 cm soil depth. For the alfalfa field, the maximum dark blue area was 247.34 cm^2 at 10 cm soil depth, whereas that in the conventional field was 337.21 cm^2 at 5 cm soil depth; for conservation tillage, the field was 351.21 cm^2 at 5 cm soil depth. The maximum green region area of the uncultivated field was 87.38 cm^2, which appeared at 15 cm soil depth; whereas that of the alfalfa field was 78.68 cm^2 at 10 cm soil depth, the conventional field was 81.86 cm^2 at 5 cm soil depth, and the conservation tillage field was 61.83 cm^2 at 10 cm soil depth. Lateral distribution flow increased the entire stained area from the soil surface to a certain soil depth, and then decreased across soil depth. The largest dye-stained area overall emerged at 10 cm for the uncultivated and alfalfa fields, and 5 cm for the conventional and conservation tillage fields.

4. Discussion

The present study demonstrated that the different management practices firstly affect the soil physical properties and improve the soil water storage capacity on the shallow soil (i.e., 0–15 cm), and then alter the infiltration behavior as illustrated by the dye stain characteristics (Table 2). In the uncultivated land, the soil structure was disturbed for lacking management practices (Fig. 1). Preferential flow was triggered by wetting front instabilities and was generally confined to the upper 15 cm of the soil profile (Figs. 2 and 3). Marshall et al. (2014) stated that management practices can improve soil hydraulic properties. In the present study, management practices not only influenced the soil physical properties (e.g., initial gravimetric water content, total porosity), but also had different effects on water flow behavior. Alfalfa is a perennial and long-living plant that creates large and deep root systems. The large numbers of pores formed by living and decaying roots were classified as continuous macropores (Gibbs and Reid, 1988), which not only served as preferential flow paths (Figs. 2 and 3), but also altered total porosity. In the present study, the total porosity from soil surface to 30 cm of soil depth was lower in the alfalfa field than in the uncultivated field (Fig. 1), a finding that does not agree with the results obtained by Yousefi et al. (2014). The differences could be attributed to the time alfalfa was planted, which was too short to form more and deeper pores. The alfalfa taproot is short, but numerous continuous and preferential paths in the alfalfa field compared with those in the uncultivated field resulting in larger preferential flow for the alfalfa field (Figs. 2 and 3). In general, macropore flow along the vertical direction was the dominant flow behavior in the alfalfa plot. Compared to the uncultivated field, higher total porosity was noted under the conventional tillage, which appeared at 25 cm of soil depth (Fig. 1). The vertical variability of the aforementioned parameters was controlled by soil disturbance caused by ploughing (Rasmussen, 1999; Wahl et al., 2003; Armand et al., 2009) and the existence of the plough pan. In the present study, the 0–25 cm topsoil and the plough layer subsoil were subject to ploughing and compaction respectively. Therefore, the loose, fragmented, and macropore-rich characteristics of the soil structure in the topsoil and the compacted soil below were the dominant characteristics of the soil structure in the subsoil. Moreover, the continuity of the preferential flow paths was disrupted by conventional tillage and trafficking compaction. Therefore, the macropore flow bypassed the compacted soil and confined it to two isolated patches, becoming the dominant prevalent flow behavior in the conventional tillage field (Figs. 2 and 3). The tillage pan did not lead to the emergence of lateral flow, this result digressed from those obtained by Jiang et al. (2012) in a black soil study. Under conservation tillage, higher bulk density and lower total porosity were observed during the first two years after changing from uncultivated field to conservation tillage field (Fig. 1). As Cullum (2009) reported, conservation tillage practices not only maintain the structure of the surface soils, but also yield more macropores and a greater continuity of vertically oriented macropores. This fact is mainly attributed to the greater abundance of anezic earthworm species and less disturbance of the topsoil on agricultural soils (Wahl et al., 2003). Conservation tillage systems promote the formation of greater continuity and connectivity of the macropore system, which favors the preferential flow of water (Figs. 2 and 3). These results agreed with those obtained by Okada et al. (2014).In general, the disturbing degree of the four management practices played a pivotal role in the degree of macropore flow and macropore–matrix transfer. The macropore transport was greater in the uncultivated field and the conservation field, however, the strong exchange between macropore and soil matrix was greater in the alfalfa field and the conventional tillage field (Table 2).The continuity and connectivity of the macropore system was extremely important to transport water and solute. The classified dye patterns and the associated dark blue area suggested that the order for continuity and connectivity degree of the macropore systemfrom highest to lowest was alfalfa field, conservation tillage field, uncultivated field, and conventional tillage field (Figs. 2 and 3). The continuity and connectivity of the macropore system and the soil water storage capacity played a key role in utilizing the uncultivated land. Greater continuity and connectivity of the macropore system would promote the uniform distribution of water and fertilizer in soil profiles. The better soil water storage capacity would extend the water and fertilizer retention time in soil. Thus the water and fertilizer use efficiency would be improved by management measures. We recommend that local governments and farmers would prefer alfalfa field and conservation tillage field to other management measures. Compared with the bare soil surface in the uncultivated field, the crops in the three other fields reduce the impact of raindrops on the soil surface, thereby reducing soil dispersion and sealing. This result will increase water infiltration into soil, lower surface runoff, and increase water storage in the soil profile. Crop residues are also incorporated into the soil, where they enhance the physical properties of soil (e.g., an increased number of medium-sized pores would strengthen water holding capacity).

Although Brilliant Blue FCF dye is adsorbed in the soil to some extent (German-Heins and Flury, 2000), dye tracer experiments are considered efficient methods for visualizing, identifying, and quantifying water flow pathways in structured soils (Flury et al., 1994) because it is nontoxic, distinctly visible in soils, and can be considered moderately mobile in high concentrations (Flury and Flühler, 1995; Kasteel et al., 2007; Janssen and Lennartz, 2008). Image analysis of photographed dye profiles can enhance the interpretation of soil water flow (Ghodrati and Jury, 1990). Further interpretation and calculations can be performed after dye concentration maps are completed by using classification techniques, which can identify the types of water flow in the soil matrix and facilitate the macropore–matrix transfer processes (Weiler and Flühler, 2004; Cey and Rudolph, 2009). In the present study, three concentrations of Brilliant Blue FCF dye were adopted to interpret the different water flow paths. Classified dye-stained patterns resulted from different concentrations of Brilliant Blue FCF dye, which could interpret the flow behavior of soil water through the soil matrix and the macropore-matrix transfer processes (Weiler and Flühler, 2004; Cey and Rudolph, 2009). Macropore flow was identified by the dark blue dye and was the dominant flow in the soil. However, the difference between the emergence of macropore flow in soil and the production of dark blue stain resulted from classification techniques of image analysis software should not be neglected. In fact, the presence of preferential flow cannot disaffiliate itself from the occurrence of soil matrix flow. During the exchange of water and solute between the macropore and matrix domains, the water flow rate through the macropores is assumed to exceed the rate of water infiltration into the soil matrix (Hoover, 1949). The dominant direction of exchange depends on whether the soil matrix had higher soil water content. Although the dominant exchange direction as roughly illustrated by the classified dye-stained patterns, the real process of water exchange could be realized clearly. At the primary stage of infiltration, similar to the unsaturated phase, the dominant water transfer is from the macropore into the surrounding soil matrix when the water content is lower in the soil matrix than in the preferential flow paths. Beven and Clarke (1986) defined this process as lateral infiltration from the macropore. Even at the saturated stage, the water velocity is higher in preferential flow paths than in the soil matrix, and the dominant transfer direction is still from the macropore into the surrounding soil matrix. One disadvantage of this present work was lack of infiltration rate. Besides soil physical properties, dye tracer experiments combined with infiltrometer could present more information on soil hydraulic properties. Future research should prefer to the methods of combining laboratory analysis of soil physical properties and dye tracer experiments with infiltrometer.

5. Conclusion

The different management practices firstly affect the soil physical properties and improve the soil water storage capacity in the shallow soil layer (i.e., 0–15 cm), and also alter the infiltration behavior as illustrated by the dye stain characteristics. In the uncultivated land, preferential flow triggered by wetting front instabilities was generally confined to the upper 15 cm of the soil profile. The presence of preferential paths (i.e., alfalfa taproot) in the alfalfa field resulted in highly continuous preferential flow. The macropore flow bypassed the compacted soil, was confined into two isolated patches, and became the dominant flow behavior in the conventional tillage field. Conservation tillage systems not only improved the continuity and connectivity of the macropore system, but also shaped the preferential flow into an inverted triangular distribution. The order of continuity and connectivity degree of the macropore system from highest to lowest was alfalfa, conservation tillage, uncultivated, and conventional tillage field. Given that the continuity and connectivity of the macropore system and the soil water storage capacity played a key role in utilizing the uncultivated land, we recommend that local governments and farmers would prefer alfalfa field and conservation tillage field to other management measures.

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