Impact of raindrop sizes and intensities on the microcharacteristics of soil aggregates

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Abstract

Aggregate breakdown caused by the impact of raindrops clogs soil pores, reduces soil infiltration and aggravates the formation of soil crusts. To determine the influence of raindrop splash on the microstructure of soil aggregates, the typical loess was studied. We used synchrotron-based X-ray microcomputed tomography (SR-µCT) to analyze the microcharacteristics of soils impacted by rainfall intensities. The results showed that raindrop splash increases the number of surface soil aggregates, especially when the rainfall intensity is 68.61 or 217.26 mm h-1. Compared to the undisturbed soil, the number of soil aggregates increased by 38.71%, 46.77% and 76.77%, and the volume increased by 1.09%, 3.21% and 3.73%, after the impact of rainfall intensities of 5.76, 68.61 and 217.26 mm*h-1, respectively. Raindrop impact on the surface affects the distribution of aggregate particles, causing a decrease in the number of aggregate particles in the 500-1000 µm range and an increase in the < 500 µm range. Compared with unsplashed soil, there is a significant increase in the fractal dimension (FD) and total specific surface area (SSA) of surface soil aggregates in splashed soil. Particularly, the rainfall intensity of 217.26 mm h-1 resulted in an increase of the FD and SSA by 30.24% and 17.49%, respectively. Under the rainfall intensities, the average particle diameter of the soil aggregates decreased by 2.43%, 3.25% and 3.55%, respectively, compared with that of the undisturbed soil. These results indicated that raindrop splash decreased the number of macroaggregates and increased the number of microaggregates in the surface layer of soil.

1 INTRODUCTION

Soil aggregates are the basic units of structure in soil. The breakdown and dispersion of soil aggregates caused by raindrop splashing, initiate soil erosion (Bronick and Lal, 2005; Legout et al., 2005; Xiao et al., 2017). Soil aggregate stability plays a key role in affecting surface runoff and soil erosion; furthermore, it has been widely used to evaluate soil structural stability and soil quality (Six et al., 2000; Ghadir et al., 2007; Anderson et al., 2019). Numerous studies have been conducted on aggregates in soil erosion (Fu et al., 2017, 2019), and these studies mostly analyzed the particle size distribution of split aggregates after rainfall. During a rainfall event, the fragmentation and separation of aggregates was mainly caused by large-diameter raindrops; as the raindrop diameter increased, the degree of fragmentation in the aggregates became stronger (Fu et al., 2017; Li et al., 2018). Additionally, Fu et al. (2019) used a simulated rainfall test to analyze the extent of soil splash erosion and the distribution of particle sizes and determined the effects of different rainfall energy levels on the breakdown of soil aggregates. Furthermore, Fu et al. (2020) assessed the effects of secondary raindrop splash erosion on aggregate fragmentation and fragment size distribution and found that secondary raindrop splash erosion would cause soil aggregates to break again, leading to a reduction in soil fertility and productivity. Obviously, previous studies have ignored the impacts of raindrop splash on the microstructure of aggregates.

In recent years, the development of X-ray computer scanning (CT) technology has allowed for its application in the study of soil structure and soil aggregates (Peth et al., 2008; Munkholm et al., 2012; Garbout et al., 2013; Gao et al., 2019). Through synchrotron-based X-ray microcomputed tomography (SR-µCT) scanning, high-resolution images of soil can be obtained, and three-dimensional qualitative and quantitative analysis of soil aggregates can be performed, thereby analyzing the internal microstructure of aggregates in a nondestructive and comprehensive manner (Taina et al., 2008; Ma et al., 2015; Han et al., 2019). Some research has utilized CT scanning technology to quantify the effects of different land use types, fertilization conditions, and types of vegetation restoration and succession on soil pore structure and aggregates (Luo et al., 2010; Zhou et al., 2012; Dal Ferro et al., 2013; Zhao et al., 2017). Hu et al. (2016) and Li et al. (2019) applied CT scanning technology to analyze soil macropores and root structure from alpine vegetation and different ecosystems in the Qinghai Lake Basin of China in an effort to explore the impact of roots on soil macropore network characteristics. In addition, work from Ma et al. (2015) based on SR-µCT scanning technology investigated the influences of pore characteristics on water stability and the tensile strength of aggregates under wetting and drying cycles. Additional research has used high-resolution CT to characterize the development of crust over time, and the results showed that the cumulative porosity varied according to soil depth (Lee et al., 2008). With the help of simulation rainfall experiments and SR-µCT scanning, Li et al. (2018) analyzed the effects of raindrop splashing on the fragmentation mechanism of aggregate microstructure from a two-dimensional perspective.

As we all know, the Loess Plateau is a region among those with the most serious soil erosion in the world, and one of its main causes of erosion is water erosion. The fragmentation and dispersion of topsoil aggregates caused by raindrops is the first step of soil erosion, but it is unclear how rainfall causes microstructural changes in soil aggregates. Although SR-µCT scanning has been widely used in soil research, this does not hold true in the field of soil erosion; to date, CT scanning has rarely been employed to analyze the impact of rainfall on the microstructure of aggregates. However, the microstructure of soil aggregates determines the soil stability and quality characteristics (Zhou et al., 2012). Therefore, utilizing SR-µCT and image analysis, the aims of this research were (1) to compare the differences in the three-dimensional microstructure of soil aggregates under raindrops and (2) to analyze the relationship between the rainfall intensity and microscopic characteristics of the soil aggregates. The results presented here may be beneficial by revealing the mechanisms of aggregate fragmentation, pore clogging and the formation of a surface crust during soil erosion.

2 MARERIALS AND METHODS

2.1 Soil samples

Soil samples were collected from Meixian County (107°45'36"E, 34°17'24"N), Shaanxi Province, which belongs to a warm and subhumid continental climate. The average annual precipitation is 610 mm, occurring mainly from July to September, with an average annual temperature of 12.9. The study area was a traditional agricultural cropland region located in the southern section of the Loess Plateau in China. The soil was formed from loess parent material (according to the USDA particle size classification criteria) (Fu et al., 2017). The diagonal method was used to collect 30 undisturbed soil samples from the surface (0-5 cm depth) with a ring knife (10 cm diameter x 5 cm height). Bulk density (1.29 +- 0.07 g cm^{-3}) was determined with oven drying at 105degC until a constant mass was obtained. The soil organic matter content (1.33% +- 0.04) was measured by the combustion method. The pipette method was used to obtain the particle size distribution (sand (0.02-2 mm) 45.96% +- 0.12%, silt (0.002-0.02 mm) 41.06% +- 0.03%, clay (<0.002 mm) 12.98% +- 0.05%).

2.2 Rainfall test

The simulated rainfall device was composed of a raindrop generator and a splashing raindrop collection device (Figure 1) (Fu et al., 2017). The raindrop generator was a cylinder (10 cm in diameter and 10 cm in height) with a top opening, 21 syringe needles were installed at the bottom of the cylinder, and raindrops of different diameters were generated by changing the needle size. The collection device for splashed raindrops was a stainless-steel pan (110 cm in diameter). To prevent the raindrops from being disturbed by the horizontal airflow, a shield was placed around the experimental device. The duration for testing each raindrop diameter was 10 minutes, and each diameter test was repeated 3 times.

Three rainfall intensity levels (5.76, 68.61, and 217.26 mm h^{-1}) determined by three raindrop diameters were selected in the experiment. The corresponding raindrop diameters were 2.67 mm, 3.39 mm and 4.05 mm, respectively. The rainfall intensity was measured by the direct method. For all needles of each size, continuous rainfall was performed for 10 minutes, and the precipitation volume was determined. The rainfall intensity was calculated according to the rainfall area and rainfall time. Each test was conducted 10 times, the maximum and minimum values were removed, and the average of the remaining 8 replicates was calculated to be the rainfall intensity. When the raindrop diameter was greater than or equal to 1.9 mm, the modified Newton formula (equation [1]) was used to calculate the final velocity of the raindrops. The raindrop velocity under this test condition was calculated using equation [2]. The raindrop energy was calculated by equation [3].

d >1.9 (1)

(2)

(3)

where V_i is the terminal velocity (m s^{-1}), d is the raindrop diameter (mm), V is the raindrop velocity (m s^{-1}), g is the acceleration of gravity (m s^{-2}), H is the height from which the raindrop falls (m), E_{rs} is the raindrop energy (J m^{-2} s^{-1}), n is the number of raindrops, i=0,. . . , and m is the individual raindrop mass (g). The main parameters of the simulated raindrops are shown in Table 1.

After the rainfall test, the soil in the cutting ring was air dried naturally. Dry clods (2 cm cubes) from the surface of the impacted soil (a depth of approximately 0.5 cm) were obtained by using a knife before and after each rainfall event. The soil clods were placed in a container with a sponge to keep the structure intact. A total of 54 dry clods were selected for CT scanning.

2.3 ΣΡ-μ῝Τ σςαννινγ ανδ ιμαγε προςεσσινγ

The soil clods (5 mm in diameter) were scanned using synchrotron-based X-ray microcomputed tomography (SR-μCT) at beamline BL13W1 in Shanghai, China. The scan was performed at an energy level of 24 kV, with an exposure time of 1.8 s, a detection distance of 11 cm, and a resolution of 3.25 μm. The sample stage rotates at a constant speed from 0 to 360°, and the scan is continuously performed at a scan interval of 0.625 mm; 720 original images (tomo images) were obtained for each soil sample. Then, PITRE (Phase-sensitive X-ray Image Processing and Tomography Reconstruction) software was used for phase retrieval and slice reconstruction based on the back-projection algorithm (Chen et al., 2012). A total of 1500-2000 slice images (2048×2048 pixels) were obtained for each soil clod and stored as 32-bit grayscale images in tiff format.

The open-source software ImagePy was used to complete image processing, visualization and quantification of the three-dimensional aggregate structure (Wang et al., 2018). To avoid the influences of soil depth and image boundary, a total of 512 images with serial numbers 512-1024 were selected, and a nonedge section of 512×512×512 pixels (i.e., 1.664 mm×1.664 mm×1.664 mm) in size was selected as the target area for image analysis. The process of dividing the grayscale image into the soil matrix and pores by thresholding, which is called binary segmentation, was key to the quantitative analysis of soil structure. This study used the automatic Otsu algorithm of the global threshold method (Zhou et al., 2012; Garbout et al., 2013) to perform binary segmentation which was subsequently completed by visual observation and manual adjustment. After image binarization, the three-dimensional visualization function of the ImagePy software was used to visualize the three-dimensional structure of soil aggregates (Wang et al., 2018) (Figure 2).

2.4 Calculation and analysis

ImagePy software (Wang et al., 2018) was used to analyze the segmented binary image and obtain the quantity, diameter, surface area and volume of soil aggregate particles; subsequently, the 3D structural characteristics of the aggregate after splashing with different raindrop sizes were obtained through calculation and analysis. Aggregate fragments were divided into six classes according to their size: 500-1000, 250-500, 106-250, 53-106, 25-53 and <25 μm.

The quantity and volume parameters of soil aggregates were used to measure the quantitative characteristics of aggregates. The three-dimensional mass fractal dimension (FD) and specific surface area (SSA) of each aggregate were used to characterize the extent of aggregate fragmentation. The FD and SSA are parameters that can appropriately reflect the geometry of soil structure. They represented the size of aggregates, soil erosion resistance and soil permeability (Pirmoradian et al., 2005; Wang et al., 2014). The FD was previously used to describe the self-similarity and scale independence of objects (Dal Ferro et al., 2013). The calculation of FD was based on the principle of the box counting method: the image stack was covered with cube boxes of different side lengths, and the number of boxes was recorded (Kravchenko et al., 2011; Perret et al., 2003) to satisfy the following relationship (equation [4]):

(4)

where N(ε) is the number of boxes, ε is the side length of the box, FD is the value of fractal dimension.

FD was calculated by linear regression of log{N(ε)} vs log(1/ε), and the range was 2-3. Fractal dimension was computed using the open-source software ImagePy (Wang et al., 2018). Specific surface area is volume-specific surface area, expressed as the ratio of surface area to volume of each aggregate fragment.

The data was analyzed using one-way analysis of variance (ANOVA). Duncan's multiple range method was used to compare mean values, and significant differences between mean values were defined as $P< 0.05$. The results were expressed as the mean standard deviation, and all tables and figures were processed in Microsoft Office Excel 2010.

3 RESULTS

3.1 Soil aggregatequantitative characteristics

Raindrop splashing increased significantly with rainfall intensity ($P < 0.05$, Table 2) and resulted in an increase in the number of soil aggregate fragments. Compared to the undisturbed soil, the total number of soil aggregate particles increased by 38.71%, 46.77% and 76.77% after the impacts of rainfall intensities of 5.76, 68.61 and 217.26 mm h^{-1}, respectively (Table 2). Overall, the number of soil aggregate particles in the undisturbed and disturbed soil showed an "increasing-decreasing-increasing" trend as the aggregate particle size decreased (Fig. 3A). Following raindrop splashing, the number of aggregate particles with different sizes (except for larger aggregates of 500-1000 μm) was higher than that in the undisturbed soil. After raindrop splashing, the quantity of soil aggregate fragments between 250-500 μm increased by 34.88%, 27.91% and 44.19%, respectively, compared to the undisturbed soil ($P< 0.05$, Figure 3A). After splashing with a rainfall intensity of 217.26 mm h^{-1}, the largest quantity of aggregate particles existed in the 106-250 μm range, accounting for 53.36% of the total amount; this value was significantly increased by 98.65% compared to that of the undisturbed soil ($P < 0.05$, Figure 3A).

With the increase in rainfall intensity, the total volume of aggregate fragments raised gradually (Table 2). Compared to the undisturbed soil, the difference was not significant after the impact with a rainfall intensity of 5.76 mm h^{-1} ($P > 0.05$, Table 2). Following impact with rainfall intensities of 68.61 and 217.26 mm h^{-1}, the total volume of aggregate fragments increased 3.21% and 3.73%, respectively, ($P <0.05$, Table 2). The percentage of aggregate volume (%) was the ratio of the aggregate volume of a particles size aggregate to the total aggregate volume in a soil clod, which reflected the distribution of aggregate fragments in the soil. The percentage of aggregate volume under different treatments showed a trend of increasing first and then decreasing with the decrease of particle size, and reached the maximum at 500-250 μm. Compared to the disturbed soil, the aggregate in 500-250 μm of the disturbed soil impacted by 5.76, 68.61 and 217.26 mm·h^{-1} rainfall intensity were significantly ($P< 0.05$) increased by 39.49%, 25.41% and 24.76%, respectively (Fig. 3B). The percentage of aggregate fragments that were >500 μm in disturbed soil was lower than that of undisturbed soil ($P < 0.05$), while it was higher for fragments < 500 μm than that of undisturbed (Figure

3B). In addition, for fragments >106 μm, the volume of soil aggregate particles accounts for more than 99.00% of the total aggregate volume (Figure 3B).

3.2 Soil aggregate fragments characteristic parameters

As shown in Fig. 4A, the fractal dimension of the soil aggregates increased significantly in comparison with the undisturbed soil following different rainfall conditions ($P < 0.05$). After being splashed by rainfall with an intensity of 5.76 or 68.61 mm h^{-1}, the fractal dimension of the soil aggregates had no significant change ($P > 0.05$). After being splashed by rainfall at an intensity of 217.26 mm h^{-1}, the fractal dimension was significantly higher than that of the other treatments ($P < 0.05$). After being splashed by three rainfall intensities, the fractal dimension of the aggregates increased by 2.26%, 2.26% and 3.67% respectively, compared to that of the undisturbed soil.

After raindrop splash, the total specific surface area of the soil aggregates increased significantly ($P < 0.05$, Fig. 4B). The total specific surface area of the splashed soil was significantly different from that of the unsplashed soil ($P < 0.05$), but there was no difference between the rainfall intensities of 5.76 and 68.61 mm h^{-1} ($P > 0.05$, Fig. 4B). The total specific surface areas of the soil aggregates splashed by rainfall intensities of 5.76, 68.61 and 217.26 mm h^{-1} increased by 18.82%, 17.79% and 30.24% respectively (Figure 4B).

The specific surface area of the soil aggregate increased with decreasing aggregate particle size, especially for the < 25 μm aggregates (Figure 4C). For the 500-1000 μm aggregates, the specific surface area of soil splashed with raindrops was significantly higher than that of the unsplashed soil ($P < 0.05$), but there was no significant difference between the different rainfall intensities ($P > 0.05$, Fig. 4C). After raindrop splash, the specific surface areas of the 250-500 μm aggregates were higher than those of the undisturbed soil, whereas the specific surface areas of the 106-250 μm and 53-106 μm aggregates fluctuated. After being splashed by rainfall at an intensity of 68.61 and 217.26 mm h^{-1}, the specific surface area of the 25-53 μm aggregates was significantly different from that of the undisturbed soil, increasing by 31.99% and 102.50% ($P < 0.05$), respectively, and the SSA was significantly higher than that of other rainfall intensities ($P < 0.05$). The specific surface areas of aggregates in the undisturbed soil and splashed soil had a maximum value in the <25 μm range; the specific surface areas of soil splashed by small, medium and large rainfall intensities increased by 9.15%, 10.92% and 17.49%, respectively, compared with undisturbed soil.

3.3 Microstructures of soil aggregates

A significant difference was observed in the two-dimensional shape between the splashed soil aggregates and the undisturbed soil (Figure 2D). The undisturbed soil aggregates primarily consisted of macroaggregates with clear outlines and boundaries, containing more macropores and a relatively loose soil structure (Figure 2A). Compared with the undisturbed soil, the soil structure after raindrop splashing was more compact, the number of macropores was reduced, the number of small and medium aggregates was increased, and the phenomenon of fragmentation was shown. Markedly, after being splashed by rainfall at the intensity of 217.26 mm h^{-1}, the soil aggregates were the most broken (Figure 2B-D). The 3D structural differences of soil aggregates were more obvious than those in 2D (Figure 2 and 3D). After splashing, the percentage of soil macroaggregates was reduced, being replaced by an increased number of microaggregates; this result indicates that the aggregates were obviously broken, and the soil structure was relatively denser. Table 3 reports that the average aggregate particle size in splashed soil was significantly smaller than that of the undisturbed soil ($P < 0.05$), especially after a rainfall intensity of 68.61 and 217.26 mm h^{-1}. The average aggregate particle size decreased by 2.43%, 3.25% and 3.55% after splashed by three rainfall intensities, respectively. This result is consistent with the micromorphology of aggregates.

4 DISCUSSION

4.1 Effect of rainfall intensity on splashed soil aggregates quantitative characteristics

The number of aggregate fragments increased corresponding to the increase in rainfall intensity, especially at 68.61 and 217.26 mm h^{-1} (Table 1). In the process of water erosion, the primary mechanisms of aggregate breakdown are fast wetting and mechanical breakdown caused by raindrop impact (Legout et al., 2005; Shi et al., 2010). The results here show that, with an increase of rainfall intensity, the quantity of aggregates and the degree of fragmentation gradually increase.

In regards to aggregate distribution, aggregates mainly consisted of 250-500 µm, 106-250 µm, and <25 µm particle sizes, whereas for volume, the 106-1000 µm range made up the majority (Fig. 3A and 3B). Raindrop impact on the surface could affect soil erosion and alter aggregate structure in various ways (Kinnell et al., 2005). When the erosion process was dominated by rainfall detachment, the particle size distribution of eroded soil was different from that of the original soil (Slattery and Burt, 1997). It was affected by the particle distribution of the original soil and the destruction of aggregates during erosion (Mahmoodabadi et al., 2014). Based on the number and volume of aggregate fragments, we found that raindrop splashing dispersed larger aggregate particles (500-1000 µm) and broke them into aggregates of smaller particles (<500 µm). Raindrop splashing changed the arrangement of soil particles, decreased the number of larger aggregate particles, and increased the quantity of smaller aggregate particles. As a result, the particles formed by dispersion and fragmentation were deposited in the pores of the upper soil, clogging the pores of the topsoil and forming a thin, dense surface crust with low permeability (Assouline, 2004). In turn, the crust further reduced soil infiltration and exacerbated soil erosion (Sajjadi and Mahmoodabadi, 2015).

4.2 Effect of rainfall intensity on splashed soil aggregate fragment parameters

The impact of raindrops increased the FD of the soil aggregates (Figure 4A). A greater FD value corresponded to a greater degree of aggregate breakdown and detachment. The FD ratios of the aggregates splashed by rainfall intensities of 5.76 and 68.61 mm h^{-1} were higher than those of the aggregates splashed by a rainfall intensity of 217.26 mm h^{-1} because the higher rainfall intensity had higher energy, which strengthened the degree of fragmentation and caused more macroaggregates to decompose into microaggregates. The higher FD value indicates that the particle size distribution of aggregates is dominated by smaller particles, a lower proportion of stable aggregates is present, and the soil structure is inferior (Tyle et al., 1992, Huang et al., 2017). The results presented here show that the raindrop splash was able to break apart the aggregate and destroy the surface soil structure. This is consistent with the result of Fu et al. (2020).

Soil aggregate index, such as specific surface area (SSA), can also reflect the stability of soil aggregates (Pirmoradian et al., 2005). Raindrop splash led to an increase in the total specific surface area of soil aggregates, which increased as the intensity of rainfall increased (Figure 4B). As the particle size decreased, the corresponding specific surface area increased (Figure 4C). This result has proven that a higher specific surface area, leads to a finer soil texture and a stronger soil dispersibility (fragmentation) (Wang et al., 2014). The specific surface area of the aggregates increased significantly, especially in the 25-53 µm and <25µm aggregate particles, after being splashed by 68.61 and 217.26 mm h^{-1} (Figure 4B and 4C). This likely occurred because large raindrops had a stronger rainfall intensity and rainfall energy, thus, increasing the rainfall intensity strengthened the aggregate decomposition (Sajjadi and Mahmoodabadi, 2015). Therefore, the splashed soil aggregates contained more fine particles than before the splash (Figure 4C). Meanwhile, as the particle size of aggregates decreased, they exhibited a smaller mass and smoother shape; furthermore, migration and denudation were more likely to occur during runoff transportation and the underlying pores were more likely to be clogged (Assouline et al., 2004), causing compaction of the aggregate microstructures (Adesodun et al., 2007; Li et al., 2018). In addition, some studies have shown that a greater amount of organic matter content was present in surface soil macroaggregates (Jastrow, 1996) and that aggregates have physical protection for organic matter (Field et al., 2006), while the total specific surface area was negatively correlated with organic matter content. Compared with soil containing higher organic matter content, soil with lower organic matter content showed higher sealing and anti-crust properties (Ramos et al., 2003). Therefore, the aggregate breakdown caused by raindrop splash decreased the soil structure and fertility, reduced the land productivity, and even aggravated the formation of crust (Hu et al., 2018; Fu et al., 2020).

4.3 Effect of raindrop diameters on microscopic characteristics splashed soil aggregates

The microstructure of soil aggregates was different in two and three dimensions after raindrop splash (Figure

2). The splashed soil, especially by large raindrops, displayed an obvious fragmentation of aggregates (Figure 2D). This result indicated that the main cause of aggregate fragmentation was large raindrops. It is easier to form a structure consisting of large aggregates after drying. The formation of surface crust depended on the degree of surface aggregate fragmentation and the stability of the soil structure (Wick et al., 2016; Gelaw et al., 2015). The splashed soil aggregate particle size was smaller than that of the undisturbed soil (Table 2). This result is consistent with that of Ramos et al. (2003), in which the fragmentation of aggregates produced smaller particles than the original soil, allowing the soil to be displaced and reoriented into a more continuous structure; this consequently clogged pores and formed a surface crust. Sajjadi and Mahmoodabadi (2015) found that soil containing finer particle aggregates had a higher transportability of preseparated particles than larger aggregates. Moreover, as particle size decreased and the texture became finer, the pore structure of the soil became denser. The impact of raindrops, which caused physicochemical compaction and dispersion of the surface soil, was the main reason for crust formation and reduction of the infiltration rate (Assouline et al., 2004; Fu et al., 2017). In this study, larger raindrop diameters resulted in greater corresponding rainfall intensity and energy. As a result, soil tends to form a surface crust after heavy rains. The formation of a soil surface crust not only further reduces porosity (Pagliai et al.,2004) but also reduces surface roughness, thereby exacerbating surface runoff and soil loss (Robinson and Phillips, 2001; Assouline and Ben-Hur, 2006).

5 CONCLUSIONS

This study found that the number of aggregates increased as the rainfall intensity increased, especially for the rainfall intensities of 68.61 and 217.26 mm h^{-1} ($P < 0.05$). The distribution of aggregate particles was affected by the original soil distribution and rainfall intensity, which decreased the number of 500-1000 µm aggregate particles and increased the number of < 500µm aggregate particles. The fractal dimension (FD) and specific surface area (SSA) increased significantly after raindrop splash ($P < 0.05$); as rainfall intensity increased, the FD and SSA values also increased. A greater degree of fragmentation led to a higher proportion of fine particles in the soil and more unstable soil aggregates. After raindrop splashing, especially from an intensity of 68.61 and 217.26 mm h^{-1}, the microstructure of aggregates was denser than the undisturbed soil, and the average particle diameter of the aggregate decreased by 2.43%, 3.25% and 3.55%, respectively, compared with the undisturbed soil.

Aggregate breakdown was mainly caused by moderate to great rainfall intensities. The degree of fragmentation increased with the increase of raindrop diameter, rainfall intensity and rainfall energy, and more aggregate particles converted to finer particles. Consequently, these tiny particles intensified the pore clogging and infiltration weakening, exacerbated surface runoff and soil loss and reduced soil fertility; this process even accelerated the formation of surface crust and destroyed the soil structure. Therefore, to improve our understanding of the soil erosion process, synchrotron-based X-ray microcomputed tomography should be more widely used in the field of soil erosion, in combination with other methods, to study microstructure and soil aggregate fragmentation mechanisms.

CONFLICT OF INTEREST

There is no conflict of interest to declare.

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