Research Article

Comparisons of soil organic carbon enrichment and loss in sediments among red soil, black soil, and loess in China

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Abstract
Water erosion could cause wide and serious soil organic carbon (SOC) loss, but differences in SOC loss and enrichment in sediments among red soil, black soil, and loess in China have received less attention. This study investigates the transport of sediments and generation regulation of runoffs during the erosion process by collecting data from indoor or outdoor artificial simulated rainfall experiments and selecting typical regional rainfall intensity and slope gradient for bare cultivate soil slopes as well as 5–8 m length and 1.5–2 m width runoff plots or soil pans. Then, the change in SOC loss for the three widely distributed and seriously eroded soils, from south to north in China, is clarified. Results show that the stable value and growth rate of soil and SOC loss rates followed the following order: black soil < red soil < loess. The SOC loss rate of loess was more sensitive to rainfall intensity and slope gradient than those of the two other soils. The SOC enrichment ratio (*ERocs*) of the sediments of the red soil and loess soil is higher than that of the black soil, and this difference increases as the soil loss rate decreases. *ERocs* generally has a negative exponential relationship with soil loss, but it has a negative logarithmic relationship with soil loss for the loess soil with high aggregate and clay contents. SOC and clay content determine the SOC enrichment in sediments for different soils. In addition, this study provides recommendations for improving SOC dynamic models for soil under water erosion.

Highlights

- Soil organic carbon (SOC) loss determined by sediment loss for loess, red soil, and black soil.
- SOC is more easily enriched in sediments of red soil and loess soil than in that of black soil.
- Logarithmic relationship exists between *ERocs* and soil loss for high aggregate and clay content soil.
- Exponential relationship exists between *ERocs* and soil loss for low clay and aggregate soils.
- SOC and clay content determine the SOC enrichment in sediments.

Keywords SOC loss · Water erosion · Soil loss · Red soil · Black soil · Loess

Mathematics Subject Classification 00-02

Zhongxuan Cao and Zhijun Chen have contributed equally to this work.

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JEL Classification Z00

1 Introduction

Soil organic carbon (SOC) pool is an important part of terrestrial carbon pool. Small changes in SOC pool may considerably destroy the global carbon balance [1] and decrease soil quality because SOC promotes soil aggregation, forms soil structure, and affects soil properties [2]. Water erosion widely and considerably affects SOC pool worldwide because of sediment loss that usually accompanies SOC transport [3]. Furthermore, given that raindrops and runoff preferentially detach and transport light particles, SOC can be enriched in sediments because of light density and easy bonding with clay-size mineral particles of SOC. Hence, further investigation of SOC loss under water erosion will help estimate SOC changes. However, soil erosion and SOC loss regulations in soils suffering from severe water erosion (e.g., red soil, black soil, and loess) vary. Thus, understanding the SOC loss for more than two serious eroded soil types will provide necessary knowledge for the SOC stock changes and soil quality degradation.

In Northern China, black soil suffers from severe soil erosion [4]. Freezing and thawing decrease the rainfall stability of soils given the cold and wet climate characteristics [5], thereby aggravating water erosion. The high annual precipitation and frequent rainfall provide sufficient water for the red soil in the hilly region of South China to be transported. The unique soil properties of loess on the Loess Plateau considerably contribute to the severe regional soil erosion. For example, factors, such as porosity, carbonate content, metal oxides, hydroxides, and soluble salts, affect loess collapsibility [6]. The erosive rainfall concentrated in summer promotes the abnormally significant soil erosive intensity. Moreover, the decreasing vegetation coverage is another primary reason for the soil erosion in China [7]. Slope is the basic unit of soil erosion. Many researchers have focused on the soil erosion on slopes for the three seriously eroded soils. Among the soil erosion factors, soil loss and runoff are positively correlated with rainfall intensity [8–11]. Soil loss is positively correlated or initially increases and then decreases with the increase in slope gradient [8, 12–14]. In addition, soil properties, such as soil bulk density and clay mineralogy, affect the slope soil erosion process [9, 10, 15]. However, studies concerning the difference of SOC loss among the three soils are few.

The sediment-bound organic carbon (OC) loss contributes remarkably to the total SOC loss under water erosion [16, 17]. Thus, many researchers have focused on SOC loss accompanying sediments, which is positively correlated with soil loss [15, 18–20]. However, light particles within SOC are usually preferentially transported [21]. SOC is enriched in eroded sediment, and the enrichment ratio of SOC (*ERoc*) changes with the relationship between soil loss and SOC loss. The transport of clay or fine particles is one of the causes of *ERoc*; other mechanisms include particulate OCs and aggregate fragments [16, 19, 22, 23]. For red soil, black soil, and loess with different soil textures and OC concentrations, SOC transportation patterns vary, affecting *ERoc*. However, the comparison of the *ERoc* of the three soils has not been studied. *ERoc* value is usually negatively correlated with rainfall intensity, rainfall duration, slope sediment loss, or runoff volume [23, 24], but detailed effects of factors on SOC enrichment of the three soils are different, and also require further investigation.

Previous studies mainly focused on the SOC loss pattern in a particular soil type. However, few studies focused on comparing the SOC loss patterns of black soil, red soil, and loess. Therefore, the objectives of this study are as follows: (1) to compare the soil loss of black soil, red soil, and loess; (2) to investigate the differences in SOC transport and enrichment in sediments for the three soils; (3) to clarify the differences in the SOC loss associated with soil loss mechanisms among the three soils. For these purposes, the study is structured as follows: the research methods used are shown in Sect. 2. The results of the study are described in Sect. 3, starting with a comparison of runoff and sediment loss for red soil, loess, and black soil in Sect. 3.1. Subsequently, the results of the SOC loss comparison are reported in Sect. 3.2, and the discussion is presented in Sect. 4. Finally, the conclusions are summarized in Sect. 5. This study can provide important theoretical bases for SOC evaluation and related modeling for soil under water erosion on a large scale.

2 Materials and methods

2.1 Study areas and soil properties

Black soil was collected from the plow layer (20 cm) of arable fields of the typical black soil region, i.e., Jilin (44° 43′ N, 126° 12′ E) and Heilongjiang (45° 43′ N, 126° 36′ E) Provinces in Northeast China (Fig. 1). The annual average temperature in the black soil regions is 3.7 °C. The mean annual precipitation in the black soil regions is 545 mm, and the rainfall from July to September accounts for 70% of the annual average precipitation. The soil textures of the black soil are silty clay loam or silty loam. The SOC contents of the black soils in Jilin and Heilongjiang Provinces are 13.61

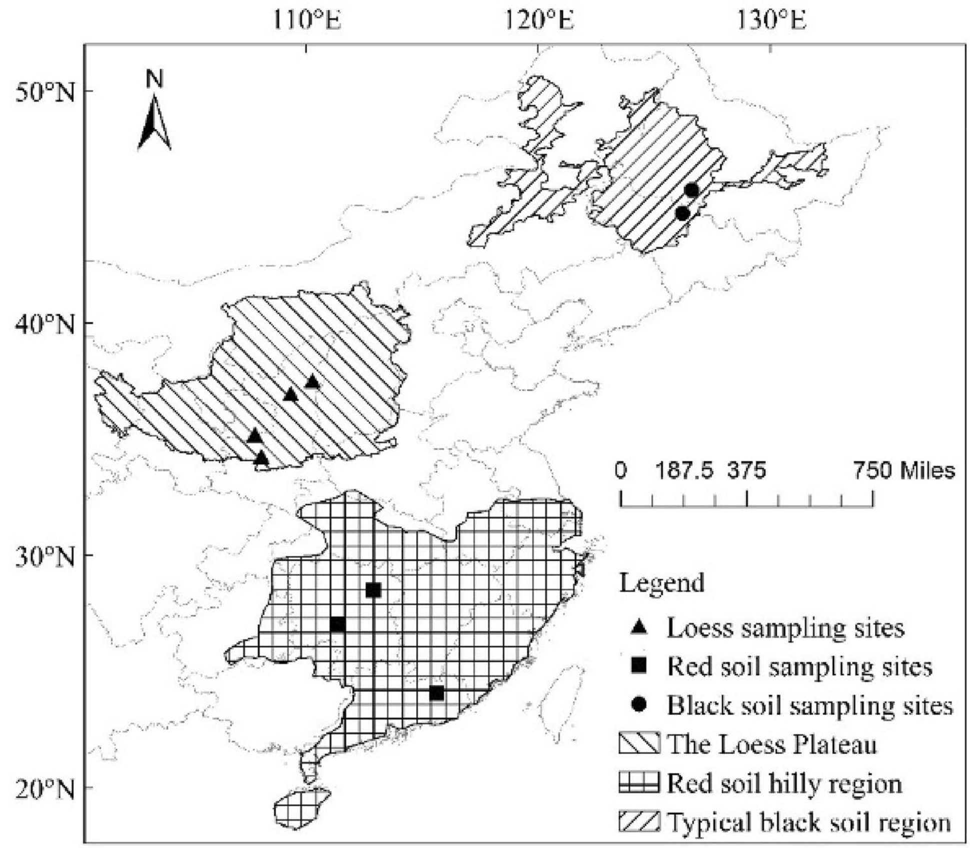

Fig. 1 Locations of the sampling sites

Table 1 Selected properties of the original soils of black soil, red soil and loess

	Location	SOC (g kg^{-1})	pH (in H_2O)	Bulk density (g cm^{-3})	Clay (%)	Silt (%)	Sand (%)
black soil	(44°43′N,126°12′E) Jilin Province	13.61 ±0.67	6.04 ±0.22	1.18 ±0.02	17.24 ±5.85	77.95 ±3.95	4.80 ±2.63
	(45°43′N,126°36′E) Heilongjiang Province	14.21 ±0.00	6.03 ±0.00	1.10 ±0.00	6.50 ±0.00	54.44 ±0.00	39.06 ±0.00
red soil	(24°05′N,115°37′E) Guangdong Province	4.95 ±0.00	4.67 ±0.00	–	27.40 ±0.00	49.00 ±0.00	23.60 ±0.00
	(27°03′N,111°22′E) Hunan Province	6.63 ±1.34	4.61 ±0.19	1.61 ±0.04	28.44 ±9.89	27.60 ±0.13	44.14 ±9.62
	(28°30′N,112°54′E) Hunan Province	2.59 ±0.01	4.00 ±0.02	1.13 ±0.00	51.00 ±0.00	42.00 ±1.00	7.00 ±1.00
loess	(34°16′N,108°04′E) Shaanxi Province	4.77 ±2.24	8.30 ±0.00	1.18 ±0.13	24.90 ±8.89	60.6 ±10.12	13.25 ±9.68
	(35°12′N,107°47′E) Shaanxi Province	7.05 ±0.69	8.30 ±0.00	1.22 ±0.04	20.63 ±1.27	70.20 ±2.01	9.17 ±0.75
	(36°58′N,109°20′E) Shaanxi Province	4.52 ±0.07	8.40 ±0.00	1.25 ±0.05	15.60 ±0.00	64.90 ±0.00	19.4 ±0.00
	(37°31′N,110°16′E) Shaanxi Province	2.59 ±0.50	8.68 ±0.04	1.25 ±0.00	12.10 ±0.00	55.72 ±0.04	32.1 ±0.00

Values are means of acquired data (± standard error)

Soil types are based on the genetic classification for Chinese soil and 14.21 g kg^{-1}, respectively (Table 1). The slope gradient in the black soil area is generally 1°–8° (mostly less than 10°). The red soil was collected from the hilly red soil area, i.e., Hunan (27° 03′ N, 111° 22′ E; 28° 30′ N, 112° 54′ E) and Guangdong (24° 05′ N, 115° 37′ E) Provinces in the southeast of China (Fig. 1). The sites of the red soil are located in a subtropical humid monsoon climate zone. The annual average temperature in the red soil region is 19.0 °C. The annual average precipitation in the red soil region is 1743.5 mm. The soil from Hunan Province was developed from quaternary red soil. The red soil from Guangdong Province is located in the hilly weathered granite red soil area. The soil textures of the red soil are silty clay, loamy clay, and clay. The loess was collected from Shaanxi Province, which is located in the Loess Plateau. Four typical loess soils from Yangling (34° 16′ N, 108° 04′ E), Changwu (35° 12′ N, 107° 47′ E), Ansai (36° 58′ N, 109° 20′ E), and Suide (37° 31′ N, 110° 16′ E) were selected (Fig. 1). Yangling and Changwu have a subhumid continental monsoon climate, whereas Ansai and Suide have a semiarid continental monsoon climate. The mean annual temperature in the loess region is 9.5 °C. The mean annual rainfall in the loess region is 565 mm, 60% of which falls between June and September. The soil textures of the loess are silty clay loam and silty loam. The clay contents (< 0.002 mm) of the four typical loess soils are 24.90%, 20.63%, 15.60%, and 12.10%, showing the characteristics of the zonal distribution. The other properties of the three soils are shown in Table 1. All soils were collected from a depth of 0–20 cm and from the farmland. Outdoor experiments were conducted by establishing runoff plots directly on cultivated land.

2.2 Experimental design

According to the Chinese Soil and Water Conservation Act [25] and the classification of farmland slopes on the Loess Plateau [26], the 25° slope is the maximum slope for cultivated land and the highest floor level of slope. Thus, the selected slopes for loess soils were 5°, 10°, and 15°. The selected slopes for black soil were 5° and 10° given that the natural black soil area has a gentle slope between 3° and 10° [27]. The selected slopes for red soil and loess were 5°, 10°, and 15°. Most erosive rainfall in northeast China is short and heavy that lasts for less than 1 h [28]. Moreover, in accordance with the standard of erosive rainfall for agricultural land in northeast black soil region [29] and the rainfall intensity under which SOC easily enriched, rainfall intensities of 45 and 90 mm h^{-1} were used in experiments on black soil. Rainfall intensities of 45 and 90 mm h^{-1}, representing the low- and high- intensity storms of this region, respectively, were also used in experiments on red soil, considering the change in rainfall intensity in the red soil area. Rainfall intensities of 90 and 120 mm h^{-1}, which represented typical rainfall intensities of strong storms in subhumid climatic regions of China [25, 30], were used in the experiments for loess.

For laboratory experiments, plant residuals and gravels were removed, and all soil samples were passed through a 10 mm sieve and mixed thoroughly prior to air drying to the desired moisture content. Prior to packing the soil, a 5 or 10 cm thick layer of coarse sand was added to the bottom of the soil pan to maintain permeable conditions. Then, the experimental soil layer was placed over the coarse sand layer in 5 cm increments. Each soil layer was raked lightly before the next layer was packed; a total of 30 cm thick soil was packed. The length and width of experimental soil pans were 8 × 1.5 m, 5 × 2 m, and 5 × 1.5 m for black soil, red soil, and loess, respectively. The cultivated soil slopes were bare and without vegetation. For field experiments, the frame of each plot was surrounded with hard impermeable material, e.g., metal or PVC, driven into the ground to shield them from runoff from adjacent plot areas to ensure minimal soil disturbance. A V-shaped runoff funnel was positioned at the end of each plot to collect runoff samples. The nozzles of the sprinkler rainfall simulator system were placed 18 and 4 m above the ground for laboratory and field experiments, respectively, to ensure that the raindrops created in the experiments were similar to natural raindrops. For all experimental treatments, pre-rain with low rainfall intensity was performed 12 or 24 h prior to each experiment. The surface soil moisture contents for black soil, red soil, and loess were 21.7–29.7%, 8–39%, and approximately 10%, respectively. Prior to each simulated event, simulated rainfall devices were tested to ensure the rainfall intensity and the evenness of the raindrop spatial distribution (uniformity > 80%). After runoff initiation, the samples of runoff and sediment were collected between 3 min intervals. After each experiment, all runoff suspensions in buckets were immediately weighed to obtain the total weights of runoff and sediment. Sediment was dried in a forced-air oven until a constant mass was achieved and weighed to determine the sediment loss parameters. All SOC contents in the original soil were determined using the dichromate oxidation method. All experimental treatments were repeated twice or three.

2.3 Data processing

Data in all studies on the SOC loss process for loess, black soil, and red soil were extracted by searching key words "water erosion" and "SOC transport" among others. Original data were used to generate the regressed process curve for data reproduction and to obtain the laws of data effectively. For the soil and SOC loss process data, a 3 min interval was used to retrieve data from the regression curve. The average retrieved data were used for analysis. Rainfall process data were calculated as runoff rate (T_r, L m^{-2} h^{-1}), soil loss rate (T_s, kg m^{-2} h^{-1}), SOC loss rate (T_{SOC}, g m^{-2} h^{-1}), and *ERoc* (T_{ERoc}) to avoid the effect of different sizes of soil pan. The average rainfall data were calculated as the average total runoff (S_r, L m^{-2}), total soil loss (*Ss*, kg m^{-2}), sediment concentration (S_{sc}, g L^{-1} m^{-2}), SOC loss rate (S_{SOC}, g m^{-2} h^{-1}), and *ERoc* (S_{ERoc}). Sediment concentration is the dry sediment mass per unit runoff volume per unit area. The process sediment or SOC loss data were determined as the sediment or SOC loss rate per unit area, respectively. All total sediment or SOC loss indices were calculated as the total sediment or SOC loss per unit area, respectively. Important indices were calculated as follows:

$$T_r = \frac{R}{S \times IT} \times 60, \quad (1)$$

$$T_s = \frac{SL}{S \times IT} \times 60, \quad (2)$$

$$T_{SOC} = \frac{C_{SOC} \times SL}{S} / IT \times 60, \quad (3)$$

$$T_{ERoc} = \frac{C_{SOC}}{C_{SOC0}}, \quad (4)$$

where *R* is the runoff over time intervals (L), *S* is the plot area (m^2), *IT* is the interval time (min), *SL* is the soil loss over time intervals (kg), C_{SOC} is the SOC concentration in sediment over time intervals (g kg^{-1}), and C_{SOC0} is the SOC concentration in the original soil (g kg^{-1}).

The change in sediment concentration (ΔSC_α) when the rainfall intensity increases by 10 mm h^{-1} or when the slope gradient increases by 1° (g L^{-1} m^{-2} h^{-1}), the change in SOC loss rate (ΔSOC_α) when the rainfall intensity increases by 10 mm h^{-1} or the slope gradient increases by 1° (g m^{-2} h^{-1}), and the change in *ERoc* ($\Delta ERoc_\alpha$) when the rainfall intensity increases by 50 mm h^{-1} or the slope gradient increases by 1° were used to normalize the effects of rainfall intensity and slope gradient on the average rainfall data, including sediment concentration, SOC loss rate, and *ERoc* for black soil, red soil, and loess. These indices could be calculated as follows:

$$\Delta SC_\alpha = \sum \left(\frac{SC_{max} - SC_{min}}{\alpha_{max} - \alpha_{min}} \times \beta \right) / n, \quad (5)$$

$$\Delta SOC_\alpha = \sum \left(\frac{SOC_{max} - SOC_{min}}{\alpha_{max} - \alpha_{min}} \times \beta \right) / n, \quad (6)$$

$$\Delta ERoc_\alpha = \sum \left(\frac{ERoc_{max} - ERoc_{min}}{\alpha_{max} - \alpha_{min}} \times \gamma \right) / n, \quad (7)$$

where α is the rainfall intensity (ΔSC_{RI}, ΔSOC_{RI}, and $\Delta ERoc_{RI}$) or slope gradient (ΔSC_{SG}, ΔSOC_{SG}, and $\Delta ERoc_{SG}$), SC_{max}/SC_{min} is the sediment concentration under the highest/lowest rainfall intensity or the maximum/minimum slope gradient (g L^{-1} m^{-2} h^{-1}), $\alpha_{max}/\alpha_{min}$ is the highest/lowest rainfall intensity (mm h^{-1}) or the maximum/minimum slope gradient (°), β is 10 (α is rainfall intensity) or 1 (α is slope gradient), *n* is the number of groups of the same slope length and slope gradient (α is rainfall intensity) or groups of the same slope length and rainfall intensity (α is slope gradient), SOC_{max}/SOC_{min} is the SOC loss rate under the highest/lowest rainfall intensity or the maximum/minimum slope gradient (g m^{-2} h^{-1}), $ERoc_{max}/ERoc_{min}$ is the *ERoc* under the highest/lowest rainfall intensity or the maximum/minimum slope gradient, and γ is 50 (α is rainfall intensity) or 10 (α is slope gradient).

2.4 Data analyses

Nonlinear regression analysis was used to investigate the relationship of the total soil loss with total runoff volume. Exponential and linear regression analysis was used to investigate the relationship of the total soil loss with *ERoc* and the relationship of the clay content in original soils with the coefficient of regression equation, respectively. Pearson correlation analyses were used to study the correlations of the rainfall intensity, slope gradient, sediment concentration, SOC loss rate, and *ERoc*. All statistical analyses were conducted with IBM SPSS Statistics 26.0 software and Origin 2019b software.

3 Results

3.1 Soil loss characteristics for black soil, red soil, and loess

The runoff rate of black soil increased slowly within 20 min and stabilized below 100 mm h^{-1} (Fig. 2). The runoff rate of red soil increased within 15 min and stabilized at 30–100 mm h^{-1}. The runoff rate of silty clay loam of loess increased rapidly within 5 min, and the increased range was approximately 40 mm h^{-1} (Fig. 3). The runoff rate of silty loam of loess increased slowly within 30 min. The stable value of the runoff rate for loess was 50–120 mm h^{-1}, which is mostly greater than 80 mm h^{-1}. In summary, the time to enter a stable period increased in the following order: loess < red soil < black soil. The stable value increased in the following order: black soil < red soil < loess.

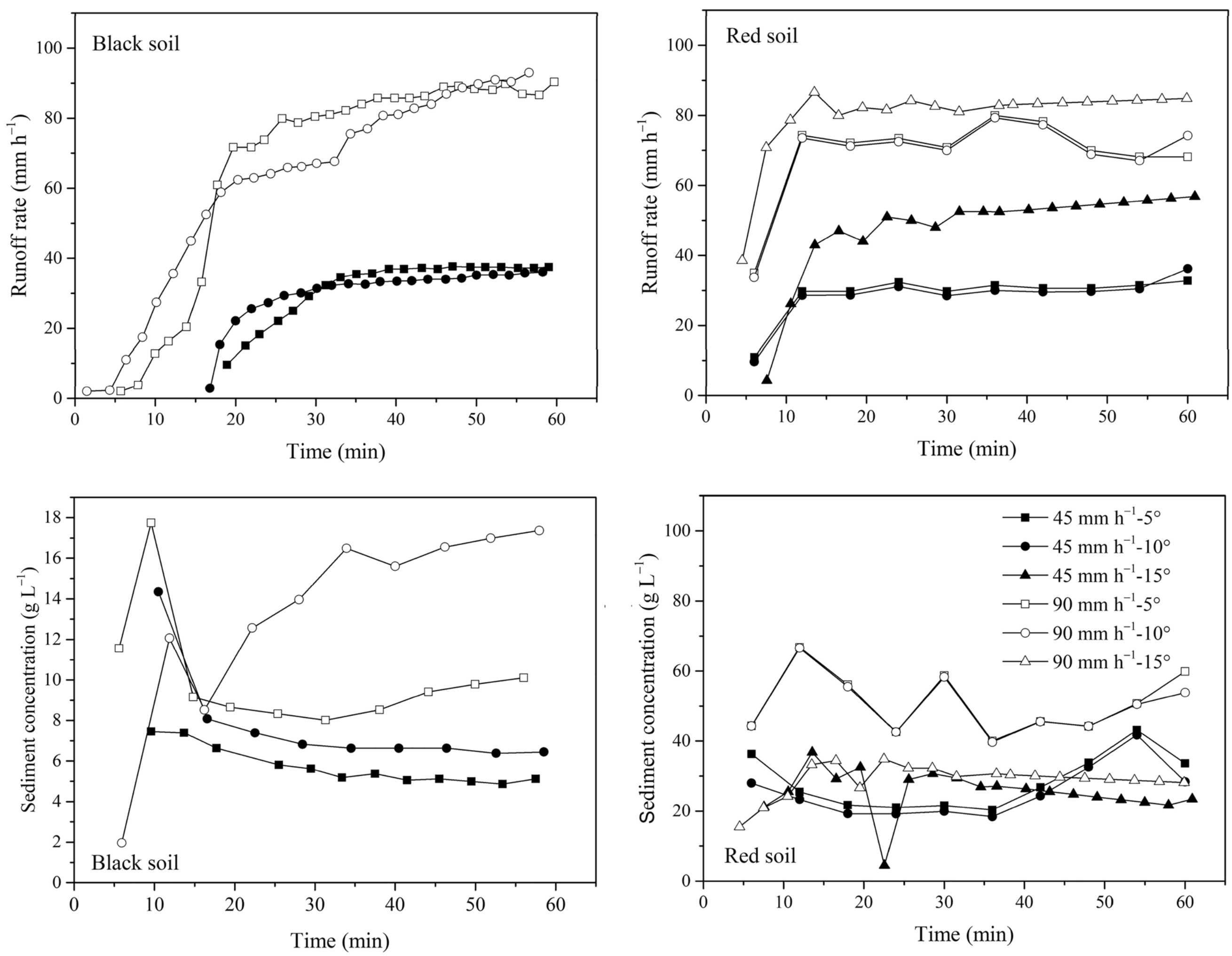

Fig. 2 Temporal variations of runoff rate and sediment concentration for black soil and red soil

The sediment concentration for black soil fluctuated approximately in the first 15 min, and then reached a stable stage (Fig. 3). The stable sediment concentration for black soil was less than 18 g L^{-1}. The sediment concentration for red soil varied approximately in the first 20 min. Most sediment concentrations for red soil fluctuated and then entered a stable stage with a sediment concentration of less than 70 g L^{-1}. The soil loss rate of loess increased and then decreased in the first 10 min. The stable soil loss rate of loess was 1–30 kg m^{-2} h^{-1}. In addition, the soil loss rate for loess increased in the late rainfall period and then decreased. The time to enter a stable period increased in the following order: loess < black soil < red soil. The stable value increased in the following order: black soil < red soil < loess.

ΔSC_{RI} and ΔSC_{SG} were investigated to compare the effect of rainfall intensity and slope gradient on soil loss of the three soils (Table 2). Rainfall intensity and slope gradient were significantly correlated with sediment concentration (Table 3; $P < 0.01$). The ΔSC_{RI} of black soil, red soil, and loess was 0.01, 0.25, and 0.06 g L^{-1} m^{-2} h^{-1}, respectively. The ΔSC_{SG} of black soil, red soil, and loess was 0.01, 0.09, and 0.70 g L^{-1} m^{-2} h^{-1}, respectively. By contrast, the variation of rainfall intensity had the greatest effect on red soil and the least effect on black soil. The variation of slope gradient had the greatest effect on loess and the least effect on black soil.

3.2 SOC loss features for black soil, red soil, and loess

The SOC loss rate of black soil increased with increasing rainfall intensity (Fig. 4). The SOC loss rate of black soil increased initially and then decreased with the increase in slope gradient, similar to the rule of soil loss rate. The SOC loss rate of red soil varied approximately in the first 20 min (Fig. 5). The SOC loss rate of red soil initially increased and then decreased, finally reaching stability.

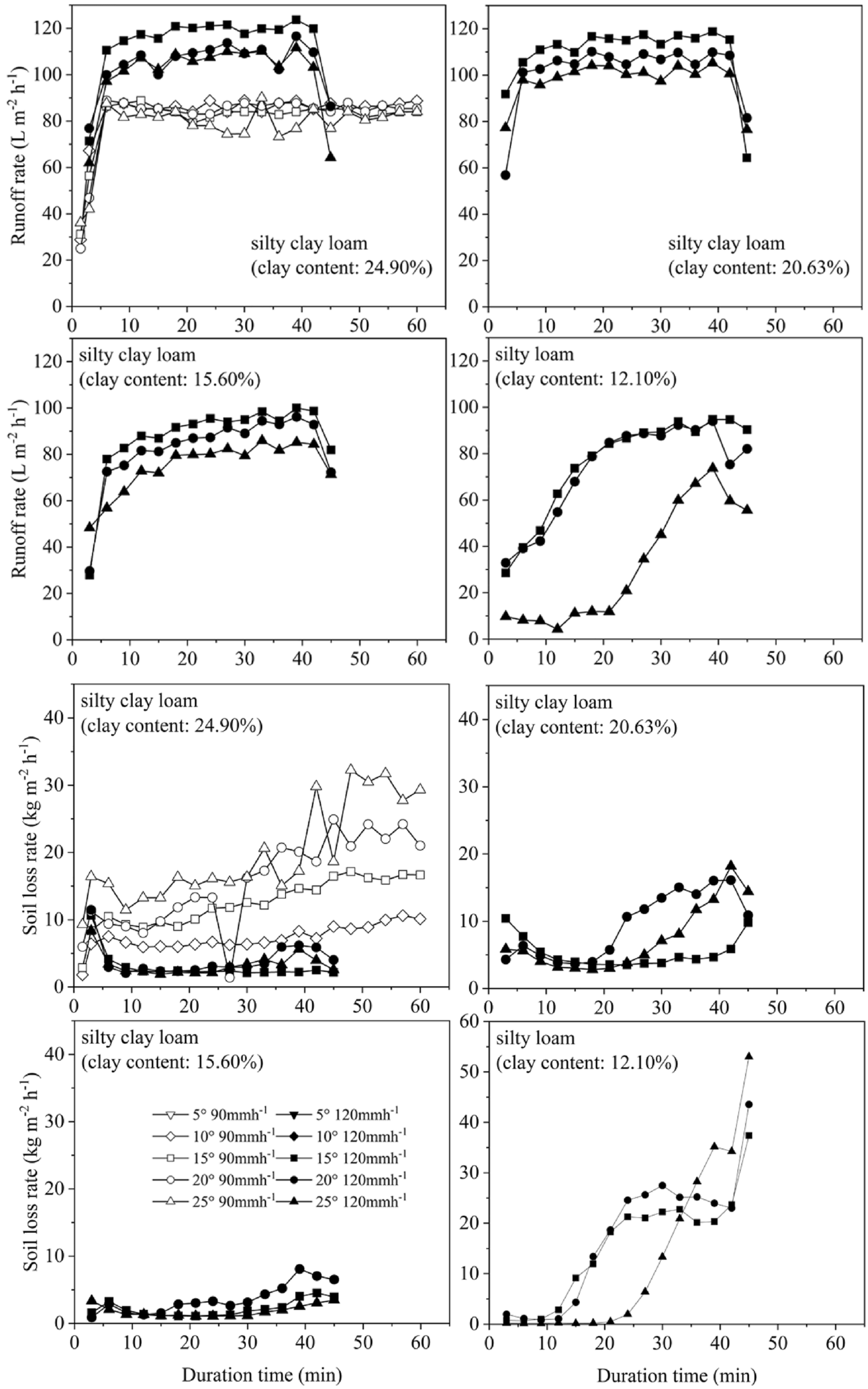

Fig. 3 Temporal variations of runoff rate and soil loss rate for loess

Table 2 Effects of rainfall intensity and slope gradient on sediment concentration (g L^{-1} m^{-2}) and SOC loss rate (g m^{-2} h^{-1}) for black soil, red soil and loess

	ΔSC_{RI}		ΔSC_{SG}		ΔSOC_{RI}		ΔSOC_{SG}	
	Mean	Standard error	Mean	Standard error	Mean	Standard error	Mean	Standard error
Black soil	0.01	0.02	0.01	0.04	1.13	0.21	0.10	0.06
Red soil	0.25	0.14	0.09	0.15	2.46	0.86	−0.16	0.27
Loess	0.06	1.41	0.70	0.70	3.36	0.62	0.47	0.15

ΔSC_{RI} is the change in sediment concentration when the rainfall intensity increases by 10 mm h^{-1}; ΔSC_{SG} is the change in sediment concentration when the slope gradient increases by 1°; ΔSOC_{RI} *is* the change in SOC loss rate when the rainfall intensity increases by 10 mm h^{-1}; ΔSOC_{SG} *is* the change in SOC loss rate when the slope gradient increases by 1°

Table 3 Correlation coefficients of the rainfall characteristics versus the sediment and SOC loss for three soils

Parameters	*RI* (mm h^{-1})	*SG* (°)	*SC* (g L^{-1} m^{-2} h^{-1})	SOC loss rate (g m^{-2} h^{-1})	*ERoc*
RI (mm h^{-1})	1				
SG (°)	0.198	1			
SC (g L^{-1} m^{-2} h^{-1})	0.456**	0.550**	1		
SOC loss rate (g m^{-2} h^{-1})	0.010	0.075	0.729**	1	
ERoc	−0.285	−0.334	−0.162	0.010	1

**Correlation is significant at the 0.01 level

RI is rainfall intensity; *SG* is slope gradient; *SC* is sediment concentration

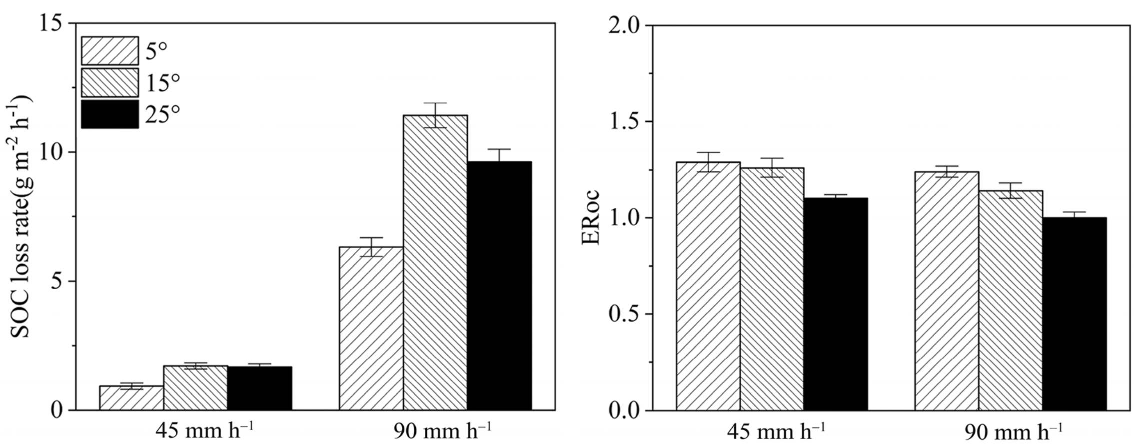

Fig. 4 SOC loss rate and *ERoc* for black soil under different rainfall intensity and slope

The stable value of the SOC loss rate of red soil was lower than 40 g m^{-2} h^{-1}, especially for treatments with small slope gradient and low rainfall intensity. The SOC loss rate of loess decreased in the first 10 min (Fig. 6). The soils with high clay content had a considerable decline. The SOC loss rate of loess was lower than 30 g m^{-2} h^{-1} after entering the stable stage. Moreover, the SOC loss rate of loess increased in the late rainfall period and then decreased, and the peak value of each rainfall event varied considerably. By contrast, the time for the red soil to enter the stable stage was approximately twice that of the loess. The SOC loss rate of red soil in stable period was mostly lower than that of loess. In addition, the loess formed peaks in the late rainfall, which were not evident in red soil. The ΔSOC_{RI} of black soil was 1.13 g m^{-2} h^{-1}, nearly 50% of that of red soil (Table 2). The ΔSOC_{RI} of loess was 3.36 g m^{-2} h^{-1}. The ΔSOC_{SG} of black soil was 0.10 g m^{-2} h^{-1}, which was 20% of loess. However, the ΔSOC_{SG} of red soil was negative, which indicated that the SOC loss rate for red soil decreased with the increase

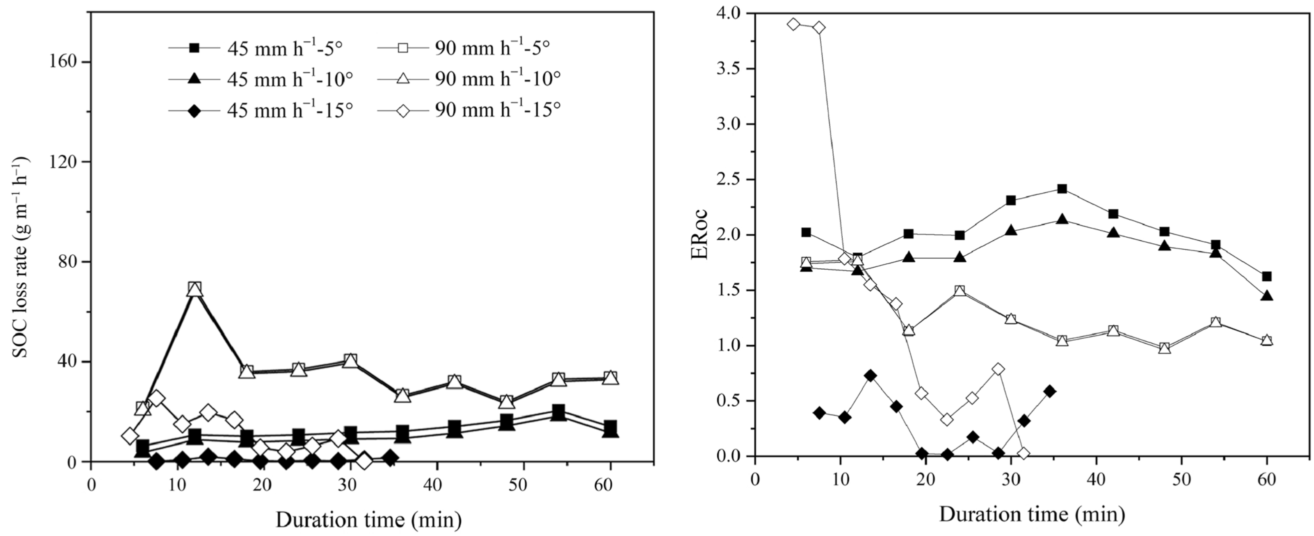

Fig. 5 SOC loss rate and *ERoc* for red soil under different rainfall intensity and slope

of in slope gradient except when the rainfall intensity was 90 mm h^{-1} (Fig. 5). The variation of rainfall intensity and slope gradient had the least effect on black soil but greatest effect on loess.

The *ERoc* of black soil decreased and tended to 1 with the increase in rainfall intensity and slope gradient (Fig. 4). The average *ERoc* of black soil ranged from 1.0 to 1.5. During erosion process, the initial value of red soil *ERoc* was between 1.5 and 4 and then tended to 1 with time (Fig. 5). The average *ERoc* of red soil ranged from 0.31 to 2.21. The *ERoc* of loess with high rainfall intensity (120 mm h^{-1}) tended to 1 (Fig. 6). However, the stable value of loess *ERoc* with 90 mm h^{-1} rainfall intensity was greater than 1 despite a decline period in the beginning. The initial value of loess *ERoc* ranged from 1 to 2.29. The average *ERoc* of loess ranged from 0.92 to 1.63. The $\Delta ERoc_{RI}$ exhibited the following order: black soil < red soil < loess (Table 4). The variation range of *ERoc* with rainfall intensity for loess was greatest, followed by red soil and black soil. The $\Delta ERoc_{SG}$ of red soil was greatest, followed by black soil and loess. Thus, slope gradient had a greater effect on the *ERoc* of red soil. All *ERocs* decreased with increasing rainfall intensity and slope gradient. The total soil loss and *ERoc* showed a negative exponential function relationship in black soil, red soil, and loess ($P < 0.001$) (Fig. 7), but it showed a negative logarithmic function relationship in loess with clay content of 24.9%. *ERoc* variation in red soil and loess with clay content of 24.9% significantly decreased with increasing soil loss rate. In addition, the clay content and coefficient of regression equation ("a" in $y = a^{bx}$) showed a positive linear correlation in black soil, red soil, and loess ($R^2 = 0.51$, $P = 0.176$) (Fig. 8).

4 Discussion

4.1 Comparisons of soil loss under water erosion for black soil, loess, and red soil

Loess has higher bulk density and smaller porosity than black soil, and appropriate capillary pores cause the infiltration water to become fully retained rather than continuously infiltrated. Loess showed the characteristics of infiltration excess runoff. Thus, entering the stable period of runoff and reaching a high stable runoff required a short time for loess, whereas black soil showed the opposite and tended to saturation excess runoff. Therefore, the runoff for soils with fine texture [15, 19], high bulk density, and low OC content increases rapidly and remains relatively high. The rainfall runoff erosivity, which is positively correlated with precipitation and runoff amount [31], causes the sediment yield of soils to show an order similar to runoff characteristics. For loess, clay mineral composition and carbonate [32] and soil microstructure [33] lead to easy collapse and mass production of eroded materials. Soluble carbonate cemented aggregates can be broken easily when suffering from water wetting [34]. This condition causes loess to enter the stable stage of soil loss in a short period of time and obtain the highest soil loss rate. By contrast, for red soil, aggregates cemented by kaolinite and Fe–Al oxides have good water stability [32]. Furthermore, the dispersion of soil aggregates during rapid wetting is reduced [35]. Thus, relatively more slaking-resistant macroaggregate contents improve the water erosion resistance of red soil. In addition, high aggregate stability and low soil erodibility are related to high SOC content [36, 37], as reflected in black soil. Thus, investigations about the

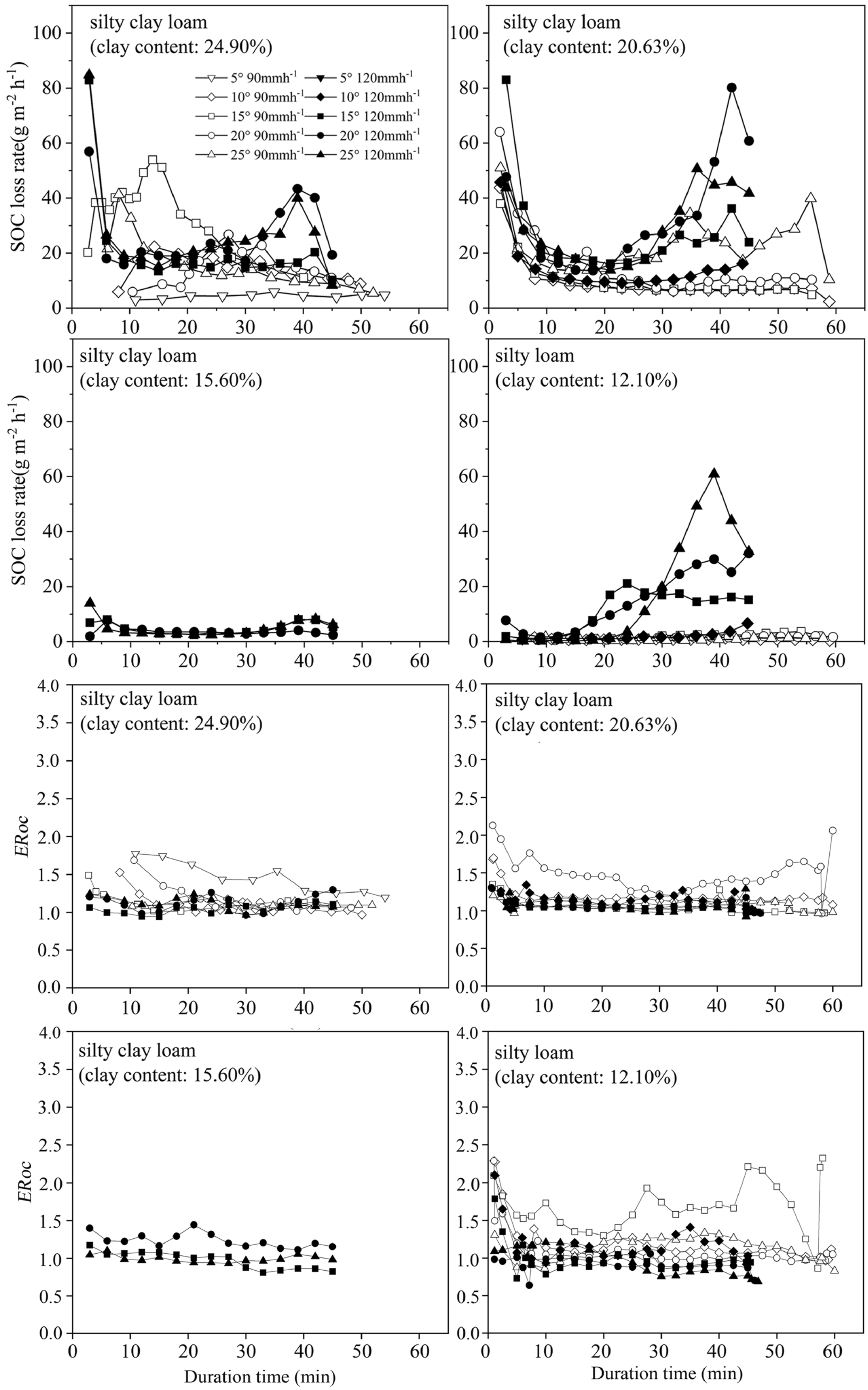

Fig. 6 SOC loss rate and *ERoc* for loess under different rainfall intensity and slope

Table 4 Effects of rainfall intensity and slope gradient on *ERoc* for black soil, red soil and loess

	$\Delta ERoc_{RI}$					$\Delta ERoc_{SG}$				
	Mean	Standard error	Max	Min	Range	Mean	Standard error	Max	Min	Range
Black soil	−0.08	0.01	−0.04	−0.10	0.06	−0.11	0.01	−0.10	−0.12	0.03
Red soil	−0.11	0.31	0.91	−0.91	1.82	−0.19	0.17	0.06	−0.88	0.94
Loess	−0.17	0.11	0.05	−1.18	1.23	−0.03	0.03	0.07	−0.18	0.25

$\Delta ERoc_{RI}$ is the change in *ERoc* when the rainfall intensity increases by 50 mm h^{-1}; $\Delta ERoc_{SG}$ is the change in *ERoc* when the slope gradient increases by 10°

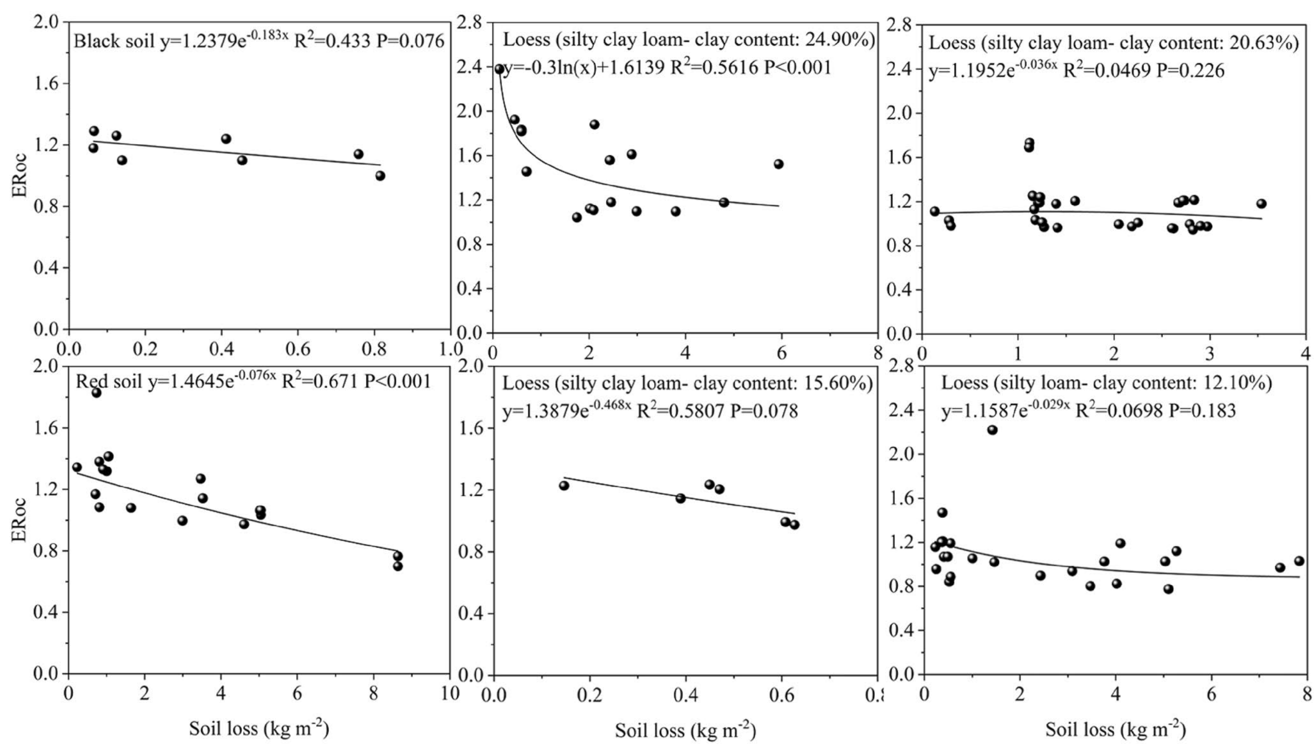

Fig. 7 Relationships between total soil loss and *ERocs*

internal mechanisms of the SOC adsorption by clay under water erosion will be beneficial to further understand aggregate stability and soil loss mechanisms.

For the effect factors on sediment loss, rainfall intensity and slope had the least effect on black soil, but rainfall intensity had the highest effect on red soil. This finding may be because the aggregated protection mechanism of clay or Fe–Al oxides in red soil [38] is more sensitive to the change in rainfall intensity than slope. The increase in rainfall intensity is accompanied by increases in raindrop splash intensity [39] and runoff coefficient [18]. The protection mechanism of large amount of SOC on aggregates for black soil is more stable than that of large amount of clay or Fe–Al oxides in red soil. Slope had the highest effect on loess soil because the increase in slope can change the contact angle between raindrops and slope surface and the acting force of raindrops and hydrodynamic characteristics of runoff erosion [40] on the eroded soil surface, to which loess erosion is sensitive. Therefore, the differences in the effects of other factors, such as mineral composition, soil microstructure, SOC features on soil aggregate stability, and soil erosion resistance for the three typical soils, should be investigated further.

4.2 Comparisons of SOC loss and enrichment for black soil, loess, and red soil

The SOC loss rate increases with increasing rainfall intensity, initially increases and then decreases with slope [16, 22], but the increase in SOC loss rate differs in different soil types. The change in SOC loss rate of loess was more sensitive to the changes in rainfall intensity and slope than

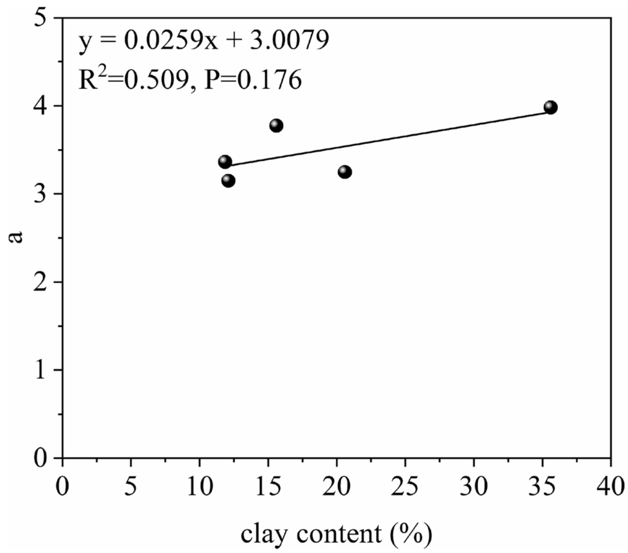

Fig. 8 Relationship between clay content and coefficient of regression equation

those of black and red soils. The runoff infiltration and the weak cementation effect of soil minerals on aggregates for loess contribute to its SOC loss and enrichment. Thus, SOC loss rates in different soils are closely associated with their SOC form [41], e.g., SOC easily bonding with clay or large-sized humus wrapped by aggregate.

The SOC in black soil with low clay and high macroaggregate contents [42] is difficult to transport preferentially [43]. By contrast, for zonal acidic soils, e.g., red soil, SOC that easily combines with clay or Fe–Al oxides [44, 45] is easily preferentially transported, leading to a relatively evident *ERocs* in sediments. For loess, macroaggregates that usually combine with inorganic calcium compounds are easily broken by raindrop impact and form a large amount of clay and silt particles [46] associated with SOC. Thus, different from that of black soil, the SOC of red soil and loess can be evidently enriched in sediments when the soil loss rate is small, and *ERocs* decrease with increasing soil loss rate [18, 47]. Therefore, the SOC enrichment in sediments easily occurs in the soil containing abundant clay minerals under low rain-induced erosive power. However, for soil with low clay content and high SOC content, SOC cannot be easily enriched in sediments. Soil texture and mineral composition are the key factors for SOC loss and enrichment. Our study suggests that the variations in soil texture and mineral composition between soil types should be considered for the SOC enrichment in SOC dynamic prediction model in future studies. In addition, among loess soils with different soil texture, in soils with high aggregate and clay contents, e.g., loess with 24.90% clay content, the SOC was most evidently enriched in sediments when the soil loss rate was small. With increased soil loss, the major sediment particle composition changes from clay and microaggregates to sand and macroaggregates after rill erosion, and the degree of SOC enrichment rapidly decreases [48]. Thus, the logarithmic function may be more suitable than the exponential function for determining the relationships between *ERocs* and sediment loss for soils with high aggregate and clay contents. Lastly, more field rainfall experiments about soil erosion and SOC loss should be conducted to verify the results obtained in this study.

5 Conclusion

Soil erosion and SOC loss and enrichment were compared for black soil, red soil, and loess. Results indicated that the stable soil loss rate followed the order: black soil < red soil < loess. Soil and SOC loss rate of loess were the highest and had a noticeable increase in late rainfall events. Moreover, the SOC loss rate of loess was more susceptible to the change in slope gradient than those of two other soils. The SOC loss rate of red soil was more susceptible to the change in rainfall intensity than those of two other soils. Sediment loss amount determines the SOC loss amount for the black soil, loess, and red soil. The *ERocs* of red soil and loess was higher than that of black soil under low rain-induced erosive power. In black soil, aggregates with high SOC and low clay contents may physically prevent the preferential transport of SOC bonded with clay. The SOC enrichment in sediments easily occur in soils containing abundant clay minerals and SOC but not in soil with high SOC content and low clay content. Relationships between *ERocs* and total soil loss could be regressed by a negative exponential function. However, for soils with high clay and aggregate, the logarithmic function was suitable for determining the relationships between *ERocs* and sediment loss. In general, SOC loss regulations in different soils are associated with soil texture, mineral composition, and soil microstructure features. In the future, the effects of combining soil minerals and SOC in soils on sediment and SOC loss should be studied to further understand soil and SOC changes under water erosion.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors. The work described has not been submitted elsewhere for publication, in whole or in part, and all the authors listed have approved of the enclosed manuscript. Results were presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation. No data, text, or theories by others are presented as if they were the author's own.

Consent to participate All authors approved to participate the research and agreed to publish the research results.

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References

1. Batjes NH (2014) Total carbon and nitrogen in the soils of the world. Eur J Soil Sci 65(1):2–3
2. Bronick CJ, Lal R (2005) Soil structure and management: a review. Geoderma 124(1–2):3–22
3. Lal R (2003) Soil erosion and the global carbon budget. Environ Int 29(4):437–450
4. Hong Y, Zhao D, Zhang F, Shen G, Yuan Y, Gao Y, Yan L, Wei D, Wang W (2021) Soil water-stable aggregates and microbial community under long-term tillage in black soil of Northern China. Ecotoxicology 30:1–15
5. Kværnø SH, Øygarden L (2006) The influence of freeze–thaw cycles and soil moisture on aggregate stability of three soils in Norway. CATENA 67(3):175–182
6. Klukanova A, Sajgalik J (1994) Changes in loess fabric caused by collapse: an experimental study. Quatern Int 24:35–39
7. Ouyang W, Hao F, Skidmore AK, Toxopeus AG (2010) Soil erosion and sediment yield and their relationships with vegetation cover in upper stream of the Yellow River. Sci Total Environ 409(2):396–403
8. Wu L, Peng M, Qiao S, Ma X (2018) Effects of rainfall intensity and slope gradient on runoff and sediment yield characteristics of bare loess soil. Environ Sci Pollut Res 25:3480–3487
9. Wu X, Wei Y, Wang J, Xia J, Cai C, Wei Z (2018) Effects of soil type and rainfall intensity on sheet erosion processes and sediment characteristics along the climatic gradient in central-south China. Sci Total Environ 621:54–66
10. Wu X, Wei Y, Wang J, Xia J, Cai C, Wu L, Fu Z, Wei Z (2017) Effects of erosion degree and rainfall intensity on erosion processes for Ultisols derived from quaternary red clay. Agric Ecosyst Environ 249:226–236
11. Xu X, Zheng F, Wilson GV, Wu M (2017) Upslope inflow, hillslope gradient and rainfall intensity impacts on ephemeral gully erosion. Land Degrad Dev 28(8):2623–2635
12. Li Z, Liu D, Li XY, Wu H, Li GY, Li YT (2016) Runoff coefficient characteristics and its dominant influencing factors in a riparian grassland in the Qinghai Lake watershed, NE Qinghai-Tibet Plateau. Arab J Geosci 9:397
13. Liu Q, Chen L, Li J (2001) Influences of slope gradient on soil erosion. Appl Math Mech Engl 22(5):510–519
14. Wu S, Yu M, Chen L (2017) Nonmonotonic and spatial-temporal dynamic slope effects on soil erosion during rainfall-runoff processes. Water Resour Res 53(2):1369–1389
15. Li Z, Nie X, He J, Chang X, Liu C, Liu L, Sun L (2017) Zonal characteristics of sediment-bound organic carbon loss during water erosion: a case study of four typical loess soils in Shaanxi Province. CATENA 156:393–400
16. Nie X, Li Z, Huang J, Huang B, Zhang Y, Ma W, Hu Y, Zeng G (2014) Soil organic carbon loss and selective transportation under field simulated rainfall events. PLoS ONE 9(8):e105927
17. Zhang X, Li Z, Tang Z, Zeng G, Huang J, Guo W, Chen X, Hirsh A (2013) Effects of water erosion on the redistribution of soil organic carbon in the hilly red soil region of southern China. Geomorphology 197:137–144
18. Li Z, Liu L, Nie X, Chang X, Liu C, Xiao H (2016) Modeling soil organic carbon loss in relation to flow velocity and slope on the loess plateau of China. Soil Sci Soc Am J 80(5):1341
19. Li Z, Nie X, Chang X, Liu L, Sun L (2016) Characteristics of soil and organic carbon loss induced by water erosion on the loess plateau in China. PLoS ONE 11(4):e0154591
20. Ma W, Li Z, Ding K, Huang J, Nie X, Zeng G, Wang S, Liu G (2014) Effect of soil erosion on dissolved organic carbon redistribution in subtropical red soil under rainfall simulation. Geomorphology 226:217–225
21. Massey HF, Jackson ML (1952) Selective erosion of soil fertility constituents. Soil Sci Soc Am J 16(4):353–356
22. Jin K, Cornelis WM, Gabriels D, Baert M, Wu HJ, Schiettecatte W, Cai DX, De Neve S, Jin JY, Hartmann R, Hofman G (2009) Residue cover and rainfall intensity effects on runoff soil organic carbon losses. CATENA 78(1):81–86
23. Nie X, Li Z, He J, Huang J, Zhang Y, Huang B, Ma W, Lu Y, Zeng G (2015) Enrichment of organic carbon in sediment under field simulated rainfall experiments. Environ Earth Sci 74(6):5417–5425
24. Liu L, Li Z, Xiao H, Wang B, Nie X, Liu C, Ni L, Wang D (2019) The transport of aggregates associated with soil organic carbon under the rain-induced overland flow on the Chinese Loess Plateau. Earth Surf Proc Land 44(10):1895–1909
25. Shi ZH, Fang NF, Wu FZ, Wang L, Yue BJ, Wu GL (2012) Soil erosion processes and sediment sorting associated with transport mechanisms on steep slopes. J Hydrol 454–455:123–130
26. Comprehensive Scientific Expedition (1990) Slope classification data set of cultivated land on loess plateau area. Beijing: National Science Technology Infrastructure China, Data

Sharing Infrastructure Earth System Science, Chinese Academic Science. http://www.geodata.cn
27. Cui M, Cai QG, Fan HM (2007) Research progress on the soil erosion in black soil region of Northeast China. Res Soil Water Conserv 05:29–34 (**in Chinese with English abstract**)
28. Zhan M, Li ZC, Xin YL (1998) On the relationship between precipitation parameter and soil erosion. J Eng Heilongjiang Univ 01:40–43 (**in Chinese with English abstract**)
29. Gao F, Zhan M, Zhan H (1989) Study on criteria of erosive rain in farmland of chernozem in Heilongjiang Province. Soil Water Conserv China 11:21–23+65 (**in Chinese**)
30. Wang L, Shi ZH (2015) Size selectivity of eroded sediment associated with soil texture on steep slopes. Soil Sci Soc Am J 79(3):917–929
31. Wang Y, Cheng C, Xie Y, Liu B, Yin S, Liu Y, Hao Y (2017) Increasing trends in rainfall-runoff erosivity in the Source Region of the Three Rivers, 1961–2012. Sci Total Environ 592(15):639–648
32. Zhao J, Chen S, Hu R, Li Y (2017) Aggregate stability and size distribution of red soils under different land uses integrally regulated by soil organic matter, and iron and aluminum oxides. Soil Till Res 167:73–79
33. Shao X, Zhang H, Tan Y (2018) Collapse behavior and microstructural alteration of remolded loess under graded wetting tests. Eng Geol 233(31):11–22
34. Wen BP, Yan YL (2014) Influence of structure on shear characteristics of the unsaturated loess in Lanzhou, China. Eng Geol 168(16):46–58
35. Bissonnais YL (1996) Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. Eur J Soil Sci 47(4):425–437
36. Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. Eur J Soil Sci 33(2):141–163
37. Chenu C, Le Bissonnais Y, Arrouays D (2000) Organic matter influence on clay wettability and soil aggregate stability. Soil Sci Soc Am J 64(4):1479–1486
38. Zheng T, Yang J, Zhang J, Tang C, Liao K, Liu Y (2018) Factors contributing to aggregate stability at different particle sizes in ultisols from Southern China. J Soil Sediment 19:1342–1354
39. Hu W, Zheng F, Bian F (2016) The directional components of splash erosion at different raindrop kinetic energy in the Chinese Mollisol region. Soil Sci Soc Am J 80(5):1329–1340
40. Shen H, Zheng F, Wen L, Han Y, Hu W (2016) Impacts of rainfall intensity and slope gradient on rill erosion processes at loessial hillslope. Soil Till Res 155:429–436
41. Pintaldi E, D'Amico ME, Stanchi S, Catoni M, Freppaz M, Bonifacio E (2018) Humus forms affect soil susceptibility to water erosion in the Western Italian Alps. Appl Soil Ecol 123:478–483
42. Gao X, Hu Y, Sun Q, Du L, Duan P, Yao L, Guo S (2018) Erosion-induced carbon losses and CO2 emissions from Loess and Black soil in China. CATENA 171:533–540
43. Liu L, Li ZW, Li ZJ, Liu EF, Nie XD, Liu C, Xiao HB (2020) Effect of aggregate breakdown on the unevenly enriched organic carbon process in sediments under a rain-induced overland flow. Soil Till Res 204:104752
44. Chorover J, Amistadi MK (2001) Reaction of forest floor organic matter at goethite, birnessite and smectite surfaces. Geochim Cosmochim Acta 65(1):95–109
45. 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
46. Li P, Xie W, Pak RYS, Vanapalli SK (2019) Microstructural evolution of loess soils from the Loess Plateau of China. CATENA 173:276–288
47. Wei S, Zhang X, McLaughlin NB, Chen X, Jia S, Liang A (2017) Impact of soil water erosion processes on catchment export of soil aggregates and associated SOC. Geoderma 294:63–69
48. Jiang Y, Zheng F, Wen L, Shen H (2019) Effects of sheet and rill erosion on soil aggregates and organic carbon losses for a Mollisol hillslope under rainfall simulation. J Soil Sediment 19:467–477