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Original Research Paper

Field Study on Preferential Flow under Different Land Uses in the Loess Hilly Region

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ABSTRACT

Evaluating the effects of different land uses on soil preferential flow is essential to improve the decision support systems for water management in the Loess hilly region in China. The objective of this study was to assess the response of preferential flow to different land uses (cropland, woodland, grassland). The study site was located in the Changwu Agri-ecological Experiment Station of the Chinese Academy of Sciences. In these experiments, an amount of 100 mm of Brilliant Blue dye solution was irrigated into the soil at constant heads of 10 mm, several vertical profiles were prepared to visualize dye stain patterns after each experiment, and photographs of the dye profile were processed by image analysis to discriminate stained and unstained areas. The results demonstrated that the preferential flow obviously existed in three land uses. The highest dye coverage was found at the soil depth of 0~10 cm, while the dye area presented serrate dye peak, dye island or dye loop below 10 cm. The average depth of dye infiltration area (D_{ave}) was found highest in woodland (35.31 cm) followed by cropland (25.75 cm) and grassland (24.49 cm). The average value of maximum depth of dye infiltration (D_{max}) was significantly higher in grassland (49.93 cm) and lower in woodland (64.50 cm) and cropland (58.22 cm). The results indicated that vegetation types and initial moisture content would be the key factors affecting the preferential flow. This paper would be helpful in soil moisture and nutrient management in the hilly region of Loess Plateau.

INTRODUCTION

Soil is considered as the natural filter of the world's water; its buffering and filtering function determine the quality and quantity of our reserves of subterranean and surface water (Clothier et al. 2008). It is generally accepted that soil ecosystem has strong ability of self-purification. The pollutants which enter the soil environment will diminish in concentration or even disappear after adsorption, decomposition, migration or transformation. However, various observations have shown that the deep soil or even groundwater had been contaminated even if pollutants do not exceed soil self-purification ability (Allaire et al. 2009, 2011). Furthermore, agricultural chemicals, which have slow mobility, quick degradation and low residual could still be detected in groundwater (Stone & Wilson 2006, Lindahl & Bockstaller 2012). This phenomenon would be a result of preferential flow which drives water and solutes moving to deeper soil rapidly. This movement is faster than that predicted by the Richards equation for uniform flow.

It is inevitable that rainfall, irrigation or other type of water recharge will produce preferential flow paths (Zhang Jian-feng et al. 2003), especially in hilly region of Loess Plateau where large cracks, worm holes, root channels and layered structure were commonly observed. Cheng & Liu (2012) indicated that in the hilly region of Loess Plateau, both the piston flow and preferential flow can be found during the rainfall infiltration. The occurrence and the degree of preferential flow would be influenced by land uses. Xu & Chen (2010) reported that macropores are the main channel which link precipitation with groundwater and contribute to the hydrological cycle in the Loess hilly region. In comparison with piston flow, preferential flow has greater contribution to recharging of subsurface runoff (Xu & Chen 2010). The soil preferential flow is a crucial way to recharge the underground water in Loess hilly region in China where there is a large scale of ecological environment construction, and plant growth and vegetation restoration are strongly influenced by the soil moisture, so it is important to carry out the study of the soil preferential flow in this area. The researches on soil preferential flow characteristics and the moisture migration mechanism have importantly practical significance for efficient utilization of water resources in this area.

Using dyes to trace and visualize water infiltration patterns has become an established method to demonstrate the occurrence of preferential flow in soil (Flury et al. 1994, Cey & Rudolph 2009, Kodešová et al. 2012). However, this approach has seldom been used to study the preferential flow under different land uses in study area. The objective of this study was to determine the characteristics of preferential flow under three land uses in the area. The gained knowledge will be a significant contribution to defining a feasible method in water management and land use development.

MATERIALS AND METHODS

Site description: The field experiment was conducted at the Changwu Agri-ecological Experiment Station of the Chinese Academy of Sciences (107°402-107°422 E and 35° 122 -35°162 N, altitude 950~1225 m), which is located in the southern part of Loess plateau. This site has a semiarid and continental monsoon climate with an annual mean precipitation of 580mm, mostly (about 65%) falling from July to September. The mean annual temperature is 9.1°C.

Three main land uses were selected at Changwu site: cropland, woodland and grassland. All land use types were established for more than 20 years. Table 1 shows an overview of the soil properties and main vegetation cover of the three experiment sites.

Dye infiltration experiment: Eight dye infiltration tests (designated C1, C2 for Cropland, W1, W2, W3 for woodland, G1, G2, G3 for grassland) were conducted during May 22nd and June 7th, 2011.144kg of Brilliant Blue FCF solution (Concentration = 4 g/L) was infiltrated by applying an initial ponding depth of 10 cm, the infiltration plot was 1.2m×1.2m covered by plastic and green roof to prevent from evaporation or outside interference. After the infiltration process, the plot was excavated in a series of vertical slices (10~20 cm apart) to observe the dye distribution within the soil profile to a depth of 100 cm. Photographs were taken with a digital camera (3027×2304 pixel, Cannon PowerShot G6). The total number of profile images taken for each land use is given in Table 2, including 11 profiles for cropland, 16 profiles for woodland and 18 profiles for grassland.

Image analysis of dye patterns: As shown in Fig. 1, image processing includes geometric correction, image enhancement processing, background removal and binary classification. There is more detailed description of image analysis procedure: (1) Geometric correction: the images obtained from field were corrected for geometric distortion by ArcGIS 9.3 software, and the transformed images have a pixel size corresponding to 1mm. The left and right borders of the images were cut for 10 cm respectively in order to eliminate boundary effect. (2) Image enhancement processing: the saturation of the blue stains in image was maximized using PhotoshopCS in order to merge similar colours and reduce the number of classification. (3) Background removal: the unstained areas were converted to white by PhotoshopCS. (4) Binary classification: the image was divided into stained or unstained area by ArcGIS 9.3 software (See Fig. 1., blue represents stained area and white represents unstained area). Then images were divided into separate horizon segments to determine the number of grid cells and furthermore to obtain the percentages of blue areas within each horizon (5 cm/layer).

Root index analysis: Three sites were randomly selected at each land use. Soil samples were collected every 10cm in range of 0~120 cm soil layer by earth drill (Φ = 9 cm). Roots were separated from the soil by washing. After washing, digital image of the roots was obtained from the Epson Perfection V700/V750 digital image scanner and was analysed using WinRHIZO 2009 software. Then, the dry weights were

Table 1: Soil properties of the three experimental sites.

Land use	Depth (cm)	Bulk density (g cm^{-3})	Initial soil water content (cm^{-3} cm^{-3})	Main vegetation cover
Cropland	0~20	1.22±0.04	12.65±1.29	Typically cropped in a maize – millet rotation and was planted with millet before experiment.
	20~50	1.38±0.04	14.06±1.49	
	50~100	1.38±0.05	16.14±2.31	
Woodland	0~20	1.26±0.09	12.01±1.18	Bothriochloa is chaemum, The accompanying plant species include small brush and herbage.
	20~50	1.36±0.09	13.14±0.47	
	50~100	1.35±0.05	14.09±0.62	
Grassland	0~20	1.29±0.09	18.18±0.61	Robinia pseudoacacia. the coverage can reach over 90%.
	20~50	1.36±0.07	12.41±2.46	
	50~100	1.34±0.05	12.25±3.16	

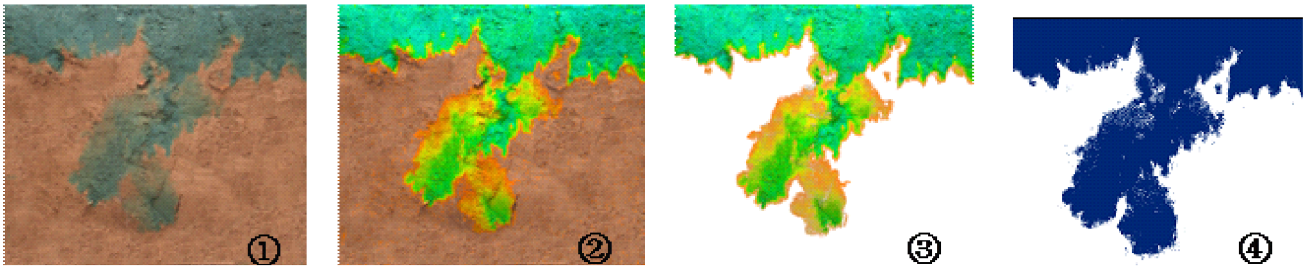

Fig. 1: Schematic illustration of image analysis procedure.
1. Geometric correction, 2. Image enhancement processing, 3. Background removal, 4. Binary classification

determined after oven-drying at 70°C for 48 h. Afterward, root biomass, root length density, root area index and average diameter were calculated.

Statistical Analysis: All statistical analyses were conducted using the program R (version 2.15.0). One-way analysis of variance (ANOVA) was used to test the statistical significance of differences of dye distribution character under three land uses, treatments were compared using least significant difference (LSD) tests at the confidence level of 95%. Relationship between preferential flow and root index was calculated by Spearman correlation analysis.

RESULTS

Vertical dye patterns: All the images were transformed to blue and white colour by ArcGIS 9.3 and PhotoshopCS software (Fig. 2). It is obvious that preferential paths can be found under all the three land uses. As shown in Fig. 2, the vertical distribution of Brilliant Blue FCF was rather irregular which appeared in the form of continuous or discontinuous patches. The depth of dye penetration under each land use was significantly different. The percentage of staining area was largest in surface soil layer, and decreased with the increase of soil depth. At 0~10cm soil layer, soils were completely dyed, while below 10cm, the distribution of staining area had the following characteristics.

1. Serrate dyeing peak was both common and widespread among soil profile. It could be seen from Fig. 2 that the depth of dye infiltration is obviously different even in the same soil profile. For instance, C1 had a 90cm long preferential flow paths whose maximum depth of dye infiltration is about 9 times larger than the minimum depth. This phenomenon could be attributed to soil spatial heterogeneity. In macroporous soils, the preferential pathway (e.g., root holes, worm channels and cracks) allowing water and solutes moves quickly through the soil profile, and bypass part of the soil matrix. However, water movement in homogeneous soils with low porous is relatively slower. In this case, water and solutes must infiltrate through the entire homogeneous soil layer resulting in a lower infiltration rate and shallower dyeing depth in comparison with those in macroporous soils.
2. Breaking patches (also known as 'dyeing island') were found in the stained area, implying that preferential flow occurred not only in vertical direction, but also in horizontal direction. As shown in Fig. 2, the dyeing islands were observed in -30cm of C1, -50cm of W1, -80cm of W2, -20cm of G1 and -40cm of G3.
3. Blank area (also known as "dyeing ring") were detected in soil profile in -20cm of F1, -50cm of F2, -20cm of W3, -30cm of G2, and -20cm of G2. This may be due to the complexity of the soil pore network which is caused by plant root growth and animal activities, as well as different degree of soil compaction. Water may bypass part of soil matrix and converge at a certain depth in the process of water infiltration. In addition, the water tended to avoid the soil where it was relatively solid and moved to the surrounding porous soil.

In order to explore the differences of stain pattern under different land use, the maximum and average depth of dye infiltration in each profile were investigated (Table 2). Total of 45 profiles were analysed in this study, including 11 profiles for cropland, 16 profiles for woodland and 18 profiles for grassland.

The maximum depth of dye infiltration which means the maximum depth that brilliant blue can reach in the soil profile is an indicator for the characteristics of rapid movement of preferential flow. For cropland, woodland and grassland, the peak value of maximum depth of dye infiltration was 74.55cm, 93.45cm and 92.95cm respectively. The mean value of maximum dye infiltration depth was found to be highest in woodland (64.50 cm), followed by cropland (58.22 cm) and grassland (49.93 cm). The results of ANOVA indicate that this difference among land use is statistically significant ($P<0.05$).

The average depth of dye infiltration, which was derived

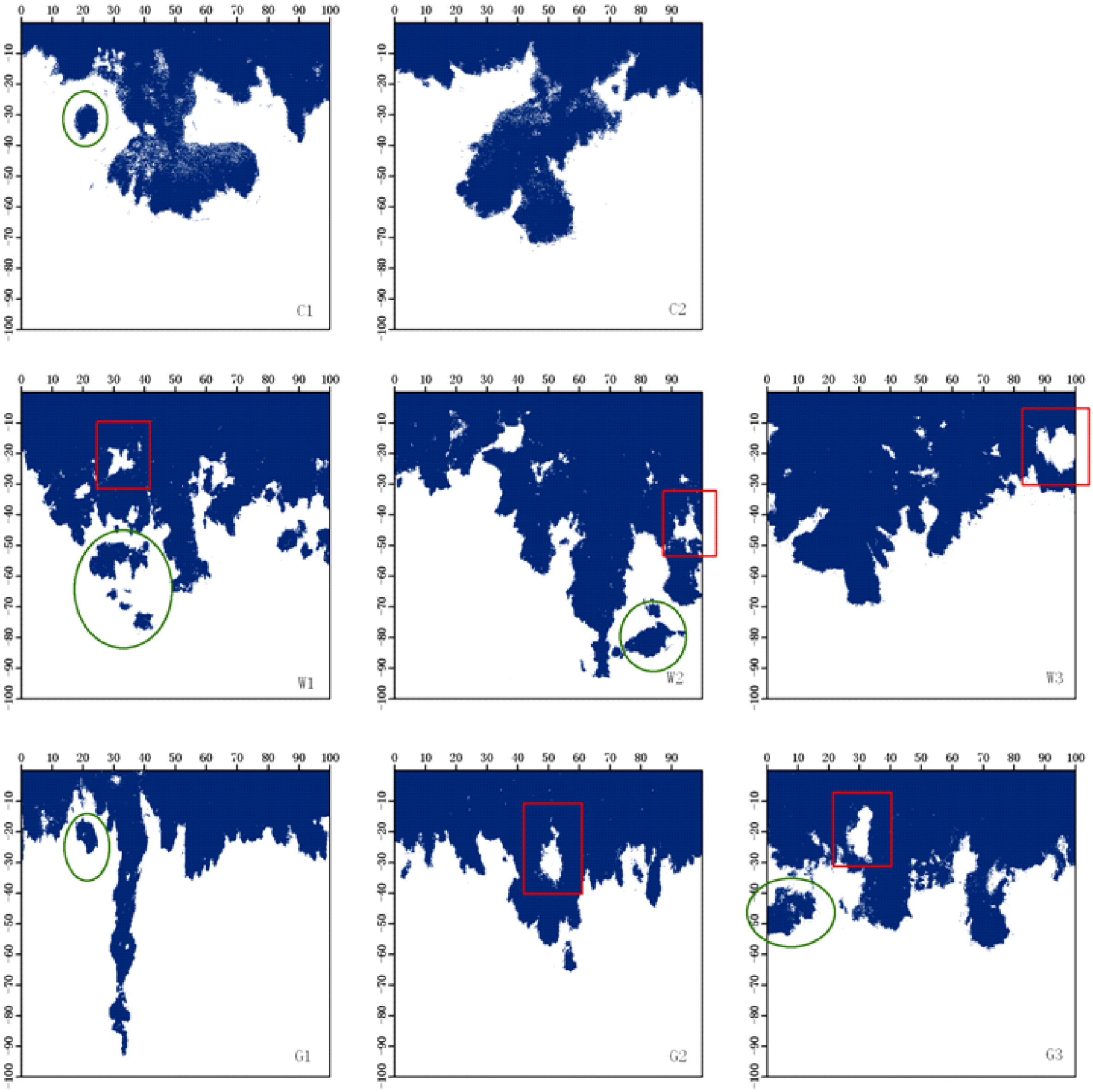

Fig. 2: Vertical dye distributions of soil profile under different land use types.

from dividing stain area by profile width, was influenced by both preferential flow and matrix flow. The average depth of dye infiltration in woodland (35.31cm) was significantly higher ($P < 0.001$) than those in cropland (25.75cm) and grassland (24.49cm). However, there was no significant difference between cropland and grassland.

Dye coverage: The variation of dye coverage is shown in Fig. 3. At 0~10 cm soil layer, cropland, woodland and grassland were completely stained, which reflected that the surface soil of these land uses were under excess infiltration. Nevertheless, at 10-30cm soil layer, dye coverage of cropland, woodland and grassland decreased from 96.18%, 99.01%, 96.18% to 20.72%, 65.85%, 34.30%, respectively, with the drop of 75.46%, 33.49% and 63.59%, respectively. The reason for this difference in drop of dye coverage could be attributed to the difference of root biomass among land uses. As shown in Fig. 4, woodland had the highest root biomass at 10-30 cm soil layer, followed by grassland and cropland. Therefore, we assume that the pores caused by root development would affect the reduction of dye

Table 2: Comparison of parameters used to characterize preferential flow under different land use types.

Parameter	Land uses	Profiles	Min	Max	Mean	SD	CV	F-value	P-value	LSD test
D_{max}	Cropland	11	25.70	74.55	58.22	16.09	0.28	4.108	0.0235*	a
	Woodland	16	48.53	93.45	64.50	13.07	0.20			a
	Grassland	18	30.78	92.95	49.93	15.56	0.31			b
D_{ave}	Cropland	11	10.94	32.46	25.75	6.63	0.26	11.89	0.0001***	a
	Woodland	16	21.46	47.86	35.31	6.62	0.19			b
	Grassland	18	13.04	37.81	24.49	7.16	0.29			a

1. D_{max} means the maximum depth of dye infiltration; D_{ave} means the average depth of dye infiltration.
2. The symbol* indicates a significant difference at the level of P<0.05, **indicates a significant difference at the level of P<0.01, ***indicates a significant difference at the level of P<0.001.
3. LSD tests: Same letter stands for no significant difference at the level of 95%.

Table 3: Correlation analysis between dye coverage and root indexes under different land uses.

		Root biomass	Root length density	Root area index
Cropland	Spearman correlation coefficient	0.8424	0.8788	0.8424
	P-value	0.0045**	0.0020**	0.0045**
Woodland	Spearman correlation coefficient	0.8182	0.9152	0.9515
	P-value	0.0068**	0.0005***	0.0000***
Grassland	Spearman correlation coefficient	0.9394	0.7818	0.7818
	P-value	0.0000***	0.0117*	0.0117*

The symbol *indicates a significant correlation at the level of P<0.05, **indicates a significant correlation at the level of P<0.01, ***indicates a significant correlation at the level of P<0.001.

converge in soil profile. At 30~50cm soil layer, dye coverage in cropland was about 20% which is similar to that at 10-30 cm soil layer. However, dye coverage in woodland and grassland decreased with soil depth. Root diameter of cropland at 30-50 cm soil layer is significantly higher than woodland and grassland, which may promote water migration rapidly, and led to a smaller decrease of dye coverage. The result was supported by Niu. et al (2008) who reported that root diameter is closely related to the occurrence of preferential flow. For the soil below 50 cm dye coverage under all land uses gradually diminished and reduced to zero. This finding is the result of infiltration and in accordance with Darcy's rule of unsaturated infiltration. It can be inferred from the results of dye coverage that preferential flow is a common phenomenon under three land uses. Plant roots would be the key factor which affects the generation and distribution of preferential flow.

Response of root index to preferential flow: Plant roots play an important role in formation of water flow pathway. Noguchi et al. (1997) found that white liquid paint concentrated on decayed and living roots in a tropical rain forest soil. Niu et al. (2008) pointed out that the dye area generally had a high density of roots. Therefore, it can be concluded that the root system tends to provide pathway for preferential flow which is beneficial for the migration of water and solutes. As given in Table 2, correlation analysis for dye coverage and root density under different land uses was performed in order to study the relationship between plant root system and the preferential flow. The result indicates that there is a positive correlation between root biomass, root length density, root area index and dye coverage; the Spearman correlation coefficients were all greater than 0.75 (p<0.05), which imply that dye coverage would increase with the increase of root density. The distribution of plant roots would affect the macropore structure of soil and the characteristic of preferential flow. However, the biomass of roots with different diameter was not analysed in this study. It is still unclear that how the preferential react to change of root diameter.

DISCUSSION

The velocity of wetting front transportation influenced by soil initial moisture: The increase of initial soil moisture would cause a decrease in initial infiltration rate, the time required to reach the stable infiltration and the runoff yielding time. Moreover, it would lead to an increase in the velocity of wetting front transport.

In our study, there was a rainfall of 25.3 mm in grassland 5 days before the measurement. The moisture content of grassland surface soil was higher (18.9%) compared to those of farmland and woodland (11.80%) where no rainfall was observed before the field measurement. Consequently, the average maximum depth of dye infiltration in woodland

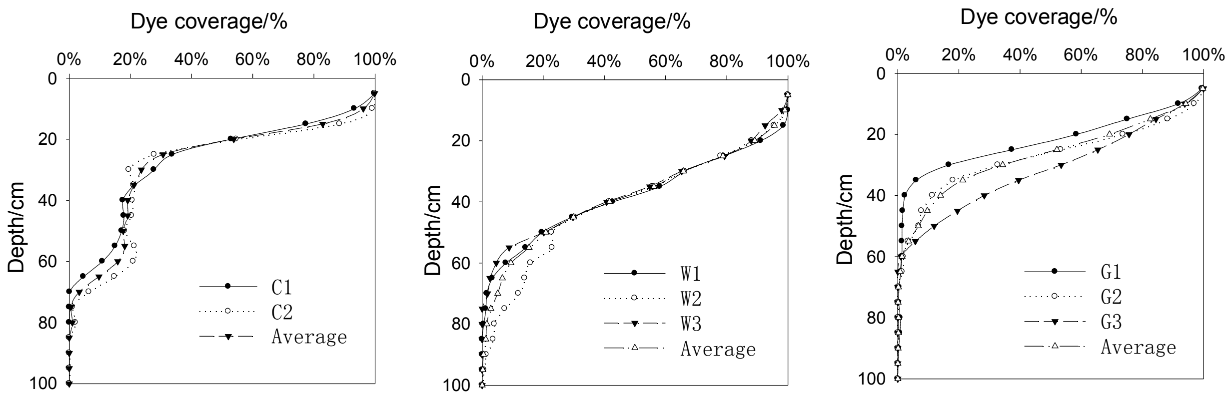

Fig.3 Comparison of depth distributions of dye coverage under different land uses.

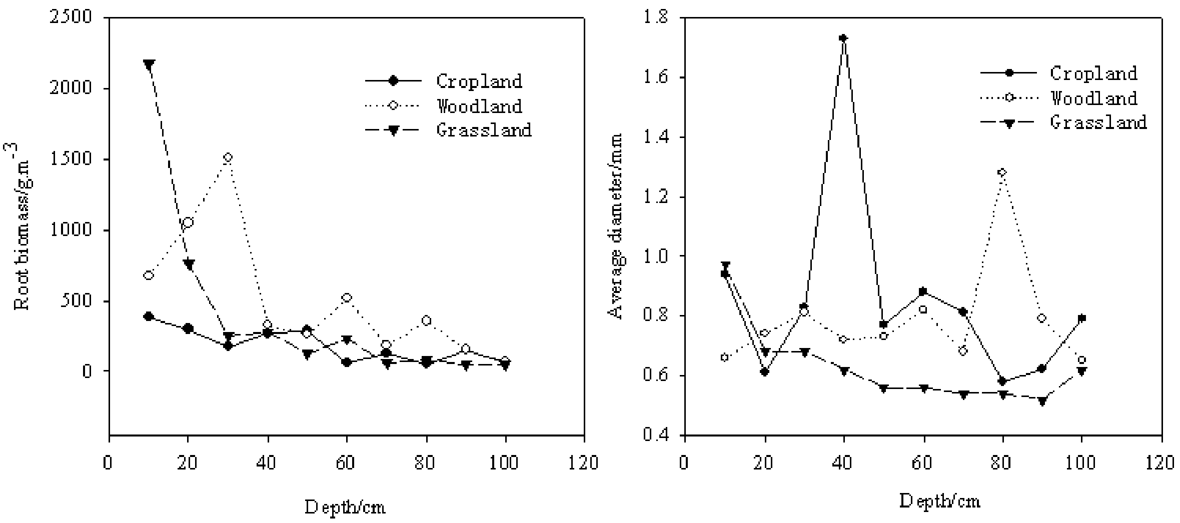

Fig.4 Comparison of depth distributions of root index under different land uses

and cropland is significantly higher than that in grassland. However, G1 from Fig. 2 showed that macropores in wet soil condition resulted in dye penetration deeper.

Surface moisture content of grassland is higher than cropland and woodland, in addition, dense root distribution is advantageous to the rainfall conservation, so the maximum depth of dye infiltration in grassland is generally shallow. Besides, antecedent moisture content had less effects on the connectivity of large flow paths and lateral recharge decrease, and induce the degree of preferential flow (G1). Connectivity of flow paths in cropland and woodland is relatively better, the average maximum depth of dye infiltration is significantly higher than grassland. Consequently, the result of this part is consistent with the viewpoint that high water content may be evidence of a lack of connectivity, as filled pores may retain water because they are poorly connected (Nimmo 2012). At the same time, it also complied with this standpoint that high initial moisture content in the soil allows deeper penetration along the macropores by reducing the lateral losses from macropores into the soil matrix (Quisenberry & Phillips 1976, Flury et al. 1995, Sheng & Fang 2012).

The preferential flow influenced by vegetation type: Studies have found that in the processing of natural vegetation succession, soil hydraulic conductivity increases significantly. The soil hydraulic conductivity is in this order: climax community > late forest > middle forest > early forest > shrub > bare land.

In this experiment, root biomass at 0~10 cm depth from high to low was grassland, woodland, cropland, below 10 cm, the order was woodland > cropland > grassland (Fig. 4).

It can be inferred from Table 3 that the roots of vegetation were the main factors affecting the magnitude of preferential flow in the loess hilly region. *Robinia pseudoacacia* with strong deep root system and high level of lateral recharge provides enough preferential flowpaths for water infiltration and redistribution, so the total dyeing area is largest in woodland, average depth of dye infiltration is significantly higher than cropland and grassland. Root biomass in cropland is greater than grassland, but there were no significant differences between cropland and grassland for average depth of dye infiltration, the reason for this similarity is probably that water repellency could offset the influence of root biomass. In the same way, the differences between woodland and cropland for average maximum depth of dye infiltration were also similar, and it can be explained by root diameter. Overall, root diameter in cropland is the largest, which counterbalances the influence of root biomass, so there was no significant difference between woodland and cropland for average maximum depth of dye infiltration.

CONCLUSIONS

1. In this study, field dye tracer experiments and image analysis technology were used to determine the characteristics of preferential flow under cropland, woodland and grassland in the Loess hilly region of China. The dye coverage was found to be highest at 0~10cm soil. For the soil below 10cm, dyed area presented Jagged shape, stainless island and dyeing island, which reflects the fact that there occurred preferential flow under cropland, woodland and grassland.
2. The average depth of dye infiltration in woodland (35.31 cm) is significantly higher than those in cropland (25.75 cm) and grassland (24.49 cm). It attributes to the well-developed root system in forest which provided more pathways for preferential flow. The soil under grassland has greater initial moisture content and smaller pore connectivity. Therefore, the average maximum depth of dye infiltration in grassland (49.93 cm) is significantly lower than those of woodland (64.50 cm) and cropland (58.22 cm). The result indicates that vegetable types and initial moisture content would be the key factors affecting the preferential flow in the Loess hilly region in China.
3. Dye coverage decreases quickly as the depth increases in woodland and grassland, but much slower in cropland. The dye coverage in cropland was relatively stable, especially for soil at 20~60cm, which can be explained by its greater root diameter.
4. For all land uses, a significant positive relationship was found between root biomass, root length density, root area index and dye coverage. It is clear that plant root system would influence the generation and distribution of preferential flow in Loess Plateau. So if we want to keep more rainwater into soil to mitigate severe soil and to reduce the water loss in Loess hilly region, it would be very useful to increase soil preferential flow. Therefore, increasing vegetation coverage would be recommended to develop more root system, which later on become pathway for soil preferential flow. Because the *Robinia pseudoacacia* with strongly deep root system has more positive impact on the preferential flow than crops and grasses, it is necessary to build up more artificial forests.

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