Application of X-ray tomography to quantify macropore characteristics of loess soil under two perennial plants

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Summary

With the advent of large-scale restoration of vegetation in the Loess Plateau, northwest China, there has been an increase in concern about the suitability of loess soil to support permanent vegetation cover. The quantification of soil macropore characteristics could be critical in determining the architecture and hydrological processes of loess soil on the plateau. In this research, we compared the effects of Purple alfalfa (*Medicago sativa* L.) and Korshinsk peashrub (*Caragana korshinskii* K.) on the macropore characteristics of a soil profile on the plateau with computed tomography (CT). To achieve this, undisturbed cores of soil were excavated from beneath purple alfalfa (ALF), 22-year-old Korshinsk peashrub (KOP₂₂) and 40-year-old Korshinsk peashrub (KOP₄₀) vegetation types in the Liudaogou watershed for evaluation. The soil macropore characteristics (including macroporosity, largest pore area, amounts of macropores, circularity, surface area density, branch density, junction density and connectivity) were determined with image analysis software. Soil under KOP₂₂ and KOP₄₀ treatments had approximately the same amounts of macropores (17 per 6359-mm² area), which was three times greater than those under ALF plants. Macroporosity ratios of soil under KOP₂₂ and KOP₄₀ plants to that under ALF plants were 2.3 and 3.6, respectively. Compared with KOP₂₂, KOP₄₀ had a larger macroporosity and the largest pore area at the 100–300-mm soil depth. The KOP plants, in particular KOP₄₀, apparently improved the macropore network structure of the soil more than ALF. However, the macropores under ALF were much rounder at the 100–300-mm soil depth than those under the other two plants. There was no correlation between macropore characteristics and organic matter content of the soil at 100–400-mm depth. Nevertheless, macroporosity was strongly correlated with the largest pore area. The findings of this research are critical for developing strategies for the restoration of vegetation in the Loess Plateau through improvement of the hydrological process of loess soil.

Highlights

- We examined macropore characteristics of loess soil on the Loess Plateau in China.
- We determined the effects of different plants on soil macropore characteristics.
- Soil under Korshinsk peashrub had better macropore structure than that under Purple alfalfa.
- Long-term recovery of KOP benefits the macropore structure most on the northern Loess Plateau.

Introduction

Severe and widespread soil erosion has brought the restoration of vegetation to the forefront of soil conservation efforts on the Loess Plateau, northwest China. Some 24% of the eroded regions of the Loess Plateau have been controlled since the 1980s (He *et al.*, 2003). The restoration of vegetation on the plateau has

benefited most from the Grain for Green Project that started in 1999. In the Loess Plateau, the objective of this project was to increase vegetation cover on the plateau by planting trees and sowing grasses on barren croplands. The Grain for Green Project involved considerable investment from the Chinese Government and by the end of 2005 it had covered some 87 000 km² of land on the plateau with the planting of about 400–600 million trees (Zhou *et al.*, 2009).

The substantial increase in vegetation cover (Zhou *et al.*, 2012) had a marked effect on properties of the soil, including deep

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soil profile water content (Cao *et al.*, 2009; Wang *et al.*, 2010; Jia & Shao, 2014). This has, however, hindered the sustainable development of vegetation in the plateau region. One reason is the development of dry layers in the soil, which is considered to be a new obstacle to vegetation growth and succession in the region (Chen *et al.*, 2008; Wang *et al.*, 2010). Because of this, efforts to increase the infiltration and storage of rainwater in the soil have become more urgent.

Zhao *et al.* (2010) noted that natural vegetation recovery could improve considerably soil pore characteristics that are closely related to water storage and the regulating capacity of the soil water reservoir. Characterization of soil pores in the arid Loess Plateau region could, therefore, be useful for developing strategies to avoid water shortage at depth in the soil profile and for vegetation recovery in the region. The uniqueness of eroded landforms on the plateau makes characterization of the soil pores especially necessary. So far, research on this feature of the Loess Plateau is largely insufficient.

Conventional methods of soil pore research are indirect and lack sufficient detail. Computed tomography (CT) procedures, however, are more exact, use non-destructive strategies for observation and have fine resolutions (Cnudde & Boone, 2013). Soil pore characteristics, such as pore shape, size, orientation and size distribution, can be determined accurately with the X-ray CT device (Rab *et al.*, 2014). Furthermore, there are promising applications of the CT method in other fields of soil science, such as the measurement of bulk density, solute transport, soil hydraulic properties, soil quality, plant root development and three-dimensional reconstruction (Jarvis, 2007; Elliot *et al.*, 2010; Alaoui *et al.*, 2011; Li *et al.*, 2014). In view of the versatility of CT, its application in soil physics, for example to quantify soil macropores, is increasing in popularity.

There is abundant research on the effect of vegetation recovery on soil physical properties in the Loess Plateau. The studies have shown that soil porosity has increased from 51.4% on agricultural land to 62.7% in forests under long-term natural vegetation in Ziwoiling (Li & Shao, 2006). Jiao *et al.* (2011) observed that land use affects markedly soil bulk density, total porosity and capillary porosity of the surface soil layer. Bulk density varies with the slope position of *Caragana korshinskii* K. (Korshinsk peashrub, KOP)

shrubs in gullies on the Loess Plateau (Xu *et al.*, 2014). Furthermore, Hu *et al.* (2009) noted a considerable change with time in the effect of soil pores on the hydrology of alfalfa and Korshinsk peashrub fields in the Liudaogou Catchment. Although this discovery has deepened our insight into soil pore structures in the Loess Plateau, soil macropore characteristics of loess soil have not been explained clearly because of limitations in traditional methods of studying them. The CT technique is used in soil science and its value as an advanced and efficient method has been proved, but it has not yet been used to study loess soil in the Loess Plateau of China. Furthermore, there has not been enough research on the characteristics of surface soil pores in relation to the period of vegetation restoration (Udawatta *et al.*, 2006; Zhao *et al.*, 2010; Yang *et al.*, 2013).

In this research, 360 CT images were used to evaluate soil pore structures at 0–400-mm depth in the soil of the Liudaogou Catchment. The objectives of this study were to (i) evaluate differences in the number of CT-measured macropores, macroporosity, largest pore area, circularity, surface area density, branch density, junction density and connectivity of loess soil under ALF (*Medicago sativa* L.), KOP₂₂ (22-year-old Korshinsk peashrub) and KOP₄₀ (40-year-old Korshinsk peashrub) vegetation types and (ii) correlate the CT-measured pore properties with soil organic matter content and root characteristics. The results of the research will provide further insight into the interactions among macropore characteristics, the plant root system and soil properties in the northern Loess Plateau.

Materials and methods

Experimental site and soil sample preparation

Liudaogou Catchment is on the northern Loess Plateau and is about 14 km west of Shenmu County, Shaanxi Province, China. The location of the catchment is 110°21'–110°23'E and 38°46'–38°51'N, and it is at an elevation range of 1094–1274 m (Figure 1). The catchment is in a moderate temperate, semi-arid zone with a mean annual precipitation of 430 mm, some 77% of which occurs between July and September. The average annual temperature is 8.4°C, with a

Figure 1 Map of the location of the study area in China and of the sampling sites in the Loess Plateau.

mean annual potential evapotranspiration of 785 mm. The catchment is representative of the transition belt because it is subjected to both wind and water erosion. The soil is a Calcaric Regosol (FAO, 1989; Wei *et al.*, 2013) of loess origin with weak cohesion, large infiltration rate, small water retention and poor fertility.

A survey of Liudaogou Catchment showed that restored grass and forest form only small patches of vegetation in the study area. The most important and widely planted species of perennial plants in the region are purple alfalfa (*Medicago sativa* L.) and Korshinsk peashrub (*Caragana korshinskii* K.). They are commonly planted on degraded slopes with no fertilizer application or irrigation, and purple alfalfa is cut once or twice a year for livestock feed. In addition, there is sporadic needlegrass (*Stipa bungeana* T.) in areas not covered by these two perennial plants above.

Cores of soil were taken under the two vegetation types, including both 22-year-old and 40-year-old KOP. Therefore, in effect three vegetation treatments (ALF, KOP₂₂ and KOP₄₀) were covered in the study. Soil texture, slope aspect and elevation were quite consistent at the three sampling sites.

To preserve the natural continuity of macropores and to improve our understanding, undisturbed cores from 0- to 400-mm depth in the profile were taken at each site on 4 and 5 June 2014, whereas previous studies apparently used short soil cores of less than 100 mm. A polyvinyl chloride (PVC) cylinder, 400-mm long, 110-mm wide and with a 3-mm-thick wall, was used to collect the soil core samples. To do this, a representative plant was selected from each plant cover type. Because of the cost of labour for deeper sampling and processing of the scanned images, two cores only were collected for each treatment.

Soil macropore characteristics can differ greatly with distance from a perennial plant because of root development. To deal with this variation, two replicate samples were taken 50 cm from the plant in each treatment. Before the core was taken, the litter was removed completely and bare soil exposed. The PVC cylinders (with a sharp edge) were hammered vertically and fully into the ground with a plastic hammer and a rubber dumbbell, then they were dug out with a shovel. Two PVC caps and masking tape were used to secure the soil inside the cylinders and protect it during transport. The soil cylinders were labelled, placed in plastic bags and sealed until they were scanned by CT. Throughout this process, care was taken to avoid disturbing the samples. Next, disturbed soil samples were taken from depths of 0 to 100, 100 to 200, 200 to 300 and 300 to 400 mm. Soil organic matter and particle-size distribution in these samples were measured in the laboratory (Table 1).

Root features can effectively explain soil pore characteristics; therefore, we used Korshinsk peashrub root data for this. The root sampling sites were the same as the soil core sampling sites; all root analyses were completed in June 2011. The sampling areas of KOP treatments were determined by the canopy areas, which were 3 m × 3 m and 2.7 m × 2.5 m with a total volume of each 10-cm layer of 9 000 000 and 6 750 000 cm³ for the KOP₂₂ and KOP₄₀ treatments, respectively. The KOP roots were obtained by manual excavation and were washed before measurement. The average diameter and length of thick roots were measured with a vernier

Table 1 Mean soil organic matter content and particle-size fractions of sand, silt and clay in the purple alfalfa (ALF), 22-year-old Korshinsk peashrub (KOP₂₂) and 40-year-old Korshinsk peashrub (KOP₄₀) treatments at the 0–100, 100–200, 200–300 and 300–400-mm depths in the northern Loess Plateau of China

Property	Organic matter / g kg ⁻¹	Particle-size distribution / %		
		Sand	Silt	Clay
ALF	6.9	39.6	51.0	9.4
KOP ₂₂	3.7	32.3	58.5	9.2
KOP ₄₀	4.6	42.2	47.2	10.7
0–100 mm	10.1	45.3	46.1	8.6
100–200 mm	4.9	38.7	52.2	9.1
200–300 mm	2.7	35.6	54.2	10.2
300–400 mm	2.6	32.5	56.4	11.1

calliper. Fine root data were obtained by scanning and image analysis. An ordinary scanner (CanoScan LiDE 100, Beijing, China) was used with the resolution set at 300 × 300 DPI. The fine root binary images obtained were analysed by Delta-T scan software, developed in 1993 by Delta-T Devices Ltd, Cambridge, UK. The absence of data on ALF roots was mainly because they have a deep taproot system and shallow roots were not considered to provide sufficient information. The root data (sample area, average diameter and length density) for KOP₂₂ and KOP₄₀ treatments only were used in this study.

Scanning and image analysis

A Philips MX16 CT scanner (Amsterdam, the Netherlands) at Yangling Hospital was used to acquire CT images. The scan system was set to 140 kV, 200 mA s and 21.4 s scan time for detailed and low-noise projection of 1 mm × 1 mm. The X-ray beam width or 'slice' thickness was 1 mm, which produced a volume element (voxel) size of 1 mm³. The scanner resolution limits the size of the smallest pore that can be detected with this procedure. Six soil cores were positioned horizontally on the scanning stage to have a perpendicular X-ray beam along the longitudinal axis. Because the soil at the top and bottom of the cores was more or less disturbed during field acquisition, transport and placement, the top and bottom 20 mm were disregarded to restrict the depth range of scanning to 360 mm. The data were then stored for subsequent image analysis.

The pore characteristics of the scanned images were analysed with the ImageJ software (version 1.48) (Rasband, 2002), which is in the public domain. A circular area of 6359 mm² (with a 90-mm diameter) was demarcated by the area selection tools as the 'region of interest (ROI)' and then the exterior area was deleted to exclude voids near core walls and to minimize beam-hardening interference. The segmentation procedure separated the two populations within an image based on intensity values. With a 'threshold tool', the intensity of water phantoms (mean = 40) was considered the standard threshold to distinguish air-filled pore areas and the other regions within the 8-bit greyscale (range 1–255) image. Values less

Figure 2 (a) Macroporosity, (b) largest macropore area and (c) macropore number at every 1-mm interval of the 20–360-mm depth under ALF (purple alfalfa), KOP₂₂ (22-year-old Korshinsk peashrub) and KOP₄₀ (40-year-old Korshinsk peashrub) vegetation in the Loess Plateau.

than the threshold value were identified as air-filled pores and those that were larger were identified as non-pores. Because of limitations of the CT resolution, the pores from the ImageJ analysis were all classified as macropores (Scott, 2000). Details of the image analysis can be found in Udawatta *et al.* (2006) and Doube *et al.* (2010).

Statistical analysis

The average value of the two samples taken for each depth was used to determine the correlation between macropore characteristics and soil depth (Figure 2). To analyse the correlation between macropore characteristics and soil properties, the 360-mm soil depth was divided into four zones (0–100, 100–200, 200–300 and 300–400 mm) as in Tables 1–4. The means of the treatment in Tables 1 and 2 denote the average values of the 360-mm depth for each treatment. Note that the mean of the depth is the average of the three treatments. Descriptive statistics (including mean, minimum, maximum, standard deviation and coefficient of variation) for the different soil depths and treatments were used to evaluate the effects of depth and treatment on macropore characteristics (Tables 2 and 3). Correlation analysis was used to determine the relations between macropore properties, particle-size distribution and organic matter content.

Results

Macroporosity and largest pore area

The results of the quantitative analysis of the macropores of loess soil in this study are given in Tables 2 and 3. The mean macroporosities of the ALF, KOP₂₂ and KOP₄₀ treatments are 0.65, 1.51 and 2.31%, respectively. The range of macroporosity of KOP₄₀ is wider than that of the other two treatments. The mean values of the largest pore areas under KOP₂₂ and KOP₄₀ are 2.1 and 3.6 times larger than those under ALF. The coefficients of variation (CVs) of macroporosity and largest pore area of the three treatments are all > 1 (Table 2). This suggests considerable variation in these two properties along the 360-mm depth beneath the vegetation types.

Table 3 also indicates that the mean values of macroporosity and largest pore area under KOP₄₀ are larger than those under ALF, especially for the first (0–100 mm), second (100–200 mm) and third (200–300 mm) soil depths. The means of macroporosity and largest pore area under KOP₂₂, however, are close to those for ALF for depths 200–300 and 300–400 mm (Table 3). The soil under KOP₄₀ has larger mean values of macroporosity and largest pore area for depths 100–200 and 200–300 mm than for soil under KOP₂₂. For the 200–300-mm depth, the values of macroporosity and largest pore area under KOP₂₂ are 36 and 21% of those under

Table 2 Summary statistics of soil macroporosity under purple alfalfa (ALF), 22-year-old Korshinsk peashrub (KOP₂₂) and 40-year-old Korshinsk peashrub (KOP₄₀) plants for the 0–100, 100–200, 200–300 and 300–400-mm depths in the northern Loess Plateau of China

Property	Macroporosity / %					Largest pore area / mm ²					Macropore count / N					Macropore circularity				
	Mean	Max.	Min.	SD	CV	Mean	Max.	Min.	SD	CV	Mean	Max.	Min.	SD	CV	Mean	Max.	Min.	SD	CV
ALF	0.65	5.30	0.00	0.76	1.17	21.4	233.0	0.0	27.3	1.28	6	24	0	4	0.71	0.93	1.00	0.50	0.06	0.07
KOP ₂₂	1.51	9.22	0.11	1.88	1.25	44.9	419.0	2.0	75.1	1.67	17	54	5	8	0.48	0.92	1.00	0.77	0.04	0.05
KOP ₄₀	2.31	20.22	0.05	2.83	1.23	77.9	750.5	1.0	116.9	1.50	18	100	2	14	0.80	0.92	1.00	0.71	0.05	0.05
0–100 mm	2.27	3.28	0.62	1.44	0.63	72.2	110.0	18.3	47.9	0.66	18	24	7	9	0.50	0.91	0.93	0.89	0.02	0.02
100–200 mm	1.61	3.26	0.46	1.46	0.91	48.7	103.1	14.8	47.6	0.98	11	15	4	6	0.55	0.92	0.93	0.91	0.01	0.02
200–300 mm	1.25	2.18	0.79	0.80	0.64	45.6	90.5	19.4	39.0	0.86	14	21	6	8	0.57	0.94	0.94	0.93	0.00	0.00
300–400 mm	0.83	0.89	0.74	0.08	0.10	25.6	29.5	21.8	3.8	0.15	11	15	7	4	0.36	0.94	0.94	0.93	0.01	0.01

Max., Min., SD and CV denote maximum, minimum, standard deviation and coefficient of variation, respectively.

Table 3 Summary statistics of macropore properties (macroporosity, largest pore area, macropore count and circularity) for the 0–100, 100–200, 200–300 and 300–400-mm soil depths under purple alfalfa (ALF), 22-year-old Korshinsk peashrub (KOP₂₂) and 40-year-old Korshinsk peashrub (KOP₄₀) treatments in the northern Loess Plateau of China

Property	Depth / mm	ALF					KOP ₂₂					KOP ₄₀				
		Mean	Max.	Min.	SD	CV	Mean	Max.	Min.	SD	CV	Mean	Max.	Min.	SD	CV
Macroporosity / %	0–100	0.62	2.21	0	0.54	0.87	3.28	9.22	0.66	2.50	0.76	2.90	7.16	0.60	1.87	0.65
	100–200	0.46	5.30	0.01	0.68	1.47	1.12	8.93	0.11	1.76	1.57	3.26	20.22	0.51	3.67	1.13
	200–300	0.79	4.02	0	0.89	1.12	0.79	3.25	0.17	0.62	0.78	2.18	12.96	0.11	2.93	1.34
	300–400	0.74	4.14	0.06	0.86	1.16	0.85	2.68	0.24	0.59	0.69	0.89	2.47	0.05	0.70	0.78
Largest pore area / mm ²	0–100	18.3	63.0	0	16.7	0.91	110.0	419.0	7.5	113.9	1.04	88.3	281.5	12.0	70.2	0.80
	100–200	14.8	51.5	0.5	14.1	0.95	28.2	364.5	2.0	57.2	2.03	103.1	750.5	13.0	134.0	1.30
	200–300	27.0	233.0	0	35.5	1.31	19.4	188.5	2.0	27.5	1.42	90.5	704.4	1.5	148.8	1.64
	300–400	25.4	231.5	2.5	36.1	1.42	21.8	81.1	2.5	21.8	1.00	29.5	104.0	1.0	29.5	1.00
Macropore count / N	0–100	7	15	0	4	0.57	24	54	10	9	0.38	22	82	4	22	1.00
	100–200	4	14	1	3	0.75	14	34	5	7	0.50	15	100	6	12	0.80
	200–300	6	24	0	4	0.67	14	33	5	6	0.43	21	48	4	9	0.43
	300–400	7	22	1	5	0.71	15	38	7	7	0.47	12	32	2	7	0.58
Circularity	0–100	0.93	1.00	0.74	0.05	0.06	0.89	0.99	0.80	0.04	0.04	0.90	0.98	0.71	0.05	0.05
	100–200	0.93	1.00	0.50	0.09	0.09	0.93	1.00	0.81	0.04	0.04	0.91	0.99	0.80	0.04	0.05
	200–300	0.94	1.00	0.76	0.05	0.05	0.93	1.00	0.77	0.04	0.04	0.94	1.00	0.82	0.04	0.04
	300–400	0.94	1.00	0.81	0.05	0.05	0.95	0.99	0.86	0.03	0.03	0.94	1.00	0.83	0.05	0.05

Max., Min., SD and CV denote maximum, minimum, standard deviation and coefficients of variation, respectively.

KOP₄₀, respectively. For the 300–400-mm depth, the difference in mean values between KOP₂₂ and KOP₄₀ is not marked (Table 3). Soil under ALF has larger means for macroporosity and largest pore area for the 300–400-mm than for the 0–100-mm depths. In contrast, these values decrease by 77 and 68% from the first to the fourth soil depths, respectively, under the two KOP treatments (Table 3).

Figure 2(a,b) also shows similar trends of macroporosity and largest pore area to those in Table 3, and provides more detail on the macropores. For soil under KOP₄₀, the CT traces of macroporosity and largest pore area are irregular, with six maxima for the 90–240-mm soil depth. In contrast, the traces change little below a depth of 110 mm under KOP₂₂. The values of macroporosity and largest pore area for soil under ALF are smaller than those for the KOP treatments, especially for the 20–120-mm depth (Figure 2a,b).

The average values for macroporosity (0.64%, ALF; 0.78%, KOP₂₂; 0.85%, KOP₄₀) and largest pore area (22.8 mm², ALF; 19.7 mm², KOP₂₂; 25.6 mm², KOP₄₀) below 285 mm are smaller than those above (Figure 2a,b). Furthermore, macroporosity was correlated with the largest pore area (not shown in the tables). The coefficients of determination between macroporosity and largest pore area are 0.807 (ALF), 0.847 (KOP₂₂) and 0.908 (KOP₄₀). The results suggest that the distribution of macroporosity is strongly affected by the largest pore area.

Number of macropores

The macropore count varied with treatment and soil depth. The KOP₄₀ and KOP₂₂ treatments have an average of 18 and 17 macropores, respectively, whereas ALF has only 6. The macropore

Table 4 Root surface area density, average diameter and length density of 22-year-old Korshinsk peashrub (KOP₂₂) and 40-year-old Korshinsk peashrub (KOP₄₀) for the 0–100, 100–200, 200–300 and 300–400-mm soil depths in the northern Loess Plateau of China

Depth (mm)	Root surface area density / mm ² cm ⁻³		Average root diameter / mm		Root length density / mm cm ⁻³	
	KOP ₂₂	KOP ₄₀	KOP ₂₂	KOP ₄₀	KOP ₂₂	KOP ₄₀
0–100	0.18	0.19	1.68	2.67	0.10	0.14
100–200	0.21	0.36	2.99	4.97	0.03	0.02
200–300	1.05	0.12	3.18	1.27	0.18	0.09
300–400	0.73	0.27	2.32	1.92	0.22	0.10

Figure 3 Typical cross-sections of scanned images of soil under ALF (purple alfalfa), KOP₂₂ (22-year-old Korshinsk peashrub) and KOP₄₀ (40-year-old Korshinsk peashrub) for cores at four selected soil depths (20, 120, 220 and 320 mm) in the Loess Plateau. Macropores are shown in black, solid particles in grey and stones in white.

count along the 360-mm depth under KOP₄₀ varies between two and 100. This range is much greater than that under KOP₂₂ and ALF (Table 2). Soil under KOP₂₂ has 3.4, 3.5, 2.3 and 2.1 and KOP₄₀ 3.1, 3.8, 3.5 and 1.7 more macropores than ALF at depths 0–100, 100–200, 200–300 and 300–400-mm, respectively (Table 3). The average macropore counts under ALF, KOP₂₂ and KOP₄₀ treatments at depth 0–100 mm are 60, 30 and 60%, respectively, larger than those at the other three depths (Table 2). For soil under KOP₂₂ and KOP₄₀, the macropore count at the 300–400-mm depth decreased by 38 and 46%, respectively, compared with the 0–100-mm depth. The average macropore count at the first depth, however, is equal to that at depth four under ALF (Table 3).

Figure 2c shows that the trace for macropore count and soil depth is relatively steady for soil under ALF. In contrast, it fluctuates markedly within the 20–40-mm soil depth under KOP₄₀ and the maximum value is at the 110–130-mm depth (Figure 2c). The

average macropore count under KOP₂₂ is close to that under KOP₄₀, with averages of 17 and 18 macropores, respectively, for the 360-mm soil depth. The values are similar for several depth ranges, which is depicted by the intersections of the two lines (Figure 2c). The maximum values of macropore counts under KOP₄₀ are larger than those under KOP₂₂ at depths 0–100, 100–200 and 200–300 mm.

Circularity

Circularity is an important characteristic of pore shape. The average macropore circularity for the three treatments was in the order ALF > KOP₂₂ > KOP₄₀. The circularity of macropores under ALF (0.93) is larger than that under KOP₂₂ (0.89) and KOP₄₀ (0.90) at the first depth. The circularity of macropores under KOP₂₂ (0.93) is approximately the same as that for ALF (0.93) at depth two (Table 3). Furthermore, the average macropore circularity increases with increasing soil depth (Tables 2 and 3). For soil under ALF, the variation in macropore circularity with soil depth is minimal (0.93–0.94). Macropore circularity increases by 6.1 and 4.1% (Table 3) from the first to the fourth depths in soil under KOP₂₂ and KOP₄₀. The larger circularity at the first depth under ALF could facilitate the infiltration of water into the deeper soil layers.

Inner visualization and three-dimensional quantification

The cross-section, profile and three-dimensional images of the macropores are plotted in Figures 3–5, respectively. Different types of macropore were observed for the three treatments. Figure 3 shows that macroporosity under KOP₄₀ is greater than that under KOP₂₂, which in turn is larger than that under ALF at the 20-mm soil depth. For the 120- and 220-mm depths, the macroporosity is greater under KOP₄₀ than under KOP₂₂, which has a macroporosity value similar to that under ALF. For profile images (where two images were used per plant), Figure 4 shows that the largest pore areas under KOP₄₀ are larger than those under KOP₂₂ and ALF, especially at the 0–300-mm depth. In contrast to the large macropores for KOP₄₀, most of the macropores under KOP₂₂ resembled threadlike channels that reflect the growth route of fine roots. The macroporosity for the fourth depth is small for all treatments (Figures 3 and 4).

Macropore surface area, branch and junction densities and connectivity were derived from three-dimensional macropore

Table 5 Macropore surface area density, branch density, connectivity and junction density derived from three-dimensional images of macropores in soil under purple alfalfa (ALF), 22-year-old Korshinsk peashrub (KOP₂₂) and 40-year-old Korshinsk peashrub (KOP₄₀) treatments in the northern Loess Plateau of China

Property	Surface area density / $\text{mm}^2 \text{cm}^{-3}$	Branch density / N cm^{-3}	Junction density / N cm^{-3}	Connectivity
ALF	4.81	0.04	0.01	45.28
KOP ₂₂	11.27	0.07	0.03	151.31
KOP ₄₀	30.43	0.18	0.08	339.49

images (Table 5). Mean macropore surface area density under ALF treatment is the smallest ($4.81 \text{ mm}^2 \text{cm}^{-3}$); it is $\sim 42\%$ of KOP₂₂ ($11.27 \text{ mm}^2 \text{cm}^{-3}$) and $\sim 16\%$ of KOP₄₀ ($30.43 \text{ mm}^2 \text{cm}^{-3}$) mean surface area densities (Table 5). Both branch and junction densities varied with treatment. Table 5 shows that soil under KOP₄₀ has 2.6 and 4.4 times more branches and 3.4 and 8.3 times more junctions than soil under KOP₂₂ and ALF treatments, respectively. Macropore continuity affects water flow and solute transport in soil, which also varied with treatment. The connectivity was validated by creating simple connected structures and measuring the related Euler characteristics. The connectivities in soil under KOP₄₀, KOP₂₂ and ALF are 339.49, 151.31 and 45.28, respectively. The large connectivity under KOP₄₀ suggests more continuous pores in the soil system.

The three-dimensional visualization of macropores is shown in Figure 5. Macropore characteristics are different for the three different treatments. The two sample cores under KOP₄₀ have more abundant and continuous macropores than those under the other two treatments (Figure 5). Macropores under KOP₂₂ and KOP₄₀ treatments are more evenly distributed along the soil profile

in the core than those under ALF. Moreover, different forms of macropores were observed. Soil under ALF has the smallest connectivity, the most random distribution of pores and fewer continuous pores (Figure 5, Table 5). These are inter-aggregate macropores formed through repeated freezing and thawing or wetting and drying (Luo *et al.*, 2010). Compared with continuous macropores, this form of macropore does not facilitate infiltration.

Discussion

Macropore characteristics

Macropores are preferential pathways for movement of water to depth in the soil following a rain event, which can reduce surface runoff (Li *et al.*, 2009). With improved macropore characteristics, more rainwater can infiltrate the soil. Li & Shao (2006) showed that soil physical properties can be improved by successions of natural vegetation from pioneer grassland to climax forest. The improvement can be attributed to enhanced root development, soil biological activity and root decay (De Gryze *et al.*, 2006). Seobi *et al.* (2005) observed that total porosity of grass and agroforestry buffer zones at 0–76.2-mm soil depth was three times greater than that of crop buffer zones. Udawatta *et al.* (2006) noted that average macropore counts under crops, grass and trees were 10, 14 and 36, respectively.

In this study, macroporosity under ALF (0.65%) and KOP (1.91%) was less than that under grass (1.5%) and tree (3.5%) buffer zones reported by Udawatta *et al.* (2006). The macropore counts under ALF (6) and KOP (17) were smaller than those reported for the grassland in inner Mongolia (Hu *et al.*, 2015). In general, fewer macropores and less macroporosity decrease water transmission and increase surface runoff. Udawatta *et al.* (2006) observed that there were no significant differences in macropores at different

Figure 4 Longitudinal cross-sections of core samples taken under ALF (purple alfalfa; (a) and (b)), KOP₂₂ (22-year-old Korshinsk peashrub; (c) and (d)) and KOP₄₀ (40-year-old Korshinsk peashrub; (e) and (f)) vegetation in the Loess Plateau. Macropores are shown in black, solid particles in grey and stones in white in the images.

Figure 5 Three-dimensional images of the 0–360-mm depth soil cores under ALF (purple alfalfa; (a) and (b)), KOP₂₂ (22-year-old Korshinsk peashrub; (c) and (d)) and KOP₄₀ (40-year-old Korshinsk peashrub; (e) and (f)) vegetation in the Loess Plateau. Macropores are shown in blue and solid particles in white in the three-dimensional images.

depths under agroforestry and grass buffer systems. Similarly here, macropore properties under ALF did not vary greatly with soil depth. However, there were large differences between the first and the fourth depths under KOP₂₂ and KOP₄₀ (Table 3). This suggested that the soil under the KOP treatments had a better macropore structure than that under ALF. The older vegetation was associated with macropore enlargement because of the stronger and larger roots, as in KOP₄₀.

More irregular pores result in more resistance to flow because of the greater pore-wall surface area. Luo *et al.* (2010) noted that macropores formed by roots were continuous and round. In this study, KOP increased irregular macropores in the soil more than for ALF. Rachman *et al.* (2005) observed 10% less circularity in soil under grass than in soil under crops in Iowa, USA. The larger is the pore, the smaller is the probability that it will be round (Lebron *et al.*, 2002). Our results support the observation that the pore circularity of soil under woody plants (KOP) is less than that under herbaceous plants (ALF). Macropores at greater soil depths tend to be more circular than those at shallower depths (Rachman *et al.*, 2005). In this study, soil depth did not have an adverse effect on macropore circularity under ALF treatment, but it increased slightly with depth under the KOP treatments (Table 3). Kim *et al.* (2010) noted that circularity under arable land was less (0.77–0.80) than that under ALF (0.89) and KOP (0.95). Pore shape, roughness and circularity could change with aggregation, root activity and macrofauna activity (Rachman *et al.*, 2005).

The conductivity of macropores in terms of water flow depends strongly on their three-dimensional geometry and topology.

Quantification of the three-dimensional macropore network has improved our understanding of soil structure under different vegetation covers. Surface area ($230 \text{ mm}^2 \text{ cm}^{-3}$) and branch (279 cm^{-3}) and junction densities (117 cm^{-3}) observed by Munkholm *et al.* (2012) in an undisturbed field soil were far larger than those for KOP₄₀ in this study ($30.43 \text{ mm}^2 \text{ cm}^{-3}$, 0.18 cm^{-3} and 0.08 cm^{-3} , respectively). Differences between these results and ours could arise partly from the differences in soil porosity and CT scanner resolution.

Soil properties

Soil organic matter contents reported by Udawatta *et al.* (2006), Kim *et al.* (2010) and Hu *et al.* (2015) were larger than those observed in our study ($1.9\text{--}13.9 \text{ g kg}^{-1}$). Organic matter content decreased with increasing soil depth (Table 1). Positive correlations have been shown between organic matter content and soil pore properties by others (Luo *et al.*, 2010; Zhao *et al.*, 2010; Ruan *et al.*, 2015). The larger organic matter content at the first soil depth corresponded to larger macropore counts under KOP₂₂ and KOP₄₀ in our study (Table 3). Unlike the organic matter content, however, macropore properties do not decrease consistently with increasing soil depth. This could be because of the much smaller organic matter contents in our samples ($2.6\text{--}10.1 \text{ g kg}^{-1}$) (Table 1) than those reported by Luo *et al.* (2010) ($5\text{--}75 \text{ g kg}^{-1}$), Zhao *et al.* (2010) ($17\text{--}73 \text{ g kg}^{-1}$) and Ruan *et al.* (2015) ($2\text{--}82 \text{ g kg}^{-1}$). This suggested that macropore structure was not affected primarily by organic matter content in the Liudaogou Catchment (Table 1).

Root properties

The plant root system is critical for the development of soil macropores by root decay and penetration to depth in the soil. Table 4 shows that root properties for the four soil depths under KOP treatments varied greatly. The root volume ratio varied from 0.01% at the second depth under KOP₂₂ to 0.14% at the first depth under KOP₄₀. The observed range in this study was smaller than that (0.03–0.28%) reported by Ji *et al.* (2012) in a study on Black locust (*Robinia pseudoacacia* L.) and Oriental arborvitae (*Platycladus orientalis* L.) root systems in Ji County in the Loess Plateau. The correlation between roots and macropore properties could be affected by inter-aggregation of macropores and other bio-pores such as ant tunnels (Tschinkel, 2003), but this was not so in our study. Root characteristics were not consistent with the distribution of macropores and did not agree with observations from the images (Figures 4 and 5).

The root biomass for different regions of the Loess Plateau had a vertical distribution similar to that we observed for ALF. In general, the root biomass of ALF decreased with increasing soil depth (Walley *et al.*, 1996; Wan *et al.*, 2004; Wu *et al.*, 2007). However, the distribution of macroporosity and macropore counts under ALF in this study did not decrease with increasing soil depth (Table 3). The contrast between macropore and root property distributions could result from differences in the scanned macropore structure and real root structure. Determination of the correlations between root indices and macropore properties could foster better understanding of pore structure in relation to vegetation growth in the Loess Plateau.

Conclusions

The restoration of Korshinsk peashrub improved soil macroporosity, macropore counts, largest pore area, surface area density, macropore branch density, junction density and connectivity more than for ALF. The longer the restoration time of KOP, the better were the macropore properties. Macropore counts, however, were approximately the same for KOP₂₂ and KOP₄₀. Compared with KOP₂₂, KOP₄₀ affected soil macroporosity and the largest pore area positively at the 110–255-mm depth. The results of this study should improve our understanding of soil macropore structure at depth in the northern Loess Plateau. This knowledge could in turn be used to devise strategies for sustainable recovery of vegetation and reduce soil erosion in this region.

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