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Characteristics of rock fragments in different forest stony soil and its relationship with macropore characteristics in mountain area, northern China

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Abstract: Rock fragments have major effect on soil macropores and water movement. However, the characteristics of rock fragments and their relationship with macropore characteristics remain elusive in forest stony soils in northern mountainous area of China. The objectives of this study are to (1) use Industrial Computed Tomography (CT) scanning to quantitatively analyze rock fragment characteristics in intact soil columns in different forest lands and (2) identify the relationship between characteristics of rock fragments and that of the macropores. Intact soil columns that were 100 mm in diameter and 300 mm long were randomly taken from six local forest stony soils in Wuzuolou Forest Station in Miyun, Beijing. Industrial CT was used to scan all soil column samples, and then the scanned images were utilized to obtain the three-dimensional (3D) images of rock fragments and macropore structures. Next, the parameters of the rock fragments and macropore structure were measured, including the volume, diameter, surface area, and number of rock fragments, as well as the volume, diameter, surface area, length, angle, tortuosity and number of macropores. The results showed that no significant difference was found in soil rock fragments content in the 10-30 cm layer between mixed forest and pure forest, but in the 0-10 cm soil layer, the rock fragments in mixed forest were significantly less than in pure forest. The number density of macropores has significant negative correlation with the number of rock fragments in the 0-10 cm soil layer, whereas this correlation is not significant in 10-20 cm and 20-30 cm soil layers. The volume density of macropore was not correlated with the volume density of rock fragments, and there is no correlation between the density of macropore surface area and the density of rock fragment surface area. Industrial CT scanning combined with image processing technology can

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provide a better way to explore 3D distribution of rock fragments in soil. The content of rock fragments in soil is mainly determined by parent rocks. The surface soil (0-10 cm) of forest contains fewer rock fragments and more macropores, which may be caused by bioturbation, root systems, gravitational settling and faunal undermining.

Keywords: Rock fragment; Macropore; Forest stone soil; Mountain area; Industrial Computed Tomography

Introduction

Soil system is relevant to most pressing global issues such as water resources, climate change, land management, food security and human health (Mol 2012; Keesstra et al. 2016). Moreover, the soil system controls the earth cycles by affecting the hydrological cycle, erosion, biodiversity and geochemistry; therefore, the United Nations believes that soil management is closely related to sustainable development (Keesstra et al. 2016). Soil water infiltration is a critical component of the hydrological cycle, which is affected by the presence of rock fragments. Rock fragments refer to crushed stone particles that are smaller than 2 mm (Miller et al. 1984) and can influence the hydrographic features of soil by affecting the density and radius of macropores (Luo et al. 2010; Flanagan et al. 1995; Eriksson et al. 1996; Shi et al. 2012). Macropores are defined as pores larger than 0.3 mm, and they play a crucial role in the transport of soil water, solutes, pollutants and chemicals. For pores at this size, the soil loses its ability to repel water (De Witte 2003). The rock fragment content of soil is very high in the Rocky Mountain Area in northern China. For instance, the amount of gravelly soil in rock area in Beijing, China is more than 22% (Fu et al. 2005). Rock fragments not only affect soil physical properties but also have a direct impact on soil hydrological characteristics (Torri et al. 1994; Valentin 1994; Ingelno et al. 1994; Perez 1998). Therefore, rock fragments will affect soil infiltration, runoff and erosion (De Figueiredo et al. 1998; Govers et al. 2006; Bunte et al. 1993; Brakensiek et al. 1994; Descroix et al. 2001; Cerdà 2001). Rock fragments also can influence the hydrological characteristics of soil by effecting the radius and density of macropores (Luo et al. 2010; Flanagan et al. 1995; Eriksson et al. 1996; Shi et al. 2012). Macropores can also be caused by plant root growth, and this also plays an important role in the determination of water flow processes (Stewart 1999; Bundt et al. 2001; Zhang et al. 2015).

However, the quantification of soil rock fragments remains challenging because of their complicated distribution and geometric features. Traditional methods such as the sieving method can only measure the size and volume of rock fragment, it is impossible to determine the position and geometry of rock fragments in soil. Moreover, soil is easily destroyed in the process of measuring rock fragments, so the 3D structure of macropores cannot be accurately obtained simultaneously.

In recent years, with technological advances in X-ray CT images, the analysis of the 3D structure of macropores has received increasing attention (Elyeznasni et al. 2012; Hu et al. 2015). Many researchers (Munoz-Ortega et al. 2015; Dal Ferro et al. 2015; Qiao et al. 2015; Ni et al. 2017; Hu et al. 2016) have used CT image analysis to quantify soil macropore characteristics including volume, surface area, diameter, and size distribution. However, most of the previous studies only explored the macropore structure of soil through CT scanning technology and the impact of macropores on soil hydrological function (Ji et al. 2016; Wang et al. 2016; Li et al. 2016; Ahmad 2016). Only by understanding the distribution characteristics of rock fragments in the soil can we identify the role of rock fragments in the process of soil moisture. In addition, the characteristics of macropores and rock fragments in forest soil can be quantified to explore the relationship between macropores and rock fragments. The impact of rock fragments on macropores and water transport in forest land also can be analyzed.

Soil rock fragment distribution is significantly different for different land use types (Govers et al. 2006). The structures of forest soil may differ in different forest communities (Meng et al. 2016). However, studies concerning interactions between forest communities and soil rock fragments are few, especially in the mountainous area in northern China. Previous studies have also neglected to quantify the relationship between rock fragments and macropores in soils in two-dimensional and three-dimensional forms. Therefore, the objectives of this study are to (1) use precise Industrial CT technology to quantify 3D soil rock fragment structures, (2) compare and analyze the characteristics and vertical variation of soil rock fragments in different forest communities and (3) explore the relationship between rock fragments and macropore network characteristics in forest stony soil of mountainous areas. This study was designed to improve understanding of the correlation between forest communities and rock fragment characteristics as well as the relationship between rock fragments and macropores in the mountainous area of northern China.

1 Materials and Methods

1.1 Experimental site and soil sampling

The experimental sampling site is located at Wuzuolou Forest Station in Beijing, Miyun (Figure 1). The region is semi-humid and semi-arid, with an annual mean temperature of 10.8°C and an annual precipitation of 661 mm. Vegetation coverage ranges from 40% to 60% in the study area. The cultivation period of typical plants such as *Pinus tabulaeformis, Castanea mollissima, Ulmus pumila* and *Juglans regia* is 55 years. The majority of rock in the study area is derived from Archean granite. The mountainous area is mainly covered by leptosols, according to the typology of the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009).

Six different forest community sites were selected for experimental sampling, and all sites have similar elevations, gradients, and slope directions. The forest community types include two mixed forests and four pure forests (Table 1). Intact soil cores were taken at six plots to measure soil bulk density and soil particle size distribution, and aluminum boxes of soil were taken to determine the moisture and nutrient content (Table 1). Soil cores were used to calculate fine root length density (Yan et al. 2011). Three soil columns were taken at each sample point, and a total of 18 soil columns with lengths of 300 mm and diameters of 100 mm were randomly selected. Details of the soil column acquisition process are described in Meng et al. (2016).

1.2 CT scanning and image analysis

An Industrial CT system (Beijing GranpectCo. Ltd., Beijing, China) was utilized to scan all undisturbed soil columns with an industrial CT system with an energy level of 450 kV and 10 mA. A continuous 0.215 mm was used as the scanning interval. 1024×1024 images with a voxel size of

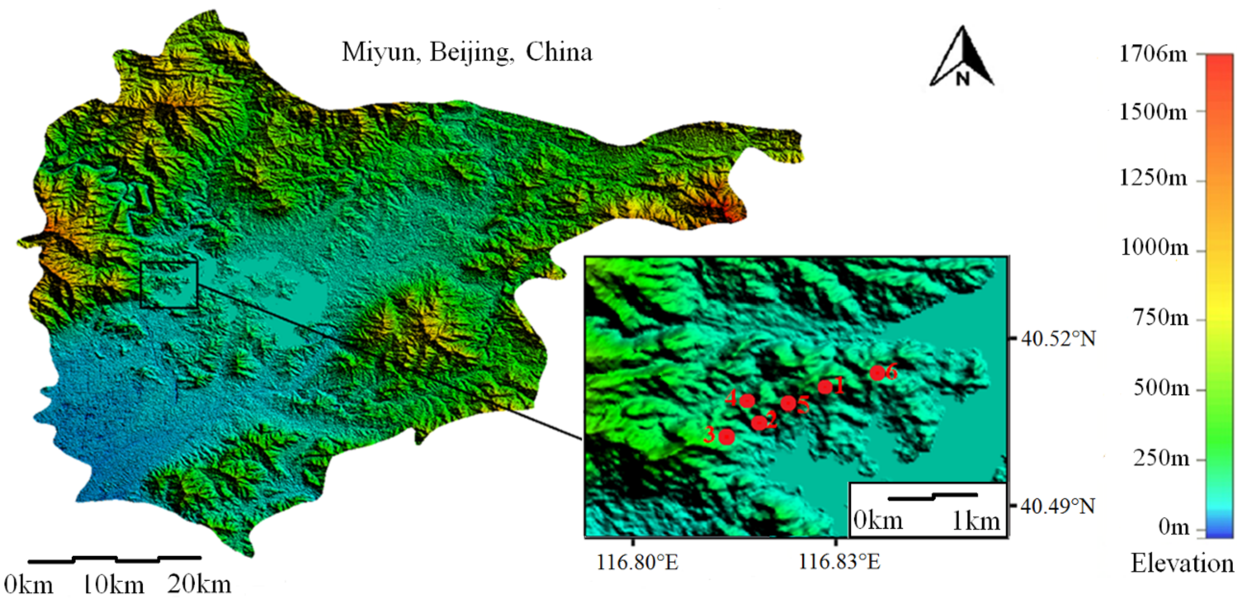

Figure 1 Study site and sampling position in Miyun, Beijing. Sampling sites: 1. mixed *P. tabuliformis, C. mollissim and U. pumila* forest; 2. mixed *P. tabulaeformis* and *C. mollissima* forest; 3. pure forest of *U. pumlia, 4.* pure forest of *C. mollissima, 5.* pure forest of *J. regia, 6.* pure forest of *P. tabuliformis.*

Table 1 Basic situation of sample plots (DBH is diameter at breast height of forest)

Sample number	Forest communities	Mean DBH (cm)	Canopy density (%)	Forest mean height (m)	Soil bulk density ($g \cdot cm^{-3}$)	Soil water content (%)	Soil organic matter (%)	Soil particle composition		
								Sand (%)	Silt (%)	Clay (%)
1	*P. tabuliformis, C. mollissim and U. pumila*	22.84	90	11.91	1.54	12.14	4.06	63.77	36.23	0
2	*P. tabulaeformis* and *C. mollissima*	25.63	90	10.29	1.61	12.58	3.27	72.82	27.18	0
3	*U. pumlia*	16.58	85	12.63	1.60	17.70	1.93	69.67	30.05	0.28
4	*C. mollissima*	28.34	80	8.64	1.54	14.04	1.16	91.34	8.66	0
5	*J. regia*	16.73	80	7.54	1.62	12.50	2.45	88.77	11.23	0
6	*P. tabuliformis*	24.46	85	11.25	1.65	15.64	1.64	55.57	44.32	0.11

0.137 mm × 0.137 mm × 0.200 mm were produced after scanning and reorientation.

The image analysis was conducted by using commercially available software (VGStudio Max 2.2, Volume Graphics GmbH, Heidelberg, Germany). The region of interest (ROI) tool of VGStudio Max 2.2 was used to select the observation range, and 5 mm at edges and 35 mm at both ends was removed to avoid the impact of any artificial forces caused by the pipe wall. A value of 75 was chosen as the maximum threshold range of macropores, and 165 was the minimum size to be considered a rock fragment (within the range of 0–255). The threshold of rock fragments was determined by observing the threshold of known rock fragments in the soil column, and the threshold of the macropores was determined by observing the threshold of an artificial macropore (Hu et al. 2015; Hu et al. 2016). These images were inspected visually to ensure that these threshold values are reasonable. Then, 3D rendering and visualization of macropores and rock fragments were obtained. Next, the characteristics of macropore (pore diameter ≥ 0.3 mm) and rock fragments (particle size ≥ 2mm) were calculated using the Particle Analysis tool of VG Studio Max 2.2. The volume, diameter, number, and distribution of macropores and rock fragments were obtained. The surface area of macropores and rock fragments was estimated through the Analyze Particles tool in ImageJ2x.The methodology of angle and mean tortuosity calculation for macropore is described in Meng et al. (2016).

After the experiment was completed, the soil column was divided into three sections (0-10 cm, 10-20 cm, 20-30 cm), the rock fragments were washed out with a 2 mm soil screen, and the surface water was dried. Then the volume of total rock fragments was measured by the drainage method, and the volume density was calculated.

1.3 Statistical analysis

Differences in soil rock fragments between different forest communities were analyzed using the Independent-Samples T Test (SPSS 22.0 for Windows). The relationship between rock fragment characteristics and macropore characteristics was tested using the Spearman's rank correlation coefficient test. A Reliability Analysis was used to determine the confidence degree of the calculated value for the rock fragment volume in the soil samples. Differences at the p=0.05 were considered statistically significant.

2 Results

2.1 Visualization of rock fragment

3D images of rock fragments were produced by Industrial CT scanning. Figure 2 showed 3D distribution characteristics of rock fragments in soil column in six forest communities. The 3D visualization reveals that there are significant differences in the distribution of soil's rock fragments among different forest communities. The average volume density of rock fragments (volume of rock fragment in unit volume of soil) in mixed *P. tabulaeformis*, *C. mollissima* and *U. pumila* forest; mixed *P. tabulaeformis* and *C. mollissima* forest; pure forests of *U. pumila*; *C. mollissima*; *J. regia* and *P. tabulaeformis* were 0.3436±0.0783 $mm^3 \cdot cm^{-3}$, 1.1038±0.1846 $mm^3 \cdot cm^{-3}$,

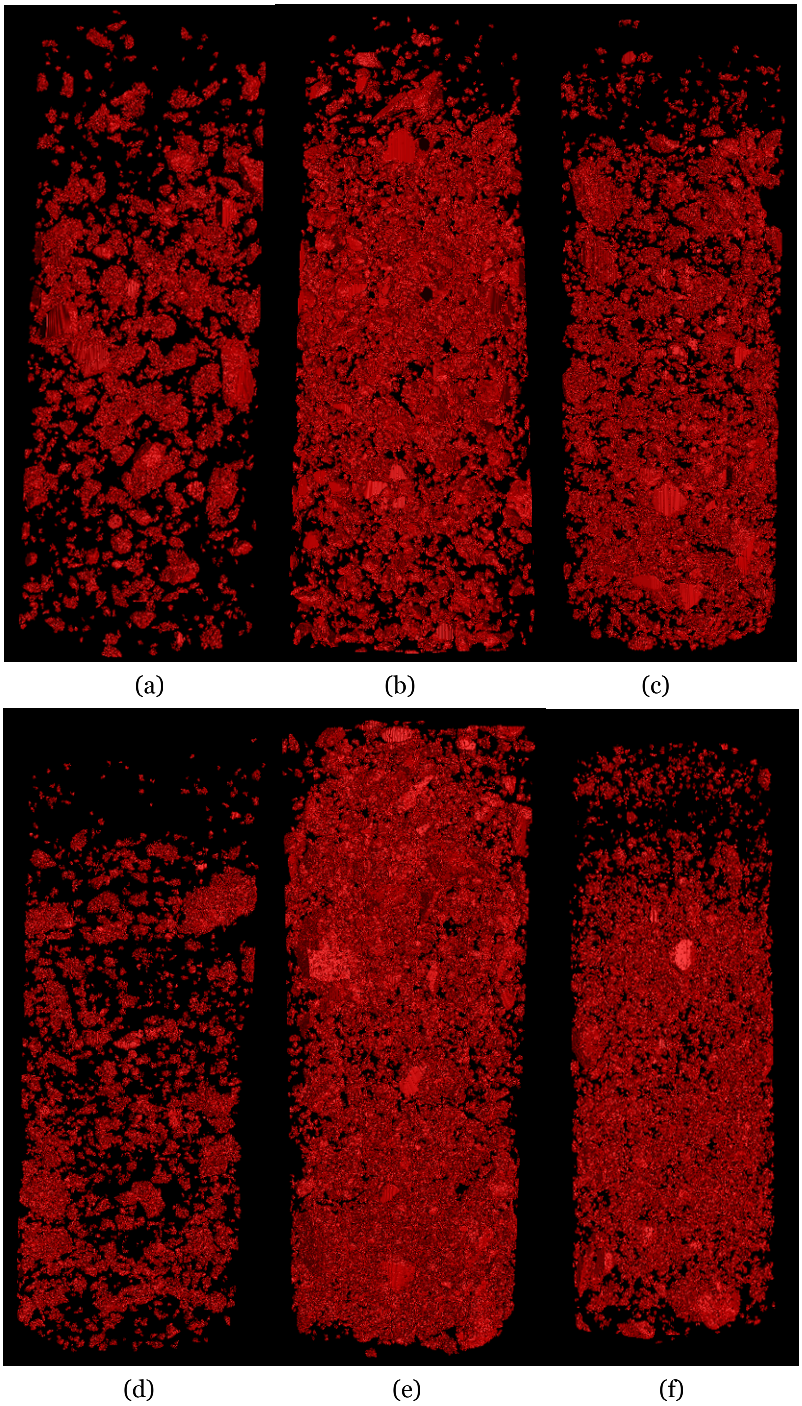

Figure 2 3-D visualization of soil rock fragment for the soil columns of mixed forest communities (*P. tabuliformis, C. mollissim and U. pumila* (a), *P. tabulaeformis* and *C. mollissima* (b)) and pure forest communities (*U. pumlia* (c), *C. mollissima* (d), *J. regia* (e) and *P. tabuliformis*(f)). The red is rock fragment and the black is not rock fragment.

0.8494±0.1632 $mm^3 \cdot cm^{-3}$, 1.1191±0.4358 $mm^3 \cdot cm^{-3}$, 1.2860±0.7605 $mm^3 \cdot cm^{-3}$ and 0.7272±0.2762 $mm^3 \cdot cm^{-3}$, respectively. The rock fragments content in mixed *P. tabulaeformis*, *C. mollissima* and *U. pumila* forest was significantly lower than that in the other pure forests, whereas the number of rock fragments in mixed *P. tabulaeformis* and *C. mollissima* forest was higher than that in pure forests of *U. pumila* and *P. tabulaeformis*.

2.2 Rock fragment volume, diameter, surface area and number

The total volume of rock fragments in these six sampling forest communities is displayed in Figure 3. The mixed *P. tabulaeformis, C. mollissima* and *U. pumila* forest has the smallest rock fragment volume density (Table 2), but the volume density of rock fragments in mixed *P. tabulaeformis* and *C. mollissima* was larger than either pure forest of *U. pumila* or pure forest of *P. Tabulaeformis*, and the T test showed that the volume density of rock fragments between mixed forest soil and pure forest soil was not significant ($p > 0.05$). Therefore, it is difficult to conclude that there is significant difference in soil rock fragment volume density between mixed forest and pure forest. But in the 0-10 cm layer, the volume density of rock fragment shows that the mixed forest soil is significantly higher than that of pure forest soil ($p < 0.05$). Among these six sampling sites, the volume density of rock fragments in the deep layer of soil was larger than that in the surface layer (Table 2). It is thus clear that the smaller rock fragment volumes were more likely to be found in the shallower soil layers.

The diameter density, surface area density, and number density of rock fragments varied among these different forest communities' soil. A

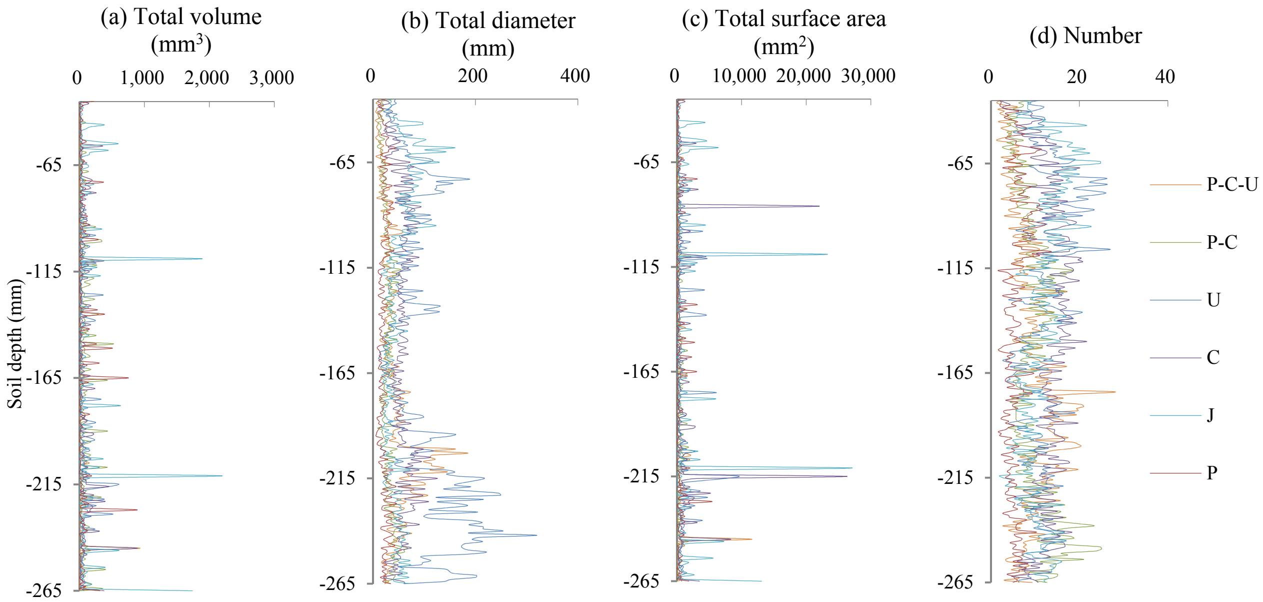

Figure 3 Total volume (a), total diameter (b), total surface area (c) and number (d) of rock fragment varied among the soil depth in 6 forest community soils. P-C-U is mixed *P. tabuliformis, C. mollissim and U. pumila* forest; P-C is mixed *P. tabuliformis and C. mollissim* forest; U, C, J, P is pure forest of *U. pumlia*, *C. mollissima*, *J. regia* and *P. tabulaeformis*, respectively.

trend that is similar to the volume density of rock fragments was found (Table 2 and Figure 3). The diameter density and surface area density showed similar vertical variation patterns to the volume density of rock fragments (Table 2 and Figure 3).

The results of this study suggest that rock fragments that are 2–3 mm in diameter accounted for 60.79%± 13.12% of total rock fragments in the soil of mixed *P. tabulaeformis, C. mollissima* and *U. pumila* forest and 53.44% ± 4.52% of total rock fragments in soil of mixed *P. tabulaeformis* and *C. mollissima* forest. In addition, rock fragments that are 2–3 mm in diameter accounted for 64.14% ± 6.08%, 55.89% ± 4.24%, 62.69 %± 2.33% and 57.47% ± 0.71% of total rock fragments in the soil of pure forest of *U. pumlia*, *C. mollissima*, *J. regia* and *P. tabulaeformis*, respectively (Figure 4). There was no significant difference in 2-3 mm particle size distribution of rock fragments between pure forest and mixed forest (p>0.05).

2.3 Relationship between rock fragments and macropores

The analysis of the number of macropores and rock fragments in forest soil (Figure 5a) found that the number of macropores was negatively correlated with the number of rock fragments in the 0-10 cm soil layer of mixed *P. tabulaeformis*, *C. mollissima* and *U. pumila* forest (r= - 0.460, p< 0.01), but positively correlated in the 20-30 cm soil layer (r=0.468, p<0.01). This correlation in the 0-10 cm soil layer of mixed *P. tabulaeformis*, *C. mollissima* forest was not significant (r=0.078, p=0.536), but was positively correlated in the 10-20 cm soil layer (r=0.583, p<0.01) and in the 20-30 cm soil layer (r=0.468, p<0.01). The number of soil macropores had a significant negative correlation with number of rock fragments in the 0-10 cm soil layer of pure forest of *U. pumlia* (r= - 0.427, p < 0.01), but it had no significant correlation in the 10-20 cm soil layer (r=0.149, p=0.137) and the 20-30 cm soil layer (r=0.197, p=0.115). There is no correlation between number of macropores and number of rock fragments in the 0-10 cm soil layer (r= - 0.114, p=0.368), the 10-20 cm soil layer (r=0.197, p=0.115) and the 20-30 cm layer (r=0.197, p=0.115) in the pure forest of *C. mollissima*. It was not significant in 0-10 cm soil layer (r=0.117, p=0.243), positively correlated in the 10-20 cm soil layer (r=0.480, p<0.01), and negatively correlated in the 20-30 cm soil layer (r= - 0.635, p<0.01) in pure forest of *J. regia*. For a pure forest of *P. tabulaeformis*, this correlation was not significant in the 0-10 cm soil layer (r=0.032, p=0.802) and the 20-30 cm soil layer

Table 2 Characteristics of rock fragment and root length in different forest land soil

Forest community type	Soil depth (cm)	Rock fragments					
		Diameter density (mm•cm-3)	Surface area density (mm2•cm-3)	Number density (number•cm-3)	Volume density calculated by CT (mm3•cm-3)	Volume density calculated by drainage method (mm3•cm-3)	Root length density (cm·cm-3)
P. tabuliformis, C. mollissim and U. pumila	0~10	3.0703±0.8966	1.6566±1.8871	0.7436±0.2662	1.1888±0.7000	3.8559±2.0657	5.28±0.38
	10~20	5.7698±2.8094	2.9480±2.4280	1.7918±1.2763	2.4438±0.2183	6.4322±3.0859	3.80±0.37
	20~30	10.0080±4.5362	10.3456±8.7021	1.4711±1.2681	7.4738±1.9927	7.1000±2.2448	3.31±0.42
P. tabulaeformis and *C. mollissima*	0~10	3.5247±1.4906	2.6694±2.2430	1.0315±0.6975	5.2908±1.3261	10.0330±1.5245	4.49±0.55
	10~20	4.9451±0.3636	6.9761±4.7612	1.4642±0.2194	14.4538±0.8009	13.1563±2.8139	3.12±0.84
	20~30	6.1278±3.4697	6.2937±5.6376	2.0090±1.3250	12.3782±4.2222	8.1112±4.3340	2.25±0.16
U. pumlia	0~10	11.7894±6.7914	6.7725±5.8096	2.2139±1.3815	5.5920±1.1526	6.0002±1.7748	2.13±0.13
	10~20	9.2827±2.4902	9.5758±8.3326	1.7336±0.2056	8.6017±1.8695	8.6653±3.9540	1.69±0.19
	20~30	22.6594±19.2464	15.4131±13.6864	1.5025±0.5410	11.8855±3.9572	9.8377±6.2199	1.58±0.82
C. mollissima	0~10	8.0266±0.9411	13.2871±14.4727	1.8864±0.9131	9.3072±1.5120	9.2171±3.9612	2.60±0.89
	10~20	8.6735±1.7500	9.8743±7.1865	2.4330±0.8334	9.4386±3.9527	8.4109±1.3492	1.55±0.45
	20~30	10.1092±3.6579	24.5396±12.4582	1.9518±0.2692	16.6321±8.3258	21.2784±14.0522	1.11±0.89
J. regia	0~10	11.2528±5.0497	13.1508±12.9763	2.3324±0.6004	11.8402±7.1486	13.6786±3.8428	2.35±0.88
	10~20	5.2470±1.6714	10.7832±5.1347	1.6875±0.7643	9.5892±2.5314	11.8631±5.9408	1.25±0.27
	20~30	7.2404±2.4820	22.9698±19.0291	1.5727±0.5215	19.9024±17.0458	21.3947±15.8895	1.07±0.71
P. tabuliformis	0~10	3.7963±0.5552	4.9855±4.1993	1.0590±0.5715	6.2979±1.5743	10.0044±3.0999	2.48±0.87
	10~20	2.7519±0.7233	4.8369±4.0505	0.7968±0.5278	7.3121±4.0898	6.8441±3.0438	1.12±0.38
	20~30	3.9619±1.6265	8.4479±4.1578	0.8186±0.5887	8.7421±3.1351	6.8758±2.4050	0.81±0.50

Notes: Diameter density of rock fragment means total diameter in unit soil column volume; Surface area density means total surface area in unit soil column volume; Number density means total number in unit soil column volume; Volume density means total volume in unit soil column volume; Root length density means total root length in unit soil column volume.

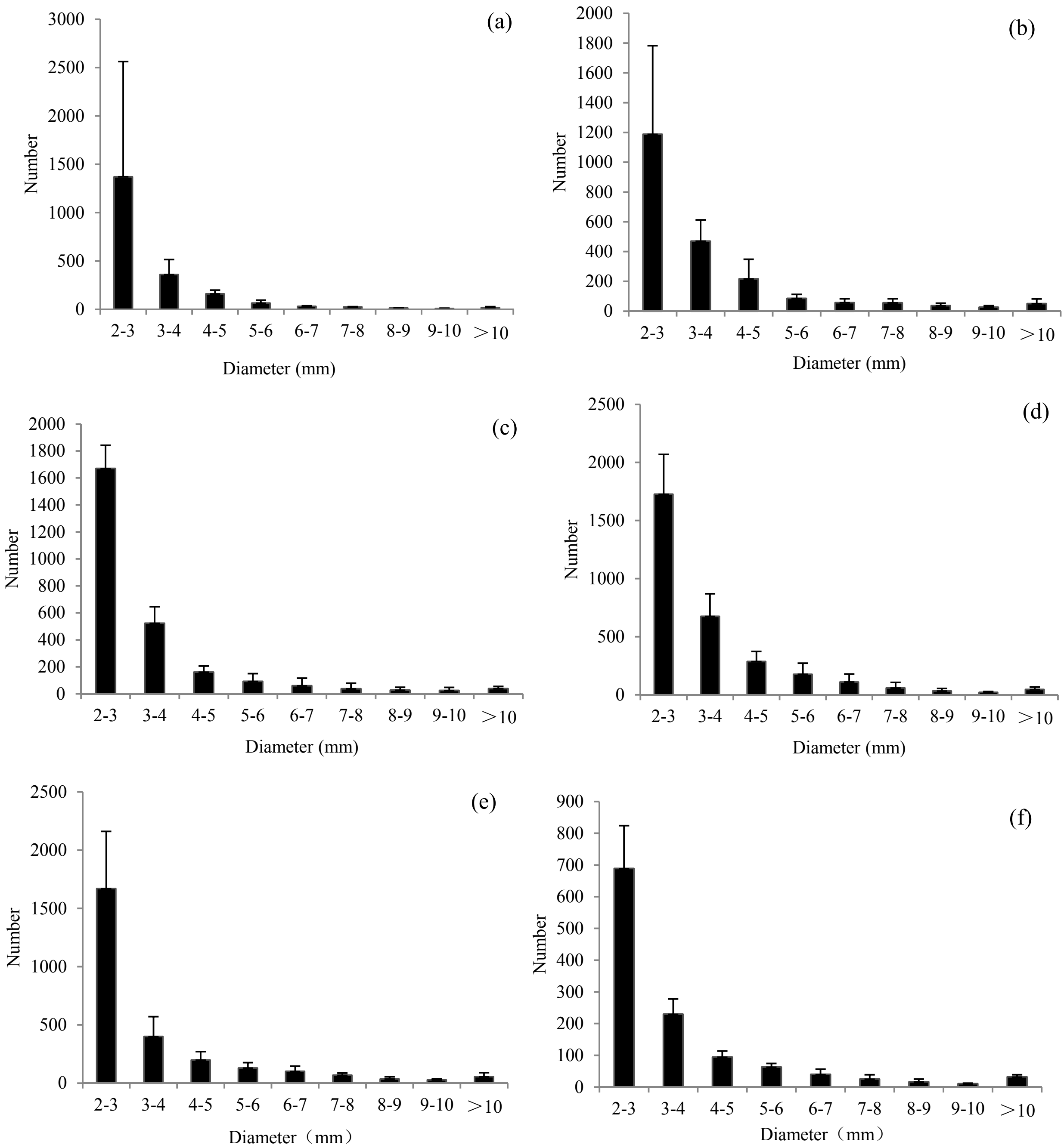

Figure 4 Diameter distribution of rock fragment in mixed forest communities (*P. tabuliformis, C. mollissim and U. pumila* (a), *P. tabulaeformis* and*C. mollissima f* (b)) and pure forest communities (*U. pumlia* (c), *C.mollissima* (d), *Juglansregia* (e) and *P. tabuliformis*(f)).

(r=-0.217, p=0.083). There was significant negative correlation between the number density of macropores and the number density of rock fragments in the 0-10 cm soil layer (r= - 0.666, p< 0.01), but there was no significant correlation between the 10-20 cm (r= - 0.036, p=0. 887) and the 20-30 cm (r=0.096, p=0.705) soil layers.

The relationship between the volume of macropores and volume of rock fragments in different forest soil was analyzed (Figure 5b). They were found to be negatively correlated in soil of mixed *P. tabulaeformis*, *C. mollissima* and *U. pumila* forest; the correlation coefficients were - 0.338 (p< 0.01), - 0.023 (p=0.817), and 0.142

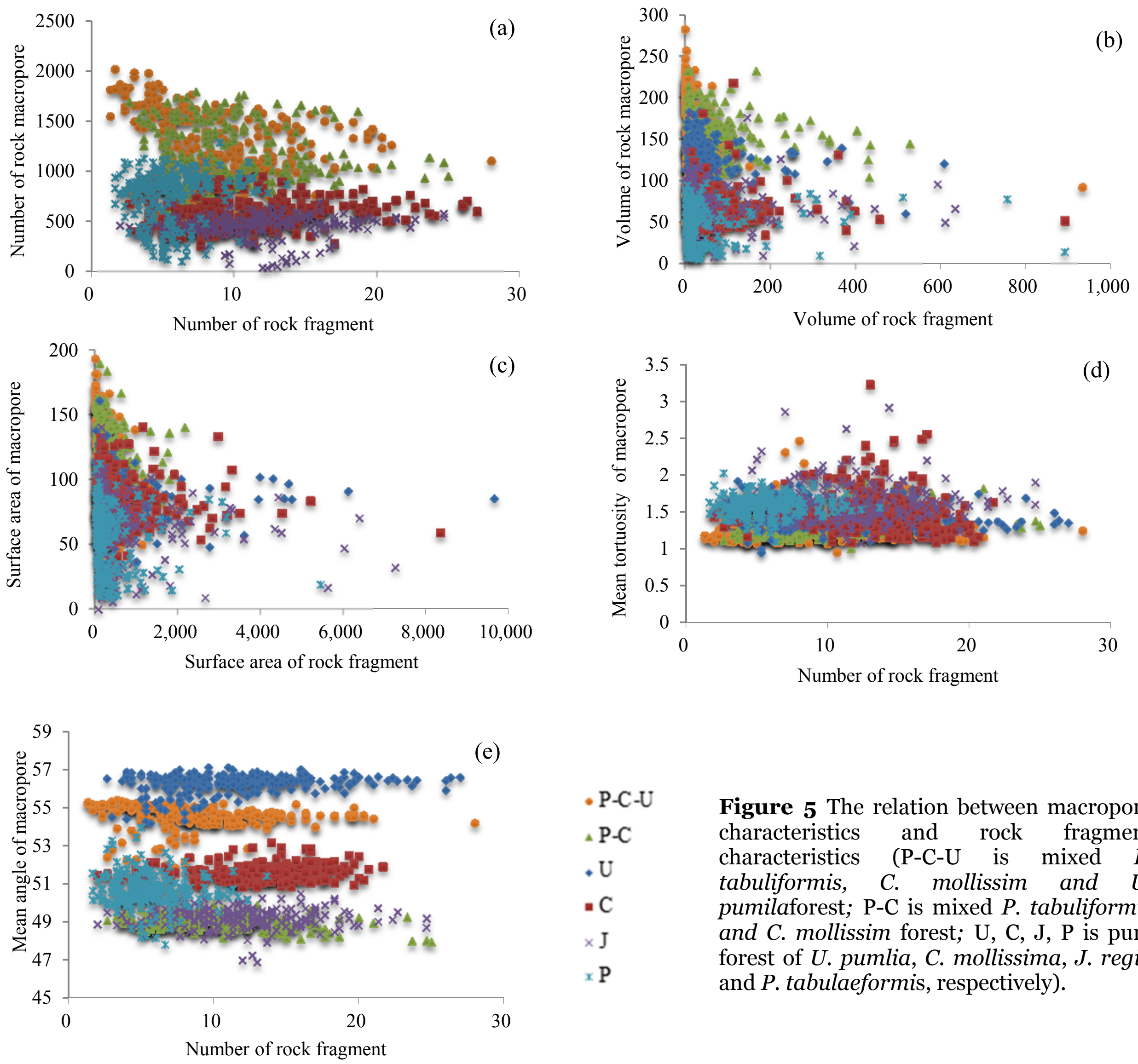

Figure 5 The relation between macropore characteristics and rock fragment characteristics (P-C-U is mixed *P. tabuliformis, C. mollissim* and *U. pumila*forest; P-C is mixed *P. tabuliformis and C. mollissim* forest; U, C, J, P is pure forest of *U. pumlia*, *C. mollissima*, *J. regia* and *P. tabulaeformis*, respectively).

(p=0.260) in the 0-10 cm, 10-20 cm, and 20-30 cm soil layers, respectively. The correlation between macropore volume and the volume of rock fragments was not significant in the three soil layers in the other five forest lands. There is no significant relationship between the volume density of rock fragments and the volume density of macropores.

Figure 5c showed that with the decrease of surface area of rock fragments, the surface area of macropore is increased. The relationship between soil macropores and rock fragments of the surface area in different forest lands was analyzed. The results showed that there was weakly positive correlation in the 0-10 cm soil layer (r= - 0.450, $p < 0.01$) and the 20-30 cm soil layer (r= - 0.296, $p < 0.05$) in mixed forest of *P. tabulaeformis*, *C. mollissima* and *U. pumila*, and there was no correlation in the 10-20 cm soil layers. It had weakly negative correlation in the 0-10 cm soil layer in the pure forest of *U. pumlia* (r= - 0.352, $p < 0.01$), but it had weakly positive correlation in the 20-30 cm soil layer (r=0.278, $p < 0.05$). It had very weakly positive correlation in the 20-30 cm soil layer in the pure forest of *C. mollissima* (r=0.267, $p < 0.05$) and had no correlation in the 0-10 cm and 10-20 cm layers. It had weakly negative correlation in the 20-30 cm soil layer in pure forest of *U. pumlia* (r= - 0.352, $p < 0.01$). The correlation between rock fragments and macropores in terms of surface area density was not significant in the three soil layers.

The comparison of the mean tortuosity of macropores and number of rock fragments (Figure 5d) found negative correlation in the 20-30 cm soil layer in mixed *P. tabulaeformis*, *C. mollissima* and *U. pumila* forest (r= - 0.440, p<0.01), whereas this correlation in the 20-30 cm soil layer in mixed *P. tabulaeformis* and *C. mollissima* forest was positive (r=0.357, p<0.01). And this correlation was not significant in the other four forest lands. At this point, it is hard to conceive of the overall relationship between the number of rock fragments and the tortuosity of macropores.

The analysis of the relationship between the mean angle of macropores and number of rock fragments (Figure 5e) found that the number of rock fragments has positive correlation with the mean angle of macropores in the 20-30 cm soil layer in mixed *P. tabulaeformis*, *C. mollissima* and *U. pumila* forest, but it has negative correlation in the 20-30 cm soil layer in mixed *P. tabulaeformis*, *C. mollissima* forest. This correlation in the 20-30 cm soil layer in pure forest of *U. pumila* was positive (r=0.529, p < 0.01). However, this correlation in the 10-20 cm soil layer in pure forest of *C. mollissima* was negative (r= - 0.509, p<0.01). It is hard to comprehend the overall relationship between the number of rock fragments and the mean angle of macropores.

3 Discussions

Industrial CT can be used to accurately observe the position and structural characteristics of rock fragments in soil column without destroying the soil. Volume, surface area, diameter, number and the distribution of rock fragments can be directly calculated. The characteristics of the angle and shape of rock fragments in the soil will be a focus of future studies. Although this study measured soil rock fragments using the industrial CT scanning method, the density of some hardened soil blocks was very close to rock fragments, which may introduce some error. We removed all rock fragments present in the soil columns and measured their volume density. Reliability analysis of volume density of rock fragment determined by CT method and drainage method was carried out, and we found that the Cronbach's Alpha is 0.924 and the Cronbach's Alpha Based on Standardized Items is 0.925. This means that the data obtained by the two methods have very high internal consistency, so the data of rock fragment volume density obtained by the CT method is reliable. In the future, we may need to optimize the method to distinguish the soil clods with high density to obtain more accurate images and data of rock fragments in soil.

Phillips et al. (2005) reported that soil rock fragments can be redistributed by the activities of roots of trees and other plants, and the root density in mixed forest is greater than that in pure forest soil (Hendriks et al. 1995). We also found that the soil root length density of the two mixed forests was higher than that of the four pure forest soils (Table 2). These two factors may result in a difference in soil rock fragment content between mixed forest and pure forest. However, this study showed that there is no obvious difference between mixed forest and pure forest. Therefore, in this study area, the content of rock fragments in soil may be mainly determined by parent rock material, and forest growth does not contribute much to the content of soil rock fragments.

Walmsley and Cerdà (2017) pointed out that earthworms have the potential to improve the infiltration function of soil by making macropores, mixing soil layers and soil aggregate. Cerdà and Jurgensen (2008; 2009) concluded that ants could increase the water infiltration and reduce soil loss, but other studies have shown that ants can increase soil erosion when rainfall intensity is greater than ants' macropore infiltration capacity (Cerdà and Jurgensen, 2011). Aalders et al. (1989) reported that the reduction of soil erosion by ants is more effective in vegetated areas. Bioturbation plays a crucial role in the redistribution of rock fragments in the surface soil (Phillips et al. 2005). Animal digging and burrowing can make soil rock fragments exhibit downward movement (Balek 2002; Johnson 1990; Leigh 1998). In addition, movement of rock fragments in the surface soil may be caused by gravitational settling and faunal undermining, which makes the surface soil contain fewer rock fragments. This can be used to explain the results of our research.

The characteristics of rock fragments in different forest communities and their relationships with macropores were analyzed in this study. The comparison of rock fragments and macropores in different forest lands shows that rock fragments in soil have some impacts on the generation and characteristics of macropores, especially for the mixed forest land. In the deep layer of soil, the number of macropores is not significantly positively correlated with the number of rock fragments, whereas there is a significantly positive correlation in the surface layer of soil. As for the surface layer of mixed forest land, they have a more significant negatively correlation than in pure forest land. More macropores can be found around the rock fragments, as shown in Figure 6. Therefore, rock fragments have some positive impact on the generation of macropores in the soil, and this is in agreement with the conclusions of previous studies (Shi et al. 2012). Vegetation cover can reduce soil loss, and vegetation index (NDVI) plays a direct role in sediment transport in forest land (Mekonnen et al. 2017; Masselink et al. 2017). The rock fragments of surface soil can make the herbaceous plants grow better (Danalatos et al. 1995). Bioturbation due to root activities and animal digging and burrowing has more impacts on the surface layer of soil. The pores produced by roots and biological activity make the soil softer, and gravitational settling is most likely in loose soils (Phillips et al. 2005). In other words, the rock fragments, roots activities and macropores influence each other. Rock fragments contribute to the generation of soil's macropores and limit the impact of root activities on the soil. In this study, the number density of rock fragments was significantly negatively correlated with the number density of macropores in the surface soil. This can be explained by more activities of roots, soil-inhabiting animals, and rock fragments being moved downward by bioturbation, gravitational settling, and faunal undermining, generating more macropores in this process. The characteristics of rock fragments are not significantly correlated with characteristics of macropores in areas with fewer activities of roots and soil animals. Our results show that the surface soil of forest land has less rock fragments than deep soil, and the smaller the content of rock fragments, the greater the content of macropores in the surface soil of forest land. Large amounts of macropores also reduce surface runoff and increase the infiltration (Yang et al. 2011). Therefore, the results of this study also imply that the infiltration function of surface soil is stronger than that of deep soil, which is conducive to the reduction of surface runoff but is more likely to lead to soil loss than deep soil. This hypothesis needs to be further verified through field data.

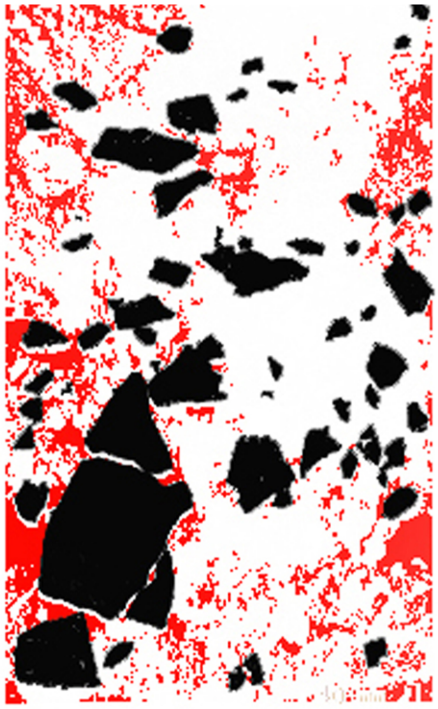

Figure 6 Two dimensional diagram of rock fragments and macropores (Black is rock fragment, red is macropore and white is other material).

In this study, it was clearly demonstrated that the topsoil has fewer rock fragments and more macropores in mixed forest land, which means that the infiltration capacity of mixed forest surface soil is stronger than that of pure forest soil; however, the soil loss is easily caused by the smaller amount of rock fragments in the surface soil of the mixed forest (Rodrigo comino 2017). For this reason, we believe that thinner soil is more suitable for planting pure forests to prevent soil loss, and the mixed forests are more beneficial to reducing surface runoff. Planting will lead to the removal of the rock fragments, which results in high erosion rates (Rodrigo comino 2016). According to the results of our study, we should pay more attention to the protection of the surface soil in forest stony land in the process of planting and later maintenance, thus reducing the loss of the surface soil.

4 Conclusions

The Industrial CT scanning method combined with image processing technology provided a better tool for exploring three-dimensional distribution of rock fragments in soil. There were no significant differences in the characteristics of soil rock fragments between mixed forests and pure forests. The content of rock fragments in soil seems to be mainly determined by parent rocks. The surface soil contains the lowest rock fragment content. The number density of rock fragments in the 0-10 cm soil layer in the mixed forest was negatively correlated with the number density of macropores. The surface soil (0-10 cm) of forest contains fewer rock fragments and more macropores, which may be caused by bioturbation, root system, gravitational settling and faunal undermining.

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References

Aalders IH, Augustinus PGEF, Nobbe JM (1989)The contribution of ants to soil erosion: a reconnaissance survey. Catena 16: 4-5, 449–459. https://doi.org/10.1016/0341-8162(89)90027-1

Ahmad, Muhammad Arslan (2016) Quantifying relationships between X-ray imaged macropore structure and hydraulic conductivity. Second cycle, A2E. Uppsala: SLU, Dept. of Soil and Environment.

Balek CL (2002) Buried artifacts in stable upland sites and the role of bioturbation: a review. Geoarchaeology 17: 41-51. https://doi.org/10.1002/gea. 10002

Brakensiek DL, Rawls WJ (1994) Soil containing rock fragments: effects on infiltration. Catena 23(1-2): 99-110. https://doi.org/10.1016/-341-8162(94)90056-6

Bundt M, Widmer F, Pesaro M, et al. (2001) Preferential flow paths: biological 'hot spots' in soils. Soil Biology and Biochemistry 33(6): 729-738. https://doi.org/10.1016/S0038-0717(00)00218-2

Bunte K, Poesen J (1993) Effects of rock fragment covers on erosion and transport of noncohesive sediment by shallow overland flow. Water Resources Research 29(5): 1415-1424. https://doi.org/ 10.1029/92WR02706

Cerda A (2001) Effects of rock fragment cover on soil infiltration, inter-rill runoff and erosion. European Journal of Soil Science 52(1): 59-68. https://doi.org/10.1046/j.1365-2389.2001.00354.x

Cerda A, Jurgensen MF (2008) The influence of ants on soil and water losses from an orange orchard in eastern Spain. Journal of Applied Entomology 132(4): 306-314. https://doi.org/10.1111/j.1439-0418.2008.01267.x

Cerdà A, Jurgensen MF, Bodi MB (2009) Effects of Ants on Water and Soil Losses from Organically-Managed Citrus Orchards in Eastern Spain. Biologia 64 (3): 527-531. https://doi.org/10.2478/s11756-009-0114-7

Cerdà A, Jurgensen MF (2011) Ant Mounds as a Source of Sediment on Citrus Orchard Plantations in Eastern Spain. A Three-Scale Rainfall Simulation Approach. Catena 85 (3): 231-236. https://doi:10.1016/j.catena.2011.01.008

Dal Ferro N, Strozzi AG, Duwig C, et al. (2015) Application of smoothed particle hydrodynamics (SPH) and pore morphologic model to predict saturated water conductivity from X-ray CT imaging in a silty loam Cambisol. Geoderma 255: 27-34. https://doi.org/10.1016/j.geoderma.2015.04.019

Danalatos NG, Kosmas CS, Moustakas NC, et al. (1995) Rock fragments II. Their impact on soil physical properties and biomass production under Mediterranean conditions. Soil Use and Management 11: 121-126. https://doi.org/10.1111/j.1475-2743.1995.tb00509.x

De Figueiredo T, Poesen J (1998) Effects of surface rock fragment characteristics on inter-rill runoff and erosion of a silty loam soil. Soil and Tillage Research 46(1-2): 81-95. https://doi.org/10.1016/S0167-1987(98)80110-4

De Witte E (2003) Hydrofoberen van natuursteen-herstelmortels-Anti-graffiti. Renovation Course. Session 3.

Descroix L, Viramontes D, Vauclin M (2001) Influence of soil surface features and vegetation on runoff and erosion in the Western Sierra Madre (Durango, Northwest Mexico). Catena 43(2): 115-135. https://doi.org/10.1016/S0341-8162(00)00124-7

Elyeznasni N, Sellami F, Pot V, et al. (2012) Exploration of soil micromorphology to identify coarse-sized OM assemblages in X-ray CT images of undisturbed cultivated soil cores. Geoderma 179: 38-45. https://doi.org/10.1016/j.geoderma.2012.02.023

Eriksson CP, Holmgren P (1996) Estimating stone and boulder content in forest soils-evaluating the potential of surface penetration methods. Catena 28(1-2): 121-134. https://doi.org/10.1016/S0341-8162(96)00031-8

Flanagan DC, Nearing MA (1995) USDA-Water Erosion Prediction Project: Hillslope profile and watershed model documentation. Vol. 10. NSERL report.

Fao I, Isric I (2009) JRC: Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria

Fu SH (2005) Effect of soil containing rock fragment on infiltration. Journal of Soil and Water Conservation 19(1): 171-175.

Govers G, Van Oost K, Poesen J (2006) Responses of a semi-arid landscape to human disturbance: a simulation study of the interaction between rock fragment cover, soil erosion and land use change. Geoderma 133(1): 19-31. https://doi.org/10.1016/j.geoderma.2006.03.034

Hendriks CMA, Bianchi FJJA (1995) Root density and root biomass in pure and mixed forest stands of Douglas-fir and beech. NJAS wageningen journal of life sciences 43(3): 321-331.

Hu X, Li ZC, Li XY, et al. (2016) Quantification of soil macropores under alpine vegetation using computed tomography in the Qinghai Lake Watershed, NE Qinghai–Tibet Plateau. Geoderma 264 (Part A): 244-251. https://doi.org/10.1016/j.geoderma.2015.11.001

Hu X, Li ZC, Li XY, Liu LY (2015) Influence of shrub encroachment on CT-measured soil macropore characteristics in the Inner Mongolia grassland of northern China. Soil and Tillage Research 150: 1–9. https://doi.org/10.1016/j.still.2014.12.019

Ingelmo F, Cuadrado S, Ibaez A, et al. (1994) Hernandez J.

Hydric properties of some Spanish soils in relation to their rock fragment content: implications for runoff and vegetation. Catena 23: 73-85. https://doi.org/10.1016/0341-8162(94)90054-X

Ji Y, Baud P, Wong T (2016) Characterization of Pore Geometry in Limestones Using X-ray Computed Microtomography. 78th EAGE Conference and Exhibition 2016. https://doi.org/10.3997/2214-4609.201600892

Johnson DL (1990) Biomantle evolution and the redistribution of earth materials and artifacts. Soil Science 149: 84-102.

Keesstra SD, Quinton JN, Vander Putten WH, et al. (2016) The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. Soil 2(2): 111-118. https://doi:10.5194/soil-2-111-2016

Leigh D (1998) Evaluating artifact burial by eolian versus bioturbation processes, South Carolina sand hills, USA. Geoarchaeology 13(3): 309-330. https://doi.org/10.1002/ (SICI) 1520-6548(199802)13:3<309::AID-GEA4>3.0.CO;2-8.

Li TC, Shao MA, Jia YH (2016) Application of X - ray tomography to quantify macropore characteristics of loess soil under two perennial plants. European Journal of Soil Science 67(3): 266-275. https://doi.org/ 10.1111/ejss.12330

Luo L, Lin H, Li S (2010) Quantification of 3-D soil macropore

Muñoz-Ortega FJ, Martínez FS, Monreal FC (2015) Volume, surface, connectivity and size distribution of soil pore space in CT images: Comparison of samples at different depths from nearby natural and tillage areas. Pure and Applied Geophysics 172(1): 167–179. https://doi.org/10.1007/s00024-014-0897-5

Ni XM, Miao J, Lv RS, et al. (2017) Quantitative 3D spatial characterization and flow simulation of coal macropores based on CT technology. Fuel 200: 199-207. https://doi.org/10.1016/j.fuel.2017.03.068

Parsons AJ, Bracken L, Peoppl R, et al. (2015) Connectivity in water and sediment dynamics. In press in Earth Surface Processes and Landforms. https://doi.org/ 10.1002/esp.3714

Perez FL (1998) Conservation of soil moisture by different stone covers on alpine talus slopes (Lassen, California). Catena 33(3-4): 155-177. https://doi.org/10.1016/S0341-8162(98)00091-5

Phillips JD, Luckow K, Marion DA, et al. (2005) Rock fragment distributions and regolith evolution in the Ouachita Mountains, Arkansas, USA. Earth Surface Processes and Landforms 30(4): 429-442. https://doi.org/10.1002/esp.1152

Qiao JC, Zeng JH, Yang ZF, et al. (2015) The Nano–Macro Pore Network and the Characteristics of Petroleum Migration and Accumulation in Chang 8 Tight Sandstone Reservoir in Heshui, Ordos Basin. Acta Geologica Sinica (English Edition) 89(s1): 207-209. https://doi.org/10.1111/1755-6724.12303_23

Rodrigo comino JR, Quiquerez A, Follain S, et al. (2016) Soil erosion in sloping vineyards assessed by using botanical indicators and sediment collectors in the Ruwer-Mosel valley. Agriculture, Ecosystems & Environment 233: 158-170. https://doi.org/10.1016/j.agee.2016.09.009

Rodrigo comino J, García Díaz A, Brevik EC, et al. (2017). Role of rock fragment cover on runoff generation and sediment yield in tilled vineyards. European Journal of Soil Science. https://doi.org/ 10.1111/ejss.12483

Shi ZJ, Xu LH, Wang YH, Yet al. (2012) Effect of rock fragments on macropores and water effluent in a forest soil in the stony networks in different soil types and land uses using computed tomography. Journal of Hydrology 393(1-2): 53-64. https://doi.org/10.1016/j.jhydrol.2010.03.031

Masselink R, Temme AJAM, Giménez R, et al. (2017) Assessing hillslope-channel connectivity in an agricultural catchment using rare-earth oxide tracers and random forests models. Cuadernos de Investigación Geográfica. http://doi.org/10.18172/cig.3169

Mekonnen M, Keesstra SD, Baartman JE, et al. (2017) Reducing Sediment Connectivity Through man - Made and Natural Sediment Sinks in the Minizr Catchment, Northwest Ethiopia. Land Degradation & Development 28(2): 708-717. https://doi.org/10.1002/ldr.2629

Meng C, Niu J, Li X, et al. (2016) Quantifying soil macropore networks in different forest communities using industrial computed tomography in a mountainous area of North China. Journal of Soils and Sediments 17(9): 2357-2370. https://doi.org/ 10.1007/s11368-016-1441-2.

Miller FT, Guthrie RL (1984) Classification and distribution of soils containing rock fragments in the United States. Soil Science Society of America 13: 1–6.

Mol G, Keesstra SD (2012) Soil science in a changing world. Current Opinions in Environmental Sustainability 4: 473–477. mountains of the Loess Plateau, China. African Journal of Biotechnology 11(39): 9350–9361. https://doi.org/10.5897/AJB12.1450

Stewart JB, Moran CJ, Wood JT (1999) Macropore sheath: quantification of plant root and soil macropore association. Plant and Soil 211(1): 59-67. https://doi.org/10.1023/A:1004405422847

Torri D, Poesen J, Monaci F, et al. (1994) Rock fragment content and fine soil bulk density. Catena 23(1-2): 65-71. https://doi.org/10.1016/0341-8162(94)90053-1

Valentin C (1994) Surface sealing as affected by various rock fragment covers in West Africa. Catena 23(1-2): 87-97. https://doi.org/10.1016/0341-8162(94)90055-8

Walmsley A, Cerdà A (2017) Soil macrofauna and organic matter in irrigated orchards under Mediterranean climate. Biological Agriculture & Horticulture 1-11. https://doi.org/10.1080/01448765.2017.1336486

Wang J, Guo L, Bai Z, et al. (2016) Using computed tomography (CT) images and multi-fractal theory to quantify the pore distribution of reconstructed soils during ecological restoration in opencast coal-mine. Ecological Engineering 92: 148-157. https://doi.org/10.1016/j.ecoleng.2016.03.029

Yan H, Li K, Ding H, et al. (2011) Root morphological and proteomic responses to growth restriction in maize plants supplied with sufficient N. Journal of plant physiology 168(10): 1067-1075. https://doi.org/10.1016/j.jplph.2010.12.018

Yang JL, Zhang GL (2011) Water infiltration in urban soils and its effects on the quantity and quality of runoff. Journal of soils and sediments 11(5): 751-761. https://doi.org/10.1007/s11368-011-0356-1

Zhang Z, Lin L, Wang Y, et al. (2015) Temporal change in soil macropores measured using tension infiltrometer under different land uses and slope positions in subtropical China. Journal Soil Sediment 16(3):854-863. https://doi.org/10.1007/s11368-015-1295-z