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Soil wet aggregate distribution and pore size distribution under different tillage systems after 16 years in the Loess Plateau of China

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ABSTRACT

In the Loess Plateau of China, conventional tillage is defined as the tillage without crop residues left on the soil surface and ploughed twice a year. The use of alternative practices is a way to reduce soil erosion. Our objectives were to assess the long-term impacts of different soil tillage systems on soil physical and hydraulic characteristics, emphasizing management practices to improve the soil physical qualities (reduce bulk density and increase stability of aggregate) under the conservation tillage system in the Loess Plateau of China. Conventional tillage (CT), no tillage (NT), and sub-soiling (SS) were applied in this experiment. Soil wet aggregates distribution and stability, soil organic carbon (SOC) content, soil water retention curves and pore size distributions were measured. The results showed that in the 0–10 cm and 10–20 cm depth soil layers, NT and SS treatments showed a significantly higher proportion of wet aggregates > 250 μm (macroaggregates) compared to CT. In these two layers, the proportion of wet aggregates < 53 μm (microaggregates) was significantly higher in CT with respect to NT and SS. SOC content increased as the aggregate fraction size increased, and was higher within wet aggregates > 250 μm than within the 250–53 μm and < 53 μm (silt + clay) fractions at both depths. In addition, the conservation tillage (NT and SS) can result in improved total porosity and reduced soil bulk density compared with CT in the surface layer. Pore size distribution in CT soil was unimodal, with the maximum in the 10–30 μm matrix pores of the surface layer. However, in the surface layer the pore size distributions from NT and SS showed a dual porosity curve, with two peaks in the matrix and structural pore areas. The 10–20 cm layer showed similar pore size distributions in each treatment. After scanning the soils by micro-computed tomography, we visualized the pore characteristics. The images showed that CT reduced the long and connected macropores compared with conservation tillage. Overall, soil aggregate stability and soil macropores are most improved under conservation tillage. Conservation tillage with crop residues should be adopted instead of conventional tillage, as an effort to improve crop yield and control soil erosion in the Loess Plateau of China.

1. Introduction

The Loess Plateau accounts for one-third of the arable land in China, and plays a vital role for the agricultural production of the country (Li et al., 2016; Qiu et al., 2016). In this region, the average annual precipitation varies 200 and 750 mm. The rainfall is mainly occurring in summer (June to September) (Li and Huang, 2008; Lin and Liu, 2016), and heavy thunderstorms cause severe soil erosion and nutrient losses (Hessel et al., 2003).

Conventional tillage is the dominant tillage practice, normally ploughing twice a year with stubble removal, in this area. However, this type of tillage practice system can cause alterations to the soil physical characteristics (bulk density, aggregate stability and pore size distribution) (Hill, 1990; Tagar et al., 2017) and increase the risk of erosion (Liu et al., 2015). In order to reduce the severe erosion under conventional tillage, considerable attention has been paid recently on the conservation tillage as a long-term sustainable practice for agricultural ecosystems (Su et al., 2007).

There are many different conservation tillage systems, such as no tillage, sub-soiling and reduced tillage (Blevins et al., 1983; Holland,

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Table 1
Long term tillage practices.

Treatment	Period		Depth (cm)	Stubble (cm)	Cultivar		Fertilization ($kg\ ha^{-1}$)		
	July	October			July	October	N	P_2O_5	K_2O
NT (no tillage)	–	–	–	30	–	Winter wheat	150	105	45
SS (sub-soiling)	1	–	30	30	–	Winter wheat	150	105	45
CT (conventional tillage)	1	1	20	10	–	Winter wheat	150	105	45

2004; Lal, 1997; van den Putte et al., 2012). Previous studies found that conservation tillage can improve the water content (Moraru and Rusu, 2010), and enhance soil structure and crop yields (Lampurlanés et al., 2016; Stroud et al., 2016; Su et al., 2007). Jin et al. (2008) found that conservation tillage showed promising trends in improving soil water storage and water-use efficiency in the Loess Plateau of China after 7 years. However, other studies pointed out that there was no difference in water content between conservation and conventional tillage in Iowa (USA) after 2 years (Licht and Al-Kaisi, 2005). Since soil water content changes slowly following an alternation in soil infiltration and evaporation, which depend on different soil type and climatic conditions, respectively, long-term experiments are needed to be locally assessed (Su et al., 2007). The long-term tillage experiments could also provide reliable results on soil quality.

Soil physical quality has been widely approached by those related to soil aggregates distribution (e.g., de Moraes et al., 2016), and pore size distribution and functioning (Starkloff et al., 2017) to evaluate the effects of different tillage systems. In addition, soil aggregate stability can be a signal of vulnerability and resilience for soils (Karlen et al., 1997). The stability of soil aggregates can protect SOC from mineralization, because it physically reduces the accessibility of organic compounds for microorganisms, enzymes, and oxygen (Bronick and Lal, 2005). Soil aggregate stability is generally determined by wet sieving, and expressed by mean weight diameter (MWD) (Le Bissonnais, 1996). Improving soil aggregate stability could maintain soil productivity, reduce soil degradation, and minimize environmental pollution (An et al., 2010). In addition, soil pore size distribution is regarded as another indicator of soil physical quality, related to aggregate size distribution and estimated by the soil water retention curve (Mamedov et al., 2016). The classic pore size distribution obtained from water retention curve model was proposed by van Genuchten (1980). In the van Genuchten model, the soil is assumed as a single continuous pore domain. Durner (1994) proposed a multimodal retention function to describe water retention curve by a linear superposition of subcurves of the van Genuchten type models. Currently, several studies apply bimodal methods, based on the overlap of two unimodal curves to fit the water retention curves due to the complex porous space in soils (Dexter et al., 2008; Ding et al., 2016; Romano et al., 2011). Kołodziej et al. (2016) studied different agricultural reclamation methods on a sandy loam soil and found that the dual porosity model showed a better result when compared to the van Genuchten model.

The objectives of this study were to investigate the impacts of long-term tillage systems on soil physical characteristics and hydraulic properties. We hypothesized that the conservation tillage improves soil physical properties, namely reduces bulk density, increases aggregate stability and macroporosity in the Loess Plateau of China.

2. Materials and methods

2.1. Field site description

The experiment was set up in 1999 at the experimental station of the Chinese Academy of Agricultural Science, located in the city of Luoyang (Henan province; 113.0° E, 34.5° N), China. The site (324 m ASL) has a warm temperate continental climate, with an average annual rainfall of 546 mm, and the temperature averages 13.8 °C over the year. Rainfall occurs mainly from June to September. The soil was classified as *Calcaric Cambisol* according to WRB (IUSS Working Group, 2006) with a sandy loam soil texture (clay: 15.2%, silt: 24.3%, sand: 60.5%) before the experiment setup at 0 to 20 cm. Winter wheat (*T. aestivum* L.) is the major crop. The site showed homogenous soil properties since it was conventionally tilled for > 30 years before the setup of the experiment. At the initiation of the experiment, soil samples contained an average SOC of 11.5 $g\ kg^{-1}$, total N 1.1 $g\ kg^{-1}$, total P 0.69 $g\ kg^{-1}$, and bulk density 1.3 $g\ cm^{-3}$ in 0 to 20 cm depth. Three treatments with three replicates were implemented in 9 plots (30 m × 3 m each).

2.2. Tillage systems

The experiment was designed as a randomized block design with three replications (Su et al., 2007). Long-term continuous winter wheat (wheat followed by summer fallow) was performed with the following treatments: annual no tillage (NT), annual sub-soiling (SS) (ploughing once each year with a shovel) and annual conventional tillage (CT) (ploughing twice each year with a shovel). Table 1 highlights major field operations for the tillage systems. Winter wheat (*T. aestivum* L.) is sown around October 5th, with chemical fertilizer being incorporated at the same time in three tillage systems. SS: sub-soiling is performed down to 30–35 cm depth in 60 cm intervals.

2.3. Sampling

At the site, undisturbed soil samples for water retention curves, bulk density, wet aggregate distribution, scanning and SOC content were randomly selected for each treatment from the 0–10 cm and 10–20 cm depth layers in June 2015 and stored at 4 °C.

2.4. Soil water retention curves

Three undisturbed soil samples for each treatment were taken by metal cylinders (5 cm high and 5 cm in diameter) with 100 cm^3 volume from 0–10 cm and 10–20 cm depth. These undisturbed soil samples were oven-dried (105 °C, 24 h) to determine soil bulk density. In addition, three samples for each treatment were taken by metal cylinders (2 cm high, 6.2 cm diameter) with 60 cm^3 volume from 0–10 cm and 10–20 cm depth to determine soil water retention curves. Soil samples were saturated by capillary rise and subsequently drained to fixed soil matric potentials (h) of −10, −40, −60, −70, −100 cm H_2O using the sandbox method (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) and −330, −700, −1000, −5000 and −15,000 cm H_2O using a pressure plate extractor (Soil Moisture Equipment Corp., CA, USA). The soil total porosity was calculated by the bulk density and particle density (assumed 2.65 $Mg\ m^{-3}$) values. The particle density was used as a constant value for 0–10 cm and 10–20 cm depth in our study. After calculating our data by the equation that proposed by McBride et al. (2012), the results showed that in the 0–10 cm and 10–20 cm depth soil layers, although the SOM were higher in NT and SS than CT, the particle density showed a similar result. Therefore, the particle density set a constant value in our experiment. Soil water content (θ) ($cm^3\ cm^{-3}$) at matric potentials of −330 cm and −15,000 cm H_2O were used to represent field capacity (FC) and permanent wilting point (WP), respectively (Botula et al., 2012). Available water content (AW) was calculated as (WP-FC).

Pores with a diameter ≥ 50 μm were considered "macropores" (pores that drain at $h \leq -60$ cm H_2O) and those with a diameter < 50 μm "micropores" (water retained at $h > -60$ cm H_2O), as suggested by Reichert et al. (2009). Volumetric water content and the degree of saturation are represented by θ_v and S_e, respectively. The soil water retention curve is obtained from the relationship between soil water content and matric potentials. The Eq. (1) was used to estimate the water retention curve using a single modal model, and Eq. (2) to estimate the water retention curve using a bimodal model (Durner, 1994; van Genuchten, 1980).

$$\theta v = \theta r + (\theta s - \theta r)[[1 + (\alpha h)^n]^{-m}] \tag{1}$$

$$Se = \sum_{i=1}^{2} w_i[1 + (\alpha_i h)^{n_i}]^{-m_i} \tag{2}$$

$$\text{where } Se = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \sum_{i=1}^{2} w_i s_i \tag{3}$$

In the equations, θ_s and θ_r represent the saturated volumetric water content and the saturated residual volumetric water contents ($cm^3\,cm^{-3}$) respectively (Durner, 1994). The α_i, n_i and m_i are curve-fitting parameters which define the curve ($\alpha_i > 0$, $n_i > 1$, $m_i = 1-1/n_i$). The w_1 and w_2 are the weighting factors, where $w_1 + w_2 = 1$ (Eq. (3)).

The pore size distribution can be expressed as

$$f(h) = \frac{d\theta}{d(log\ |h|)} \tag{4}$$

where h is the soil matric potential (cm) and f(h) can be defined as the slope of volumetric water release curve plotted against the pore diameter (d_e) in Eq. (4).

Pore diameter (μm) is based on Jurin's law equation, expressed as

$$de = -\frac{4v\cos\alpha}{\rho g h} \tag{5}$$

where d_e is the pore diameter, h is the pressure head (cm), ν is the surface tension of water ($75 \times 10^{-3}\,N\,m^{-1}$), α is the contact angle between the water and the soil, ρ is the water density ($kg\,m^{-3}$) and g is the gravitational acceleration ($m\,s^{-2}$). The pore diameter (μm) is simplified as

$$de = \frac{3000}{|h|} \tag{6}$$

To evaluate the simulations' performance, the root mean square error (RMSE) was calculated as follows:

$$RMSE = \sqrt[2]{\frac{\sum_{i=1}^{N}(\theta p - \theta m)^2}{N}} \tag{7}$$

where θ_m and θ_p represent the measured and predicted soil water content, respectively, and N is the number of data points.

2.5. Soil fractionation and SOC content

The wet-sieving fractionation method was used to separate water stable aggregates according to Cambardella and Elliott (1993). Three undisturbed soil samples were collected in each treatment with a soil auger and crushed by hand along the natural planes of weakness. Bulk soil was separated into three fractions: macroaggregates (> 250 μm), microaggregates (250–53 μm) and silt + clay (< 53 μm). Briefly, 30 g of air dried bulk soil were submerged in water on a sieve with 250 μm mesh size for 10 min. The sieve was then vertically moved 50 times to isolate the fraction of > 250 μm. Thereafter, the remaining part of the soil (< 250 μm) was placed on a sieve with 53 μm opening size to isolate the 250–53 μm and < 53 μm fractions. The aggregate fractions remaining on the sieves were dried at 50 °C for 48 h and weighed. The mean weight diameter (MWD, mm) can be expressed as:

$$MWD = \sum_{i=1}^{n} w_i\overline{x_i} \tag{8}$$

where n is the number of fractions, $\overline{x_i}$ is the mean diameter of each fraction size, and w_i is the weight ratio of soil aggregates occurring in the fraction.

SOC was determined using Walkley–Black $K_2Cr_2O_7$ oxidation method (Nelson et al., 1996).

2.6. Images acquisition and processing

Three undisturbed soils were collected in each treatment with 50 mm diameter × 50 mm long PVC tubes and oven-dried at 40 °C for 7 days before scanning. Then, the soil samples were submitted to sky-scan-1172 high-resolution desktop micro-computed tomography (Bruker, Kontich, Belgium) within the Chemical Engineering research unit at the University of Liège. The scanner was set at 100 kV/100 μA. The 2D image slices were produced with a rotation step at 0.3° over 180° with a pixel of 27.27 μm. After reconstruction, the greyscale value of the images was ranged from 0 to 255. The 3D images were then processed using ImageJ software (Rasband, 2016). In order to reduce the size of the file, the images were resampled with a pixel size of 54.54 μm. The 3D pore visualizations were established using the ImageJ 3D viewer plug-in.

2.7. Statistical analyses

The parameters of the soil water retention curves were performed using SWRC Fit software (Seki, 2007). Regression analysis was used to examine the relationships between MWD and SOC. The data were subjected to analysis of variance with SAS (SAS Institute Inc., Cary, NC, 2011). Mean values were compared using least significant difference (LSD) tests ($P \leq 0.05$). The analysis of variance (ANOVA) was performed to compare the effects of three tillage practices on the measured variables within each depth.

3. Results and discussion

3.1. Soil total SOC content

In the 0–10 cm depth soil layer, conservation tillage (NT and SS) significantly increased SOC content by 18.9% and 21.7% compared to conventional tillage (CT) (Table 2) in bulk soils after 16-year tillage, respectively. Our results were consistent with Blanco-Canqui and Lal (2008) and Li et al. (2014); they found that SOC content in the 0–10 cm layer of soils under conservation tillage was higher compared to that of ploughed ones. In the present study, SOC content showed a decreasing trend for these three treatments from the surface to the 10–20 cm layer. There was no significant difference between SS and NT at the 10–20 cm depth. However, at this depth NT and SS showed a higher SOC content than CT. The higher SOC content in the 0–20 cm depth in conservation tillage is attributed to the absence of disturbance, which promotes root development and increases crop residue accumulation at the soil surface (Bronick and Lal, 2005; Paustian et al., 2000). On the contrary, intensive ploughing resulted in faster SOC decomposition and macro-aggregates (> 250 μm) turnover (Holland, 2004; Six et al., 1998, 1999).

3.2. Wet aggregates size distribution and stability

Fig. 1 shows the effect of different tillage systems on wet aggregate size distribution. In the three treatments, the proportion of < 53 μm wet aggregates were the dominant size class for all the treatments, followed by the 53–250 μm and > 250 μm size fractions in the 0–10 cm and 10–20 cm layers. Wet aggregate size distribution plays a

Table 2

Aggregate mean weight diameter (MWD), soil organic carbon (SOC) content, bulk density (BD), and soil porosity from dual porosity model in the 0–10 cm and 10–20 cm layers under CT, NT and SS treatments.

Layer (cm)	Treatment	MWD (mm)	SOC (g kg^{-1})	BD (g cm^{-3})	Total porosity (cm^3 cm^{-3})	Macro porosity (cm^3 cm^{-3})	Micro porosity (cm^3 cm^{-3})
0–10	CT	0.30b ± 0.01	8.78b ± 0.87	1.17a ± 0.02	0.558b ± 0.009	0.115b ± 0.016	0.443a ± 0.007
	NT	0.33a ± 0.02	10.44a ± 0.07	1.01b ± 0.02	0.624a ± 0.008	0.237a ± 0.035	0.388b ± 0.026
	SS	0.33a ± 0.01	10.70a ± 0.49	1.02b ± 0.01	0.614a ± 0.003	0.210a ± 0.026	0.405b ± 0.023
10–20	CT	0.26b ± 0.01	5.52b ± 0.17	1.10a ± 0.04	0.584b ± 0.014	0.160b ± 0.046	0.424a ± 0.032
	NT	0.29a ± 0.01	6.26a ± 0.20	1.04ab ± 0.02	0.608ab ± 0.008	0.244a ± 0.036	0.364b ± 0.028
	SS	0.29a ± 0.01	6.65a ± 0.17	1.03b ± 0.05	0.613a ± 0.018	0.234a ± 0.011	0.380b ± 0.006

The data represent means ± SD. Different lowercase letters in the same layer indicate significant differences between different tillage systems at the 0.05 probability level.

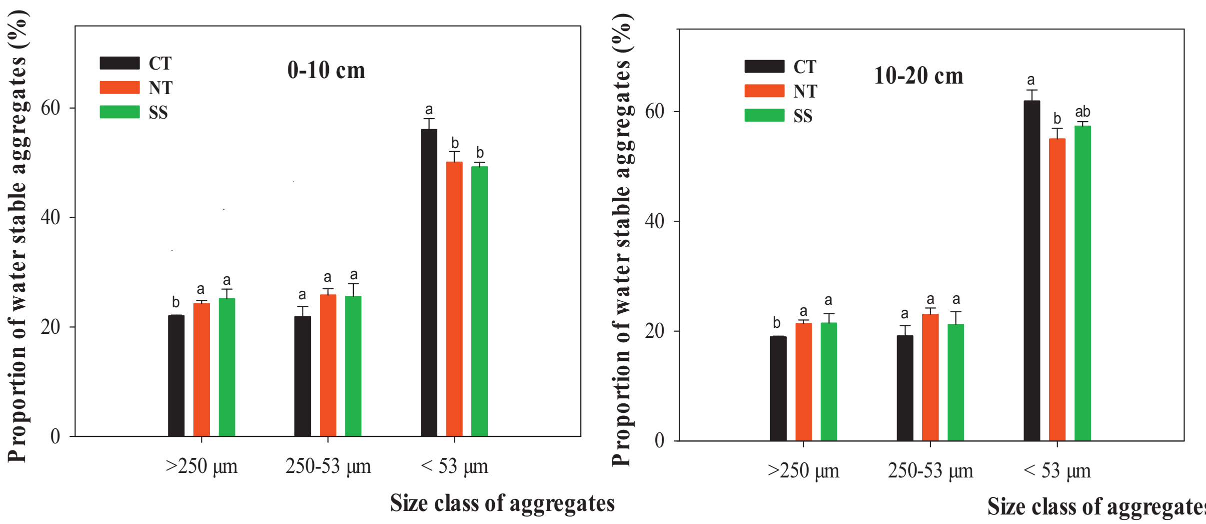

Fig. 1. Water stable aggregate distribution in the 0–10 cm and 10–20 cm depth layers under CT, NT and SS treatments. Bars show the 95% confidence intervals. The data represent means ± SD. Different lowercase letters in the same aggregate fractions indicate significant differences between different tillage systems at the 0.05 probability.

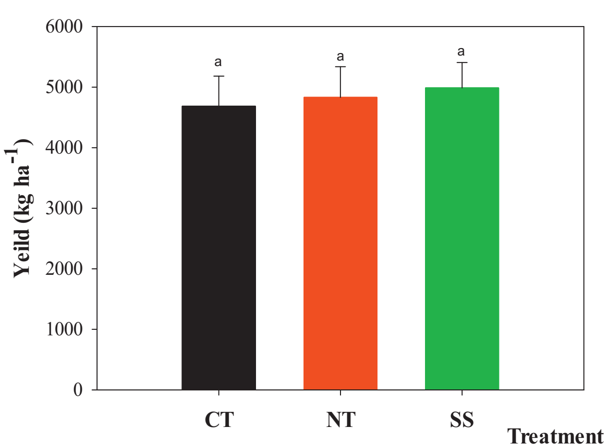

Fig. 2. Average crop yields (2000–2014) in the Luoyang long-term field experiment. The data represent means ± SD. Bars show the 95% confidence intervals. Different lowercase letters in the same aggregate fractions indicate significant differences between different tillage systems at the 0.05 probability.

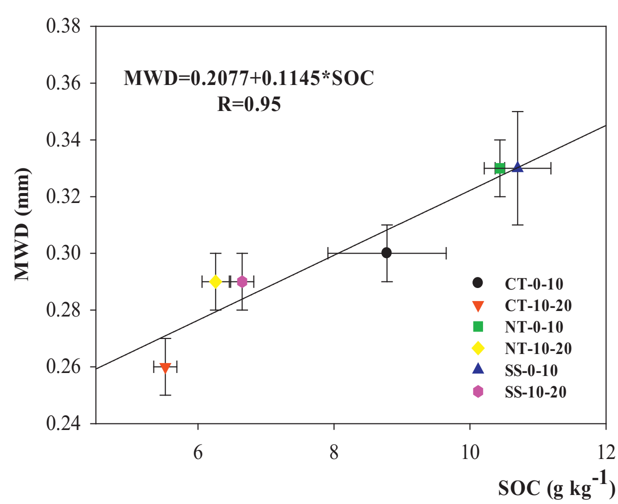

Fig. 3. Linear relationship between MWD and SOC content. The data represent means ± SD.

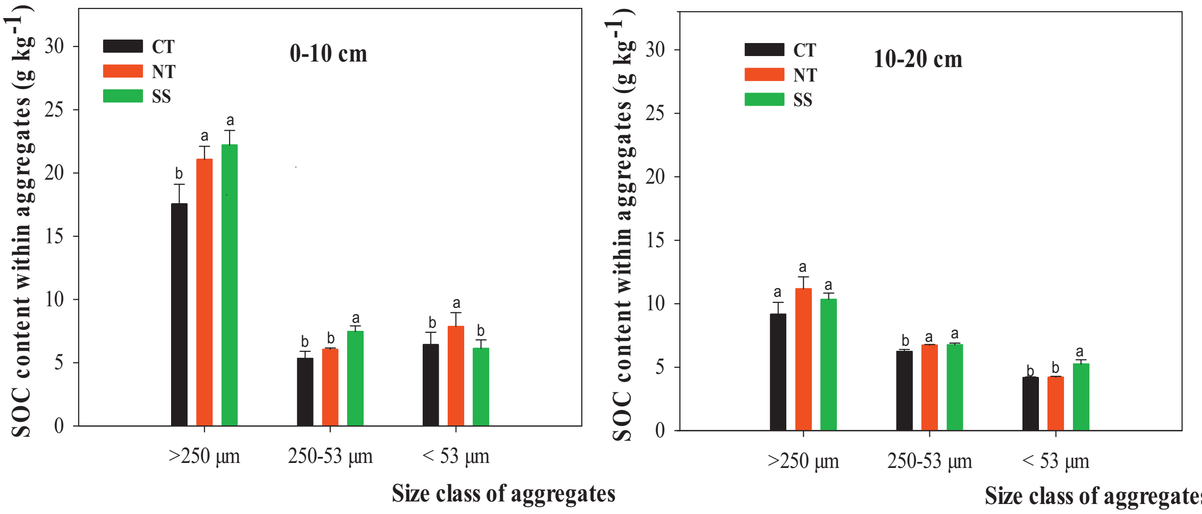

Fig. 4. SOC content within aggregate fractions in the 0–10 cm and 10–20 cm depth layers under CT, NT and SS treatments. Bars show the 95% confidence intervals. The data represent means ± SD. Different lowercase letters in the same aggregate fractions indicate significant differences between different tillage systems at the 0.05 probability.

determining role in the availability of water, nutrition and soil gas exchanges, thus influences the soil quality (Shrestha et al., 2007). Le Bissonnais (1996) proposed that the clay + silt fraction was primarily released from the macroaggregates by mechanical impacts during wet sieving. In the present study, NT and SS treatments showed a significantly higher proportion of wet aggregates > 250 µm compared to CT in the 0–10 cm and 10–20 cm layers. The proportion of wet stable aggregates > 250 µm was 22.05%, 24.25% and 25.17% for CT, NT and SS in the 0–10 cm layer, and 18.96%, 21.40% and 21.45% for CT, NT and SS in the 10–20 cm, respectively. These results indicated that CT decreases the proportion of large water-stable macroaggregates and increases the proportion of the silt + clay fraction, consistently with the findings of previous studies (Grunwald et al., 2016; Six et al., 2000). In addition, the content of macroaggregate affects the crop yields (Limon-Ortega et al., 2009). In our study, the average crop yield of NT and SS was higher when compared to CT (Fig. 2).

The proportion of soil macroaggregates has been recognized as an effective way to evaluate soil quality (Six et al., 2000; Yu et al., 2016). Soil aggregation is a complex process and mediated by a wide range of biotic and abiotic factors (Asano and Wagai, 2014). Biotic mechanisms play a crucial role in the formation of macroaggregates, while abiotic mechanisms mainly perform the formation of microaggregate (Six et al., 2000). Macroaggregates are generally formed with microaggregates and minerals by ephemeral binding agents, such as roots, fungal hyphae, microbial and plant-derived polysaccharides, which are highly susceptible to disruptive forces (Mummey and Stahl, 2004; Six et al., 2000) by soil disturbance with a fast turnover, especially for the soils with high sand content. Our study showed a lower proportion of macroaggregates under CT compared with NT and SS soils. One reason for this might be due to less crop residues (carbon sources for microbes) covered on the soil surface which might induce a lower production of microbial-derived binding agents to form macroaggregates compared with conservation tillage (Jacobs et al., 2009). Another reason could be that CT might breakdown the macroaggregates and reduce the development of fungi and other microbes, ultimately affecting soil aggregation (Kabir, 2005). The increased soil aggregation indicated that the conservation tillage is less vulnerable to raindrops and surface flow, eventually reducing soil erosion and degradation in agricultural soils (Pan et al., 2017) and which is especially important in the Chinese Loess Plateau (Wang et al., 2017).

Aggregate stability is considered as an important indicator of soil structural features and soil functionality (Bronick and Lal, 2005; Six et al., 2000) under different climates and tillage systems (Amezketa, 1999). The results are consistent with our hypothesis, and show that MWD in NT and SS was significantly higher with respect to CT at both depths, without significant differences between NT and SS (Table 2). Moreover, MWD values decreased from the surface to the 10–20 cm depth layer. Kabiri et al. (2015) found that the increase in MWD with conservation tillage was correlated to an improvement in the macroaggregates and/or reduction in microaggregates during absence of tillage processes. These results are in agreement with previous studies in arid and semi-arid ecosystems (Barzegar et al., 2003). Mechanical breakdown and differential swelling were the reasons attributed to macroaggregate breakdown (Le Bissonnais, 1996; Kabir, 2005). In this study, NT and SS increased the MWD and aggregate stability due to the fewer disturbances when compared to CT (Barzegar et al., 2003). In CT, tillage mainly disrupted the macroaggregates, prevented formation of macroaggregates and reduced the stability of macroaggregates. Generally, the macroaggregates were more basically fragile compared with microaggregates due to their higher "weakness" (Utomo and Dexter, 1981). In microaggregates, the pore size was smaller than in macroaggregates, which resulted in a more stable structure under disturbances (Utomo and Dexter, 1981). Moreover, crop residues covering the soil surface reduced the opportunities of exposure to drying and wetting cycles (Piccolo et al., 1997). A significantly positive correlation between SOC and aggregate MWD (r = 0.95, P < 0.05) (Fig. 3) indicated that higher SOC content enhances aggregate stability in this type of soil.

3.3. SOC content within the aggregate fractions

In this study, SOC content increased with the increasing aggregate fraction sizes, which were higher within wet aggregates > 250 µm (macroaggregates) than within the 53–250 µm (microaggregates) and wet aggregates < 53 µm (slit + clay) fractions at both depths (Fig. 4), regardless of treatment. These results are consistent with the findings of Six et al. (2000). They also pointed out that SOC was initially stored in macroaggregates during a short time (0.3 to 5.3 years), and then stored in microaggregates (0.7 to 5.4 years) (Li et al., 2016). The conceptual model for aggregate hierarchy proposed by Tisdall and Oades (1982) found an increasing SOC content with increasing aggregate size. The results are likely due to the fact that the decomposition of organic matter, roots, hyphae and polysaccharides bind mineral particles into macroaggregates, which contribute to C-enrichment in

Table 3
Parameters of the fitted water retention curves in the 0–10 cm and 10–20 cm depth layers under CT, NT and SS treatments from dual porosity and van Genuchten models.

Layer (cm)	Treatment	Dual porosity								van Genuchten				
		θ_s ($cm^3\ cm^{-3}$)	θ_r ($cm^3\ cm^{-3}$)	w_1	α_1	n_1	α_2	n_2	RMSE ($cm^3\ cm^{-3}$)	θ_s ($cm^3\ cm^{-3}$)	θ_r ($cm^3\ cm^{-3}$)	α	n	RMSE ($cm^3\ cm^{-3}$)
0–10	CT	0.558b ± 0.008	0.090a ± 0.002	0.390b ± 0.065	0.062a ± 0.000	1.419a ± 0.091	0.009a ± 0.001	1.843a ± 0.002	0.001	0.550b ± 0.007	0.085a ± 0.009	0.017b ± 0.002	1.594a ± 0.052	0.005
	NT	0.624a ± 0.008	0.084a ± 0.005	0.461b ± 0.184	0.161a ± 0.098	2.418a ± 1.306	0.008a ± 0.001	1.647a ± 0.013	0.001	0.614a ± 0.012	0.000c ± 0.000	0.106a ± 0.052	1.263b ± 0.016	0.014
	SS	0.614a ± 0.003	0.087a ± 0.013	0.632a ± 0.179	0.142a ± 0.083	1.524a ± 0.229	0.005a ± 0.000	1.925a ± 0.083	0.003	0.602a ± 0.002	0.024b ± 0.034	0.065a ± 0.031	1.311b ± 0.066	0.013
10–20	CT	0.584b ± 0.014	0.082a ± 0.017	0.424a ± 0.325	0.767a ± 0.833	1.419a ± 0.143	0.007a ± 0.002	1.960a ± 0.246	0.002	0.559b ± 0.024	0.057a ± 0.030	0.029b ± 0.020	1.496a ± 0.154	0.016
	NT	0.608ab ± 0.008	0.091a ± 0.013	0.531a ± 0.000	0.882a ± 1.043	1.603a ± 0.213a	0.005a ± 0.003	1.892a ± 0.425	0.001	0.593a ± 0.003	0.000b ± 0.000	0.210a ± 0.174	1.227b ± 0.039	0.019
	SS	0.613a ± 0.018	0.088a ± 0.004	0.475a ± 0.083	0.523a ± 0.02	1.662a ± 0.278	0.006a ± 0.001	1.880a ± 0.149	0.001	0.584ab ± 0.019	0.000b ± 0.000	0.105a ± 0.010	1.248b ± 0.016	0.026

The data represent mean ± SD values. Different lowercase letters in the same soil layer indicate significant differences between different tillage systems at the 0.05 probability level.

macroaggregates. Moreover, in the present study, the higher SOC content within the macroaggregate fraction in conservation tillage (NT and SS) than that in CT indicates its high potential to stabilize SOC and soil macroaggregate, and thus improve the soil structure (Puget et al., 1995; Shahbaz et al., 2016).

3.4. Soil bulk density and total porosity

There were significant differences in soil bulk density, θ_s and total porosity among these three treatments (Table 2, Table 3). In the 0–10 cm layer, NT and SS showed a significantly higher level in θ_s and total porosity than that of CT. In the 10–20 cm layer, NT and SS were higher in θ_s and total porosity than that in CT treatment (Table 3). The conservation tillage (NT and SS) significantly reduced soil bulk density compared with CT in the surface layer (Table 2). Similar results were shown in previous studies. Wang et al. (2014) studied the effects of tillage treatments in Northern China. Their results showed that no-tillage with straw cover increased total porosity by 20.9% compared with ploughing and straw removal in the 0–30 cm soil layer. Bai et al. (2009) also found a decline of soil total porosity and poor soil structure after 10-year long-term conventional tillage with straw removal in the Loess Plateau. In this study, although the bulk density was higher in CT compared with NT in the 10–20 cm depth, there were no statistically significant differences between these two treatments. These results indicated that the tillage is mainly affecting the surface layer.

3.5. Soil water retention

In this study, all the data obtained in the treatments were used to fit either dual porosity model or the van Genuchten model. Soil water retention curves obtained by the dual porosity model for 0–10 cm and 10–20 cm layers are shown in Fig. 5. The results of the dual porosity model were better than those of the fit of the van Genuchten model when comparing their RMSE (Table 3). The parameters of the fitted soil water retention curves in the 0–10 cm and 10–20 cm layers under CT, NT and SS treatments are presented in Table 3. The values of RMSE were very low, indicating a good reliability in modelling the retention curves. There was no significant difference in FC, WP or AW (Table 4). Our results were consistent with Minasny and McBratney (2018), they studied a large number of samples from several sources by the meta-analysis method and found that SOC had a positive effect on soil water retention, especially for the water content at saturation. Eden et al. (2017) also proposed that the total water holding capacity can be improved by increasing in the pore volume between FC and saturation (macropores).

3.6. Pore size distribution

The bulk soil was constituted by macroaggregates and microaggregates (Six et al., 2000, 2002). Several studies have reported that the shape and size of aggregates play a key role in the pore size distributions (Miller and Jastrow, 1992; Shi et al., 2016). In previous studies, several researchers found that soil pore size distributions depend on the soil aggregates hierarchy (Dexter, 1988; Dexter et al., 2008; Ding et al., 2016). Dexter et al. (2008) proposed that each level of aggregates had a corresponding level of pores. Generally, soil matrix pores (intra-aggregates pores) and soil structural pores (inter-aggregates pores) were considered to segregate the pore space (Dexter et al., 2008; Ding et al., 2016; Kutilek, 2004). In this study, different pore size distributions (Fig. 6) were determined by the bi-model in water retention curves. Pore size distribution of CT was unimodal, with the maximum in the matrix pores from 10 to 30 μm in the surface and sub-layer. However, the pore size distributions from NT and SS soils showed a dual porosity curve, with two peaks in the matrix and structural pores areas in the surface layer. These data agree with the results reported by Ehlers et al. (1995). They found that the pores were

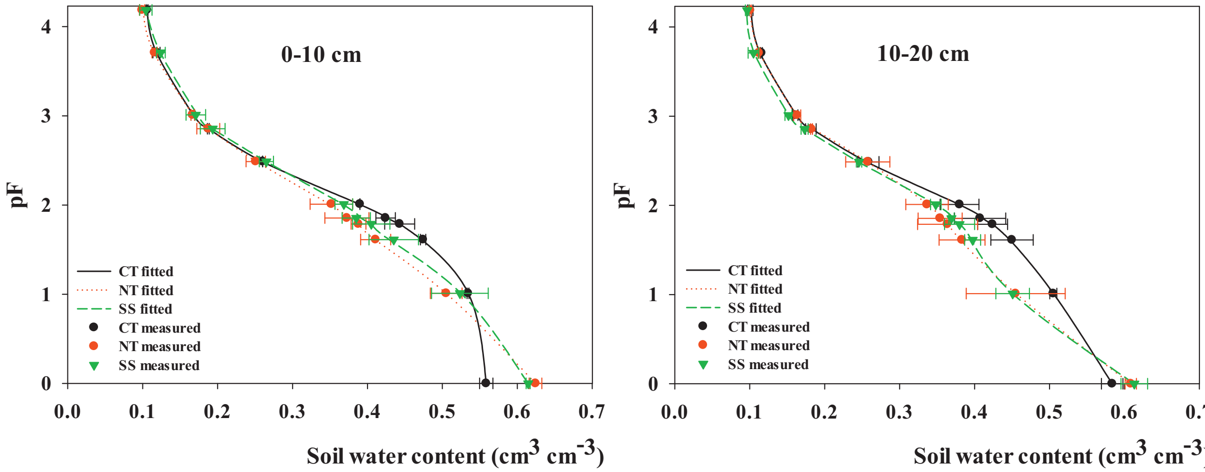

Fig. 5. Soil water retention curves in the 0–10 cm and 10–20 cm depth layers under CT, NT and SS treatments as obtained by fitting the dual porosity model. The points represent the measured values, the lines are the fitted retention curves. pF = $\log_{10}|h|$, h is the pressure head (cm). Bars show the 95% confidence intervals.

Table 4
Soil field capacity (FC), permanent wilting point (WP) and available water (AW) content in the 0–10 cm and 10–20 cm depth layers under CT, NT and SS treatments.

Layer (cm)	Treatment	FC ($cm^3 cm^{-3}$)	WP ($cm^3 cm^{-3}$)	AW ($cm^3 cm^{-3}$)
0–10	CT	0.252a ± 0.001	0.105a ± 0.002	0.146a ± 0.003
	NT	0.245a ± 0.015	0.100a ± 0.003	0.145a ± 0.012
	SS	0.258a ± 0.010	0.106a ± 0.005	0.151a ± 0.005
10–20	CT	0.248a ± 0.012	0.101a ± 0.003	0.147a ± 0.009
	NT	0.250a ± 0.026	0.101a ± 0.002	0.149a ± 0.026
	SS	0.238a ± 0.002	0.096a ± 0.004	0.142a ± 0.006

The data represent mean ± SD values. Different lowercase letters in the same layer indicate significant differences between tillage systems at the 0.05 probability level.

more uniformly distributed in weak aggregated soils.

A better balance between macropores and micropores can improve the soil structure (Shi et al., 2016). The macropores control the air movement and are important for roots penetration and growth (Lal and Shukla, 2004). Reichert et al. (2009) suggested that pores with a diameter ≥50 μm were considered "macropores" and those pores with a diameter of < 50 μm "micropores". In 0–10 cm and 10–20 cm depth, the macroporosity (pore diameter > 50 μm) was significantly higher in NT and SS compared with CT (Table 2). On the contrary, CT showed a significantly higher microporosity (pore diameter < 50 μm) than NT and SS. These results are consistent with our hypothesis. Soil tillage and compaction generally decrease soil macroporosity and change the pore size distribution (Costa et al., 2015; Lipiec et al., 2015). The peak of NT and SS in macropore area were more likely caused by bio-pores, formed by the decayed roots and animal channels (Hoang et al., 2016; Kutilek, 2004). The higher proportion of macroaggregates in conservation tillage might also be due to the occurrence of swelling-shrinking processes, which can cause soil structure change and form macropores (Hadas et al., 1990). The pre-existing cracks could be widened during drying and wetting (Ma et al., 2015). In the CT treatment, disturbance destructed the inter-aggregate pores by breaking the macroaggregates and accelerating their turnover, which resulted in reduced aeration and water infiltration and worsening of pore functions. This resulted in a more significant horizontal diffusivity of water, which may favour soil erosion (Horn et al., 1995).

In order to observe the macropores morphology inside of the soils, we scanned the samples using X-ray micro tomography. The

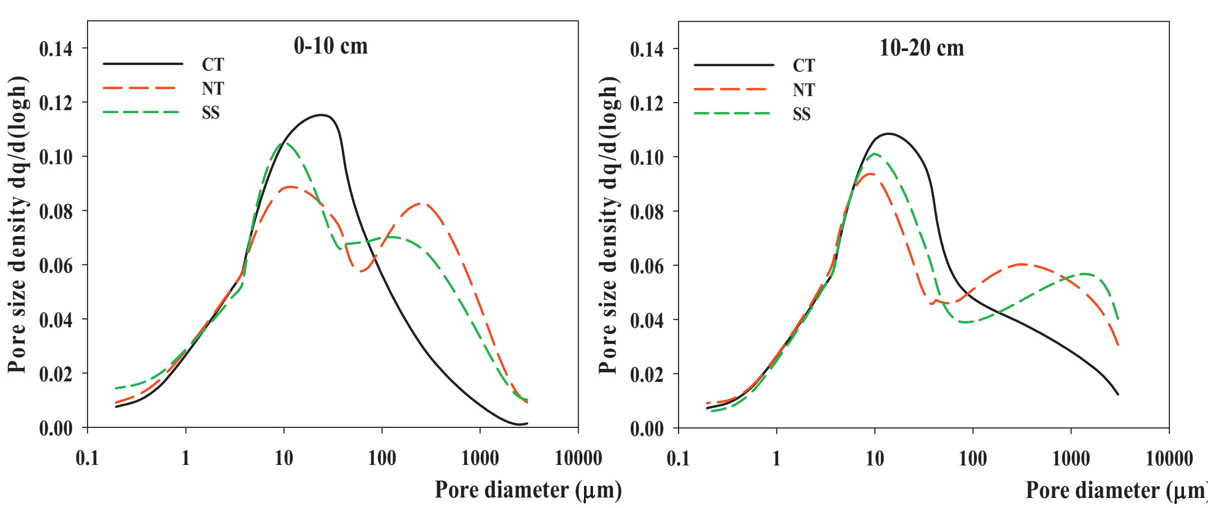

Fig. 6. Soil pore size distribution in the 0–10 cm and 10–20 cm depth layers under CT, NT and SS treatments as obtained from the dual porosity model. The lines are the fitted water retention curves.

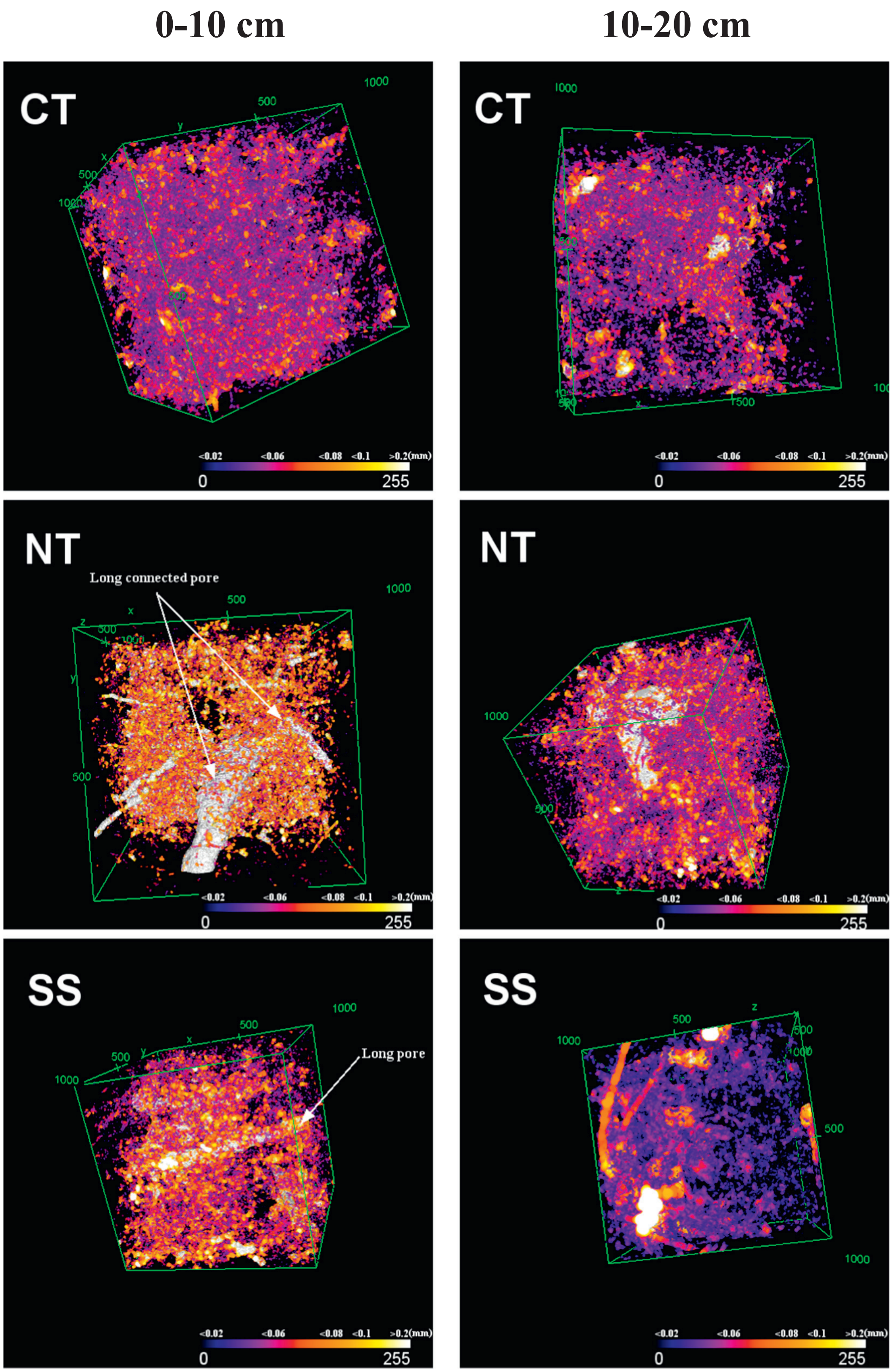

Fig. 7. 3D visualizations of pores in the 0–10 cm and 10–20 cm depth layers under CT, NT and SS. The different colors in the heat map indicate different soil pore diameter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reconstructed images were processed using 3D viewer to visualize the pore characteristics. As a result of CT, the images directly showed that the long and connected pores were reduced compared with conservation tillage (NT and SS) (Fig. 7). Pituello et al. (2016) reported that covering crop residues on the surface contribute to change the pore morphology, reducing regular pores and improving irregular and elongated pores. Furthermore, Gao et al. (2017) suggested that more connected pores within aggregates were displayed in treatments covered with crop residues compared with treatments in which crop residues were removed. The formation of connected and irregular elongated pores is vital for soil water and gas transport, ranging from 50 to 500 μm (Pagliai et al., 2004), which can improve soil functions, such as soil water holding capacity, soil saturated hydraulic conductivity and nutrient availability, eventually, meditate soil–water–-plant relationships (Valboa et al., 2015). In the light of these results, further work should be focused on the visualization and quantification of macropore characteristics to better understand the soil structure and hydrological functions under different tillage systems in the Loess Plateau of China.

4. Conclusions

The results obtained support our hypothesis that conservation tillage (NT and SS) can improve soil physical properties, particularly by reducing bulk density and increasing stability of aggregate and the quantity of macropores in bulk soil. Conservation tillage (NT and SS) increased the formation of wet stable macroaggregates. NT and SS increased the aggregate MWD due to fewer disturbances and covering crop residues on the soil surface when compared to CT. A significant positive correlation between SOC and MWD of aggregates indicated that higher SOC content could enhance the aggregate stability. SOC content showed a positive effect on soil porosity. In the 0–10 cm and 10–20 cm depth layers, the macroporosity (pore diameter > 50 μm) was significantly higher in NT and SS compared with CT. On the contrary, CT showed a significantly higher microporosity (pore diameter < 50 μm) than that in NT and SS. The reason for the higher macroporosity in NT and SS could be caused bio-pores, which were formed by the decayed roots and animal channels. From the results presented, it becomes clear that conservation tillage in the Loess Plateau is a sustainable practice to improve soil physical quality in agricultural soils.

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References

Amezketa, E., 1999. Soil aggregate stability: a review. J. Sustain. Agric. 14, 83–151.
An, S., Mentler, A., Mayer, H., Blum, W.E.H., 2010. Soil aggregation, aggregate stability, organic carbon and nitrogen in different soil aggregate fractions under forest and shrub vegetation on the Loess Plateau, China. Catena 81, 226–233.
Asano, M., Wagai, R., 2014. Evidence of aggregate hierarchy at micro- to submicron scales in an allophanic Andisol. Geoderma 216, 62–74.
Bai, Y., He, J., Li, H., Wang, Q., Chen, H., Kuhn, N.J., Hikel, H., Chen, F., Gong, Y., 2009. Soil structure and crop performance after 10 years of controlled traffic and traditional tillage cropping in the dryland Loess Plateau in China. Soil Sci. 174, 113–119.
Barzegar, A.R., Asoodar, M.A., Khadish, A., Hashemi, A.M., Herbert, S.J., 2003. Soil physical characteristics and chickpea yield responses to tillage treatments. Soil Tillage Res. 71, 49–57.
Blanco-Canqui, H., Lal, R., 2008. No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Sci. Soc. Am. J. 72, 693–701.
Blevins, R.L., Thomas, G.W., Smith, M.S., Frye, W.W., Cornelius, P.L., 1983. Changes in soil properties after 10 years continuous non-tilled and conventionally tilled corn. Soil Tillage Res. 3, 135–146.
Botula, Y.-D., Cornelis, W.M., Baert, G., Van Ranst, E., 2012. Evaluation of pedotransfer functions for predicting water retention of soils in Lower Congo (D.R. Congo). Agric. Water Manag. 111, 1–10.
Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3–22.
Cambardella, C.A., Elliott, E.T., 1993. Methods for physical separation and characterization of soil organic matter fractions. Geoderma 56, 449–457.
Costa, J.L., Aparicio, V., Cerdà, A., 2015. Soil physical quality changes under different management systems after 10 years in the Argentine humid pampa. Solid Earth 6, 361–371.
de Moraes, M.T., Debiasi, H., Carlesso, R., Franchini, J.C., da Silva, V.R., da Luz, F.B., 2016. Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil. Soil Tillage Res. 155, 351–362.
Dexter, A.R., 1988. Advances in characterization of soil structure. Soil Tillage Res. 11, 199–238.
Dexter, A.R., Czyż, E.A., Richard, G., Reszkowska, A., 2008. A user-friendly water retention function that takes account of the textural and structural pore spaces in soil. Geoderma 143, 243–253.
Ding, D., Zhao, Y., Feng, H., Peng, X., Si, B., 2016. Using the double-exponential water retention equation to determine how soil pore-size distribution is linked to soil texture. Soil Tillage Res. 156, 119–130.
Durner, W., 1994. Hydraulic conductivity estimation for soils with heterogeneous pore structure. Water Resour. Res. 30, 211–223.
Eden, M., Gerke, H.H., Houot, S., 2017. Organic waste recycling in agriculture and related effects on soil water retention and plant available water: a review. Agron. Sustain. Dev. 37, 1–21.
Ehlers, W., Wendroth, O., De Mol, F., 1995. Characterizing pore organization by soil physical parameters. In: Soil Struct. Its Dev. Funct. pp. 257–275.
Gao, L., Becker, E., Liang, G., Houssou, A.A., Wu, H., Wu, X., Cai, D., Degré, A., 2017. Effect of different tillage systems on aggregate structure and inner distribution of organic carbon. Geoderma 288, 97–104.
Group, I.W, 2006. WRB, 2006. In: World Ref. Base Soil Resour..
Grunwald, D., Kaiser, M., Ludwig, B., 2016. Effect of biochar and organic fertilizers on C mineralization and macro-aggregate dynamics under different incubation temperatures. Soil Tillage Res. 164, 11–17.
Hadas, A., Hadas, A., Quinton, J., 1990. Long-term effects of high application rates of NPK fertilizer on tensil strength and water stability of the soil structure. Geoderma 47, 381–392.
Hessel, R., Jetten, V., Liu, B., Zhang, Y., Stolte, J., 2003. Calibration of the LISEM model for a small Loess Plateau catchment. Catena 54, 235–254.
Hill, R.L., 1990. Long-term conventional and no-tillage effects on selected soil physical properties. Soil Sci. Soc. Am. J. 54, 161–166.
Hoang, D.T.T., Pausch, J., Razavi, B.S., Kuzyakova, I., Banfield, C.C., Kuzyakov, Y., 2016. Hotspots of microbial activity induced by earthworm burrows, old root channels, and their combination in subsoil. Biol. Fertil. Soils 52, 1105–1119.
Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric. Ecosyst. Environ. 103, 1–25.
Horn, R., Domżżał, H., Słowińska-Jurkiewicz, A., Van Ouwerkerk, C., 1995. Soil compaction processes and their effects on the structure of arable soils and the environment. Soil Tillage Res. 35, 23–36.
Jacobs, A., Rauber, R., Ludwig, B., 2009. Impact of reduced tillage on carbon and nitrogen storage of two Haplic Luvisols after 40 years. Soil Tillage Res. 102, 158–164.
Jin, K., De Neve, S., Moeskops, B., Lu, J., Zhang, J., Gabriels, D., Cai, D., Jin, J., 2008. Effects of different soil management practices on winter wheat yield and N losses on a dryland loess soil in China. Soil Res. 46, 455–463.
Kabir, Z., 2005. Tillage or no-tillage: impact on mycorrhizae. Can. J. Plant Sci. 85, 22–23.
Kabiri, V., Raiesi, F., Ghazavi, M.A., 2015. Six years of different tillage systems affected aggregate-associated SOM in a semi-arid loam soil from Central Iran. Soil Tillage Res. 154, 114–125.
Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil quality: a concept, definition, and framework for evaluation (a guest editorial). Soil Sci. Soc. Am. J. 61, 4–10.
Koſodziej, B., Bryk, M., Sſowiſska-Jurkiewicz, A., Otremba, K., Gilewska, M., 2016. Soil physical properties of agriculturally reclaimed area after lignite mine: a case study from central Poland. Soil Tillage Res. 163, 54–63.
Kutilek, M., 2004. Soil hydraulic properties as related to soil structure. Soil Tillage Res. 79, 175–184.
Lal, R., 1997. Long-term tillage and maize monoculture effects on a tropical Alfisol in western Nigeria. I. Crop yield and soil physical properties. Soil Tillage Res. 42, 145–160.
Lal, R., Shukla, M.K., 2004. Principles of Soil Physics. CRC Press.
Lampurlanés, J., Plaza-Bonilla, D., Álvaro-Fuentes, J., Cantero-Martinez, C., 2016. Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. Field Crop Res. 189, 59–67.
Le Bissonnais, Y.L.E., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. Eur. J. Soil Sci. 47, 425–437.
Li, Y., Huang, M., 2008. Pasture yield and soil water depletion of continuous growing alfalfa in the Loess Plateau of China. Agric. Ecosyst. Environ. 124, 24–32.
Li, Y., Zhang, F., Han, Z., Wang, P., Chen, H., Zhang, Z., 2014. Evolution characteristics and influence factors of deep groundwater depression cone in North China Plain, China-a case study in Cangzhou region. J. Earth Sci. 25, 1051–1058.
Li, S., Gu, X., Zhuang, J., An, T., Pei, J., Xie, H., Li, H., Fu, S., Wang, J., 2016. Distribution and storage of crop residue carbon in aggregates and its contribution to organic carbon of soil with low fertility. Soil Tillage Res. 155, 199–206.
Licht, M.A., Al-Kaisi, M., 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Tillage Res. 80, 233–249.
Limon-Ortega, A., Govaerts, B., Sayre, K.D., 2009. Crop rotation, wheat straw management, and chicken manure effects on soil quality. Agron. J. 101, 600–606.
Lin, W., Liu, W., 2016. Establishment and application of spring maize yield to evapotranspiration boundary function in the Loess Plateau of China. Agric. Water Manag. 178, 345–349.
Lipiec, J., Turski, M., Hajnos, M., Świeboda, R., 2015. Pore structure, stability and water repellency of earthworm casts and natural aggregates in loess soil. Geoderma 243, 124–129.

Liu, E., Chen, B., Yan, C., Zhang, Y., Mei, X., Wang, J., 2015. Seasonal changes and vertical distributions of soil organic carbon pools under conventional and no-till practices on Loess Plateau in China. Soil Sci. Soc. Am. J. 79, 517–526.
Ma, R., Cai, C., Li, Z., Wang, J., Xiao, T., Peng, G., Yang, W., 2015. Evaluation of soil aggregate microstructure and stability under wetting and drying cycles in two Ultisols using synchrotron-based X-ray micro-computed tomography. Soil Tillage Res. 149, 1–11.
Mamedov, A.I., Huang, C., Aliev, F.A., Levy, G.J., 2016. Aggregate stability and water retention near saturation characteristics as affected by soil texture, aggregate size and polyacrylamide application. Land Degrad. Dev. 28, 543–552.
McBride, R.A., Slessor, R.L., Joosse, P.J., 2012. Estimating the particle density of clay-rich soils with diverse mineralogy. Soil Sci. Soc. Am. J. 76, 569–574.
Miller, R.M., Jastrow, J.D., 1992. The role of mycorrhizal fungi in soil conservation. In: Mycorrhizae Sustain. Agric. pp. 29–44.
Minasny, B., McBratney, A.B., 2018. Limited effect of organic matter on soil available water capacity. Eur. J. Soil Sci. 69, 39–47.
Moraru, P.I., Rusu, T., 2010. Soil tillage conservation and its effect on soil organic matter, water management and carbon sequestration. J. Food Agric. Environ. 8, 309–312.
Mummey, D.L., Stahl, P.D., 2004. Analysis of soil whole-and inner-microaggregate bacterial communities. Microb. Ecol. 48, 41–50.
Nelson, D.W., Sommers, L.E., Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E., 1996. Total carbon, organic carbon, and organic matter. In: Methods Soil Anal. Part 3-Chemical Methods, pp. 961–1010.
Pagliai, M., Vignozzi, N., Pellegrini, S., 2004. Soil structure and the effect of management practices. Soil Tillage Res. 79, 131–143.
Pan, T., Hou, S., Wu, S., Liu, Y., Liu, Y., Zou, X., Herzberger, A., Liu, J., 2017. Variation of soil hydraulic properties with alpine grassland degradation in the eastern Tibetan Plateau. Hydrol. Earth Syst. Sci. 21, 1–21.
Paustian, K., Six, J., Elliott, E.T., Hunt, H.W., 2000. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48, 147–163.
Piccolo, A., Pietramellara, G., Mbagwu, J.S.C., 1997. Use of humic substances as soil conditioners to increase aggregate stability. Geoderma 75, 267–277.
Pituello, C., Dal Ferro, N., Simonetti, G., Berti, A., Morari, F., 2016. Nano to macro pore structure changes induced by long-term residue management in three different soils. Agric. Ecosyst. Environ. 217, 49–58.
Puget, P., Chenu, C., Balesdent, J., 1995. Total and young organic matter distributions in aggregates of silty cultivated soils. Eur. J. Soil Sci. 46, 449–459.
Qiu, L., Hao, M., Wu, Y., 2016. Potential impacts of climate change on carbon dynamics in a rain-fed agro-ecosystem on the Loess Plateau of China. Sci. Total Environ. 557, 267–278.
Rasband, W.S., 2016. ImageJ. U.S. National Institutes of Health, Bethesda, Maryland, USA.
Reichert, J.M., Suzuki, L.E.A.S., Reinert, D.J., Horn, R., Håkansson, I., 2009. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Tillage Res. 102, 242–254.
Romano, N., Nasta, P., Severino, G., Hopmans, J.W., 2011. Using bimodal lognormal functions to describe soil hydraulic properties. Soil Sci. Soc. Am. J. 75, 468–480.
SAS Institute Inc., Cary, NC, U, 2011. SAS. SAS Inst. Inc., Cary, NC, USA.
Seki, K., 2007. SWRC fit? A nonlinear fitting program with a water retention curve for soils having unimodal and bimodal pore structure. Hydrol. Earth Syst. Sci. Discuss. 4, 407–437.
Shahbaz, M., Kuzyakov, Y., Heitkamp, F., 2016. Decrease of soil organic matter stabilization with increasing inputs: mechanisms and controls. Geoderma 304, 76–82.
Shi, Y., Zhao, X., Gao, X., Zhang, S., Wu, P., 2016. The effects of long-term fertiliser applications on soil organic carbon and hydraulic properties of a loess soil in China. Land Degrad. Dev. 27, 60–67.
Shrestha, B.M., Singh, B.R., Sitaula, B.K., Lal, R., Bajracharya, R.M., 2007. Soil aggregate- and particle-associated organic carbon under different land uses in Nepal. Soil Sci. Soc. Am. J. 71, 1194–1203.
Six, J., Elliott, E.T., Paustian, K., Doran, J.W., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 62, 1367–1377.
Six, J., Elliott, E.T., Paustian, K., 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63, 1350–1358.
Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32, 2099–2103.
Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241, 155–176.
Starkloff, T., Larsbo, M., Stolte, J., Hessel, R., Ritsema, C., 2017. Quantifying the impact of a succession of freezing-thawing cycles on the pore network of a silty clay loam and a loamy sand topsoil using X-ray tomography. Catena 156, 365–374.
Stroud, J.L., Irons, D., Watts, C.W., Whitmore, A.P., 2016. *Lumbricus terrestris* abundance is not enhanced after three years of compost amendments on a reduced tillage wheat cultivation conversion. Appl. Soil Ecol. 98, 282–284.
Su, Z., Zhang, J., Wu, W., Cai, D., Lv, J., Jiang, G., Huang, J., Gao, J., Hartmann, R., Gabriels, D., 2007. Effects of conservation tillage practices on winter wheat water-use efficiency and crop yield on the Loess Plateau, China. Agric. Water Manag. 87, 307–314.
Tagar, A.A., Gujjar, M.A., Adamowski, J., Leghari, N., Soomro, A., 2017. Assessment of implement efficiency and soil structure under different conventional tillage implements and soil moisture contents in a silty loam soil. Catena 158, 413–420.
Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33, 141–163.
Utomo, W.H., Dexter, A.R., 1981. Soil friability. J. Soil Sci. 32, 203–213.
Valboa, G., Lagomarsino, A., Brandi, G., Agnelli, A.E., Simoncini, S., Papini, R., Vignozzi, N., Pellegrini, S., 2015. Long-term variations in soil organic matter under different tillage intensities. Soil Tillage Res. 154, 126–135.
van den Putte, A., Govers, G., Diels, J., Langhans, C., Clymans, W., Vanuytrecht, E., Merckx, R., Raes, D., 2012. Soil functioning and conservation tillage in the Belgian Loam Belt. Soil Tillage Res. 122, 1–11.
van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.
Wang, Q., Lu, C., Li, H., He, J., Sarker, K.K., Rasaily, R.G., Liang, Z., Qiao, X., Li, H., Mchugh, A.D.J., 2014. The effects of no-tillage with subsoiling on soil properties and maize yield: 12-year experiment on alkaline soils of Northeast China. Soil Tillage Res. 137, 43–49.
Wang, L., Li, X.G., Lv, J., Fu, T., Ma, Q., Song, W., Wang, Y.P., Li, F.-M., 2017. Continuous plastic-film mulching increases soil aggregation but decreases soil pH in semiarid areas of China. Soil Tillage Res. 167, 46–53.
Yu, X., Wu, C., Fu, Y., Brookes, P.C., Lu, S., 2016. Three-dimensional pore structure and carbon distribution of macroaggregates in biochar-amended soil. Eur. J. Soil Sci. 67, 109–120.