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# The effects of raindrop impact and runoff detachment on hillslope soil erosion and soil aggregate loss in the Mollisol region of Northeast China

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ABSTRACT

Soil aggregates profoundly influence soil fertility and soil erosion. A large number of studies have showed that soil aggregate loss was mainly affected by raindrop impact and runoff detachment during hillslope erosion process; however, few attempts have been made to investigate which one plays the dominant role in soil aggregate loss. Therefore, a laboratory study was conducted to quantify the effects of raindrop impact and runoff detachment on soil erosion and soil aggregate loss during hillslope erosion processes. A soil pan (8 m long, 1.5 m wide, and 0.6 m deep and with an adjustable slope gradient of 0–35°) was subjected to rainfall simulation experiments under two soil surface conditions: with and without raindrop impact through placing nylon net over soil pan. Two rainfall intensities (50 and 100 mm $h^{-1}$) of representative erosive rainfall and two slope gradients (5 and 10°) in the Mollisol region of Northeast China were subjected to two soil surface conditions. The results showed that raindrop impact played the dominant role in hillslope soil erosion and soil aggregate loss. Soil loss caused by raindrop impact was 3.6–19.8 times higher than that caused by runoff detachment. The contributions of raindrop impact to hillslope soil erosion were 78.3% to 95.2%. As rainfall intensity and slope gradient increased, soil loss caused by raindrop impact and runoff detachment both increased. The loss of each size aggregate was greatly reduced by 46.6–99.4% after eliminating raindrop impact. Meanwhile, the contributions of raindrop impact to the >2, 1–2, 0.5–1, 0.25–0.5 and <0.25 mm soil aggregate loss were 79.1% to 89.7%. Eliminating raindrop impact reduced rainfall intensity effect and increased slope gradient impact on aggregate loss.

## 1. Introduction

Soil erosion is a worldwide problem that directly affects national food security and agricultural sustainability (Yu et al., 2003; Liu et al., 2010). Rain-induced erosion includes the detachment and transport of particles respectively by erosive agents of raindrops and runoff (Ellison, 1947a; Zhang et al., 2007a; Kinnell, 2009; Wakiyama et al., 2010). Raindrop impact makes a large contribution to soil erosion by enhancing soil detachment and runoff disturbance (Gao et al., 2005). When raindrops impact the soil surface, raindrop energy is used to overcome the bonds holding particles in the soil surface (Ma et al., 2014). Then, the detached particles are transported away from the site of drop impact. Runoff, as one of the main erosive agents in water erosion process (Meyer and Monke, 1965), affects soil erosion by transport the eroded particles. Young and Wiersma (1973) showed that the transportation of detached soil particles occurs mostly by surface flow, rather than by rainsplash. Walker et al. (1977) found that sediment delivery with rainfall was about five times greater than that in equivalent flows without rainfall. Guy et al. (1987) designed the experiments to separate the contributions to transport capacity from surface runoff and raindrop impact, and noted that the transport capacity of the rainfall-disturbed flows was 85% attributable to raindrop impact, and only 15% was attributable to runoff.

Soil aggregates as the fundamental unit of soil structure, which have a profound effect on soil fertility and soil erosion (Six et al., 2004; Legout et al., 2005; Wuddivira et al., 2009; Bhattacharyyaa et al., 2010; Hu et al., 2015). Soil aggregates detached by raindrop impact had been recognized as the initiating mechanism of water

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erosion (Ma et al., 2014). Several studies reported that raindrop impact could directly hit soil surface (Young and Wiersma, 1973; Meyer, 1981; Kinnell, 1990; Barthès and Roose, 2002), which led to transport and/or disruption of soil particles and aggregates (Van Dijk et al., 2002; Marzen et al., 2015). The detached particles might be transported within splash-drops or via a shallow overland flow. The loss of disrupted soil material and the size of transported particles depend on the energy of the raindrops and the soil surface properties (Kinnell, 2005).

Numerous studies have shown that interrill soil erosion processes are size selsctive (Poesen and Savat, 1981; Savat and Poesen, 1981; Legout et al., 2005). Studies of the particle-size distribution of eroded sediment can provide a basic understanding of soil erosion processes (Proffitt and Rose, 1991; Meyer et al., 1992; Wan and El-Swaify, 1998). The broken aggregates provide the size distribution of available soil fragments during hillslope water erosion processes, and the process of soil aggregate breakage can greatly control the erosion rate (Leguéois and Le Bissonnais, 2004). In many studies, the size distributions of primary particles and eroded aggregates discharged by rain-impacted flows have been observed to be finer than those in the soil matrix (e.g. Meyer and Harmon, 1984; Sutherland et al., 1996; Wan and El-Swaify, 1998).

The Mollisol in Northeast China, which is rich in organic matter, is considered as one of the most fertile soils in China (Xu et al., 2010). It also has superior physical and chemical characteristics. Therefore, the Mollisol region has became one of the most important food production areas of China (Liu et al., 2010; Liu et al., 2011; Zhang et al., 2012). However, in recent decades, soil erosion has become increasingly serious in this region (Yang et al., 2003; Fang et al., 2012). Severe soil erosion has occurred since large-scale cultivation in the 1950s, and the thickness of the Mollisol has decreased from 50–80 cm in the 1950s to 20–40 cm at present (Zhang et al., 2007b). Yu et al. (1992) reported that 37.9% of the total cultivated land in this area was subject to water erosion. Several studies paid their attention on the effects of raindrop impact on soil erosion and soil aggregate breakage. An et al. (2013) noted that soil loss from the Mollisol hillslopes decreased 59.4–71.6% when eliminate raindrop impact. Chen et al. (2010) reported that soil aggregate dispersion tended to be more obvious with an increase in rainfall intensity. Zhou et al. (2008) reported that during the splash process, the Mollisol aggregates of ≥1.0 mm were difficult to transport, whereas they were easily detached by raindrop impact. Shen et al. (2008) noted that macroaggregates tended to be broken down by water erosion, including raindrop impact and surface flow detachment, and microaggregates were preferentially transported. Although numerous studies of soil aggregates have been conducted in the Mollisol region, the breakdown mechanisms and loss characteristics of the Mollisol aggregates require further investigation.

To promote studies in the Mollisol region of Northeast China, additional experimental studies are necessary to understand soil aggregate loss characteristics to prevent soil erosion. Therefore, a laboratory study was conducted under controlled experimental conditions. The objectives of this study were to investigate the effects of raindrop impact and runoff detachment on soil erosion and soil aggregate loss, and to analyze the aggregate size distribution in the sediment. The results can provide a scientific basis for protecting the precious Mollisol resources.

## 2. Materials and methods

### 2.1. Experimental materials

The experiments were completed in the rainfall simulation laboratory of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Yangling City, China. A side sprinkler rainfall simulator system was used to apply rainfall. This rainfall simulator can be set to any selected rainfall intensity, ranging from 20 to 300 mm h$^{-1}$, by adjusting the water pressure and spray nozzle size. The height of the nozzles is approximately 16 m above the surface ground. The simulated rainfall, with a uniformity greater than 90%, is similar to natural rainfall with respect to both raindrop size distribution and kinetic energy (Zhou et al., 2000). Calibration of rainfall intensity was conducted prior to the running experiments in order that the experimental rainfall intensity reached the target rainfall intensity. The experiments were conducted in a slope adjustable pan measuring 8 m long, 1.5 m wide and 0.6 m deep, with holes (2 cm aperture) at the bottom to facilitate drainage. The pan could be inclined at any slope gradient from 0 to 35°. A runoff collector was installed at the bottom of the soil pan, which was used to collect runoff samples during the experimental process.

The soil used in this study, which was classified as a Mollisol (USDA Taxonomy), had 3.3% sand (>50 μm), 76.4% silt (50–2 μm), 20.3% clay content (<2 μm) and 23.8 g kg$^{-1}$ soil organic matter. The pipette method and the potassium dichromate oxidation-external heating method were used to analyze soil texture and soil organic matter, respectively. The experimental soil was collected from the plow layer of a maize field in Liujia Town (44°43′N, 126°11′E), Yushu City, Jilin Province, in the center of the Mollisol region in Northeast China. Prior to conducting the experiments, the soil was air-dried. Impurities such as organic matter and gravel were removed, but the soil was not passed through a sieve to maintain its natural state of the soil.

### 2.2. Experimental setup

The experimental treatments in this study included two surface conditions, i.e. with and without raindrop impact. For the soil surface condition with raindrop impact, the soil surface of the soil pan was bare and fallow. For the soil surface without raindrop impact, a nylon net (1-mm aperture) was placed 10 cm above the soil pan, which reduced the raindrop kinetic energy by 99.6% (Zheng et al., 1995). These two surface conditions were subjected to two rainfall intensities (50 and 100 mm h$^{-1}$) and two slope gradients (5 and 10°). Moderate intensity of soil erosion is generally caused by momentary rainfall intensities ≥42.6 mm h$^{-1}$, and in some cases, the momentary rainfall intensity has reached 103.2 mm h$^{-1}$ in the typical Mollisol region of Northeast China (Zhang et al., 1992). Thus, the 50 and 100 mm h$^{-1}$ were designed as the representative rainfall intensities. Slope gradients are mainly between 1 and 8°, and sometimes they exceed 10° in the Mollisol region of Northeast China. The 10° was representing the gradient of severe soil erosion region. Therefore, 5 and 10° was determined as the experimental slope gradient.

### 2.3. Experimental procedures

Before packing each soil pan, the soil water content of the tested soil was determined, which was used to calculate how much soil was needed to pack the soil pan and to obtain the target bulk densities for the different soil layers. First, a 10-cm-thick layer of sand was packed at the bottom of soil pan, which allowed free drainage of excessive water. Then, a 20-cm Mollisol layer (simulated plow pan) with a bulk density of 1.35 g cm$^{-3}$ was packed above the sand layer, and a 20-cm Mollisol layer (simulated tilth layer) with a bulk density of 1.20 g cm$^{-3}$ was packed above the plow pan. Additional details on the packing process can be found in An et al. (2012).

After the preparation of the soil pan, a pre-rain with a rainfall intensity of 25 mm h$^{-1}$ was applied to the experimental soil pan until surface flow occurred. The duration of this pre-rain was approximately 30 min. The purposes of the pre-rain were to maintain consistent soil moisture and reduce spatial variation of soil surface. One day after the pre-rain, the rainfall intensity was calibrated to confirm the run-rainfall intensity reached the target rainfall intensity and met the experimental requirements. Then, the soil pan was adjusted to the designed slope gradients (5 or 10°) and rainfall intensities (50 or 100 mm h$^{-1}$). All experimental treatments had the same run time of 60 min. Each treatment was conducted twice.

### *2.4. Experimental measurements*

#### *2.4.1. Runoff and soil loss*

The designed rainfall intensity (50 or 100 mm h$^{-1}$) was applied to the soil pan. For each treatment, after runoff occurred, runoff samples were collected in 15-L buckets. The samples were measured for the duration of the run (60 min). In the same time interval, two runoff samples were collected; one was used for the calculation of soil loss. The samples were weighed and allowed to stand such that the suspended sediments settled out. The clear supernatant was decanted, and the remaining sediment was oven-dried at 105 °C and weighed to calculate sediment yield. The remaining runoff sample was immediately sieved to calculate the soil aggregate loss.

Ellison (1944) and Ellison (1947a,b,c) divided the erosion process into rainfall erosion, runoff erosion and rainfall transport, and runoff transport. Kinnell (2000, 2001, 2006) identified four detachment and transport systems operate in rainfall erosion: raindrop detachment-splash transport, raindrop detachment-raindrop-induced flow transport, raindrop detachment- flow transport, and flow detachment-flow transport. Accordingly, soil loss for the treatments with raindrop impact was considered as the contribution of raindrop impact and runoff detachment simultaneously. For the treatments without raindrop impact, soil loss was mainly caused by runoff detachment. The difference between the treatments with and without raindrop impact could be identified the contribution of raindrop impact to soil erosion and soil aggregate loss.

#### *2.4.2. Aggregate size distribution in the sediment*

As runoff occurred, the samples for analyzing aggregate size distribution were measured in 6 min intervals during rainfall duration, so total 8 samples were collected during each run. The runoff samples, which were used to investigate aggregate loss, were immediately processed through a set of sieves with apertures of 5, 2, 1, 0.5, and 0.25 mm. After sieving, the lost aggregate samples were oven-dried to calculate the soil aggregate loss and aggregate size distribution.

#### *2.4.3. Aggregate size distribution of the tested soil*

The aggregate size distribution was measured using a wet-sieving method (Yoder, 1936; ISSAS, 1978). The air-dried soil samples were sieved using an electric oscillator on a column of six sieves: 5, 3, 2, 1, 0.5 and 0.25 mm. The mass percentage of each size fraction was calculated. Based on these percentages, composite soil samples were used for wet sieving. The soils were wetted slowly by adding water to saturation and kept for 10 min so as to drive entrapped air from the aggregates. Next, the fractions of aggregates remaining on each sieve were collected, oven-dried (at 40 °C) and weighed to calculate the percentage of each aggregate size.

### *2.5. Data analysis*

Statistical analysis was performed using SPSS 19.0 software (SPSS Inc., Chicago, IL, USA). Analysis of variance (ANOVA) was conducted to examine significant differences in runoff and soil loss. For the results of multiple comparisons, the method of least significant difference (Tukey test) procedure was used, and the values were statistically significant at the 95% confidence level.

## **3. Results and discussion**

### *3.1. Runoff and soil loss*

#### *3.1.1. Runoff*

Runoff for the treatments without raindrop impact (without RI) was lower than that for the treatments with raindrop impact (with RI), but there were no significant differences in runoff between with and without raindrop impact (with and without RI) treatments (Table 1). Because the elimination of raindrop impact by the nylon net cover reduced the raindrop kinetic energy, which prevented surface soil sealing formation and increased soil infiltration.

For the treatments with and without RI, with an increase of rainfall intensity, runoff was significantly increased. Runoff was 1.5–1.7 and 1.7–1.8 times higher at the 100 mm h$^{-1}$ rainfall intensity than that at the 50 mm h$^{-1}$ rainfall intensity for the treatments with RI and without RI, respectively (Table 1). When slope gradient changed from 5° to 10°, runoff significantly increased at 100 mm h$^{-1}$ rainfall intensity, but there was no significant difference in runoff between 5° and 10° at 50 mm h$^{-1}$ rainfall intensity. With an increase of rainfall intensity, raindrop impact increased correspondingly. This induced greater soil compaction and sealing, which decreased soil infiltration and resulted in more runoff production. Ribolzi et al. (2011) also reported that the surface seal was more developed under higher rainfall intensities and on steeper hillslopes.

**Table 1**
Runoff and soil loss for the treatments with and without raindrop impact under different rainfall intensities and slope gradients.

| Slope gradient (°) | Rainfall intensity (mm h$^{-1}$) | Runoff (mm) | | Soil loss (g m$^{-2}$) | |
|---|---|---|---|---|---|
| | | With raindrop impact (with RI) | Without raindrop impact (without RI) | Caused by raindrop impact | Caused by runoff detachment |
| 5 | 50 | 35.8 ± 1.5 A[§]c[†] | 29.3 ± 2.2 Ac | 179.5 ± 1.9 Ab | 14.3 ± 0.6 Bb |
| | 100 | 54.5 ± 0.0 Ab | 50.6 ± 2.3 Ab | 387.7 ± 21.3 Ab | 107.2 ± 9.4 Ba |
| 10 | 50 | 37.8 ± 0.7 Ac | 33.3 ± 0.7 Ac | 295.1 ± 18.5 Ab | 34.8 ± 2.2 Bb |
| | 100 | 64.6 ± 3.8 Aa | 61.0 ± 2.7 Aa | 2484.7 ± 220.0 Aa | 125.5 ± 7.8 Ba |

[§] Mean values with treatments between with and without raindrop impact followed by any identical capital letters at the same row are not statistically different at the 95% confidence level according to *T* tests.

[†] Mean values at the same column followed by any identical lowercase letters are not statistically different at the 95% confidence level according to Tukey tests.

**Table 2**
The aggregate loss in the sediment for the treatments with and without raindrop impact under different rainfall intensities and slope gradients.

| Slope gradient (°) | Rainfall intensity (mm h$^{-1}$) | Aggregate loss (g m$^{-2}$) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | >2 mm | | >1 mm | | >0.5 mm | | >0.25 mm | | <0.25 mm | |
| | | With RI | Without RI | With RI | Without RI | With RI | Without RI | With RI | Without RI | With RI | Without RI |
| 5 | 50 | 3.5 ± 0.2 A[§]b[†] | 0.3 ± 0.0 Bc | 16.4 ± 1.3 Ab | 1.3 ± 0.0 Bb | 26.5 ± 1.3 Ab | 2.4 ± 0.0 Bb | 33.6 ± 1.9 Ab | 3.4 ± 0.0 Bb | 160.2 ± 0.5 Ab | 11.0 ± 0.6 Bd |
| | 100 | 4.5 ± 0.4 Ab | 0.4 ± 0.0 Bbc | 9.5 ± 0.8 Ab | 1.7 ± 0.0 Bb | 12.8 ± 1.1 Ab | 2.9 ± 0.1 Bb | 15.8 ± 1.2 Ab | 4.6 ± 0.1 Bb | 479.0 ± 10.8 Ab | 95.7 ± 0.3 Bb |
| 10 | 50 | 4.1 ± 0.0 Ab | 0.8 ± 0.1 Bb | 30.1 ± 0.6 Ab | 3.7 ± 0.5 Ba | 50.9 ± 0.2 Ab | 6.5 ± 0.7 Ba | 65.7 ± 0.4 Ab | 8.8 ± 0.9 Ba | 264.2 ± 16.7 Ab | 26.0 ± 1.4 Bc |
| | 100 | 143.2 ± 10.2 Aa | 2.0 ± 0.2 Ba | 435.0 ± 19.2 Aa | 4.3 ± 0.6 Ba | 656.4 ± 31.6 Aa | 6.1 ± 0.9 Ba | 965.6 ± 49.4 Aa | 7.8 ± 1.1 Ba | 1644.5 ± 162.7 Aa | 117.6 ± 6.7 Ba |

[§] Mean values with treatments between with and without raindrop impact followed by any identical capital letters at the same row are not statistically different at the 95% confidence level according to T tests.
[†] Mean values at the same column followed by any identical lowercase letters are not statistically different at the 95% confidence level according to Tukey tests.

### 3.1.2. Soil loss

Soil loss between the treatments caused by raindrop impact and runoff detachment was showed a significant difference (Table 1). Soil loss caused by raindrop impact was 3.6–19.8 times higher than that by runoff detachment. The contribution of raindrop impact in soil loss was greater than that of runoff detachment, which accounted for 78.3–95.2% to the total soil loss. This result was similar to that obtained by Guy et al. (1987), who noted that 85% of the total soil loss was induced by raindrop impact. The results indicate that raindrop impact played a key role during the rainfall process. Therefore, taking effective measures to prevent the soil loss by weakening the effect of raindrop impact, e.g., with the use of wheat straw mulch (Jin et al., 2009; Zhang et al., 2009) or a temporary grass ley (Fullen, 1998), are useful for soil conservation. Once raindrop kinetic energy was eliminated, the broken soil aggregates caused by raindrop impact were reduced, and soil loss obviously decreased correspondingly.

As rainfall intensity increased from 50 to 100 mm h$^{-1}$, soil loss caused by raindrop impact and runoff detachment increased 2.2–8.4 and 3.6–7.5 times, respectively. The result was similar to that obtained by Mermut et al. (1997), who noted that soil loss with high rainfall intensity (100 mm h$^{-1}$) was 3.8 times higher than the lower rainfall intensity (40 mm h$^{-1}$). Soil loss caused by raindrop impact and runoff detachment increased 1.6–6.4 and 1.2–2.4 times with an increase of slope gradient, respectively (Table 1).

## 3.2. Soil aggregate loss

### 3.2.1. The effect of raindrop impact on soil aggregate loss

The loss of <0.25 mm aggregates was the highest for all treatments, which was 1.7–30.2 times higher than the loss of >0.25 mm aggregates (Table 2). The loss of <0.25 mm aggregates accounted for 63.0–96.8% of the total aggregate loss. This result indicated that the loss of <0.25 mm aggregates played a dominate role in soil aggregate loss. Le Bissonais (2006) reported that fine material was more easily transported than coarse material.

Compared with the treatments without RI, the each size soil aggregate loss was significantly increased in the treatments with RI. The contributions of raindrop impact to the >2, 1–2, 0.5–1, 0.25–0.5 and <0.25 mm soil aggregate loss were 89.7%, 89.1%, 84.2%, 79.1%, and 88.7%, respectively (Table 2). Meanwhile, the contribution of raindrop impact to the >1 mm soil aggregate loss reached to 90.4%. This result indicated that the crucial mechanism of soil aggregate breakage was raindrop impact.

For the treatments with RI, as rainfall intensity increased from 50 to 100 mm h$^{-1}$, the loss of >1, >0.5, and >0.25 mm soil aggregate at 5° slope decreased 42.4%, 51.6%, and 52.8%, respectively; while the loss of > 2 mm soil aggregate increased 27% (Table 2). Furthermore, the loss of >2, >1, >0.5, and >0.25 mm soil aggregate at 10° slope increased 33.8, 13.4, 11.9, and 13.7 times, respectively. Relatively large sized aggregates are prone to mechanical breakdown during rainfall under higher rainfall intensities (Ma et al., 2014). Because raindrop impact preferred to break the large sized soil aggregates into small sized aggregates. The detachment capability of the large sized aggregates increased with an increase of rainfall (Shen et al., 2008). Additionally, at 5° slope, runoff was generally not sufficiently energetic to transport the larger aggregates, or alternatively, they were preferentially deposited. As slope gradient increased from 5 to 10°, the loss of >2, >1, >0.5, and >0.25 mm soil aggregate at the 50 mm h$^{-1}$ rainfall intensity increased 0.2, 0.8, 0.9, and1.0 times, respectively; while there was no significant difference between 5 and 10°. For the 100 mm h$^{-1}$ rainfall intensity, the loss of >2, >1, >0.5, and >0.25 mm aggregate significantly increased 31.1, 45.0, 50.2, and 59.9 times with an increase of slope gradient. An increase in slope gradient resulted in increasing of flow velocity and shear force, which enhanced runoff

**Table 3**
Aggregate size distribution in the sediment as affected by raindrop impact, rainfall intensity, and slope gradient.

| Slope gradient (°) | Rainfall intensity (mm h$^{-1}$) | With or without raindrop impact (with or without RI) | Aggregate size distribution (%) | | | | |
|---|---|---|---|---|---|---|---|
| | | | >2 mm | 1–2 mm | 0.5–1 mm | 0.25–0.5 mm | <0.25 mm |
| 5 | 50 | With RI | 1.8 ± 0.1 a[§] | 6.7 ± 0.5 a | 5.2 ± 0.0 a | 3.7 ± 0.3 b | 82.6 ± 0.8 a |
| | | Without RI | 2.3 ± 0.1 a | 6.7 ± 0.1 a | 8.1 ± 0.7 a | 6.4 ± 0.3 a | 76.5 ± 1.0 b |
| | 100 | With RI | 0.9 ± 0.1 a | 1.0 ± 0.1 a | 0.7 ± 0.1 a | 0.6 ± 0.0 b | 96.8 ± 0.2 a |
| | | Without RI | 0.4 ± 0.0 b | 1.1 ± 0.1 a | 1.2 ± 0.1 a | 1.6 ± 0.1 a | 95.7 ± 0.3 b |
| 10 | 50 | With RI | 1.3 ± 0.1 b | 7.9 ± 0.6 a | 6.3 ± 0.2 b | 4.5 ± 0.3 b | 80.0 ± 1.1 a |
| | | Without RI | 2.4 ± 0.1 a | 8.1 ± 0.6 a | 8.2 ± 0.2 a | 6.5 ± 0.1 a | 74.8 ± 0.9 b |
| | 100 | With RI | 5.5 ± 0.1 a | 11.2 ± 0.6 a | 8.5 ± 0.2 a | 11.9 ± 0.3 a | 62.9 ± 1.1 b |
| | | Without RI | 1.6 ± 0.1 b | 1.8 ± 0.2 b | 1.5 ± 0.1 b | 1.4 ± 0.1 b | 93.7 ± 0.5 a |
| The tested soil (wetting-sieving method) | | | 2.0 | 6.8 | 22.8 | 22.2 | 46.2 |

[§] Mean values with treatments with and without raindrop impact followed by any identical lowercase letters are not statistically different at the 95% confidence level according to *T* tests.

detachment and transport capacity, and subsequently, increased soil aggregate loss (Poesen, 1984). Thus, as the influence of raindrop impact continued, slope gradient exhibited greater impact on the soil aggregate loss.

### 3.2.2. The effect of runoff detachment on soil aggregate loss

For the treatments without RI, the each size loss of >0.25 mm soil aggregate caused by runoff detachment was very low with value of 8.8 g m$^{-2}$. The >0.25 mm soil aggregate loss caused by runoff detachment increased as slope gradient changed from 5 to 10° for the treatments without RI. The loss of >2, > 1, >0.5, and >0.25 mm soil aggregate increased 1.6–1.8 and 0.7–3.7 times at the 50 mm h$^{-1}$ and 100 mm h$^{-1}$ rainfall intensity, respectively. However, there was no significant difference in the >2, >1, >0.5, and >0.25 mm soil aggregate loss between 50 and 100 mm h$^{-1}$ rainfall intensity. These results showed that after eliminating raindrop impact, the effect of rainfall intensity on aggregate loss has weakened. Instead, the role of slope gradient on aggregate loss increased.

### 3.3. Aggregate size distribution in the sediment

The aggregate size distribution in the sediment resulting from erosion is a complex process (Rienzi et al., 2013). The aggregate size distribution in the sediment was affected by raindrop impact and runoff detachment during the rainfall process. The difference in aggregate size distribution between different treatments indicated selectivity during hillslope soil erosion process (Table 3).

Compared with the treatments without RI, the loss percentage of the >0.25 mm (>2, 1–2, 0.5–1, and 0.25–0.5 mm) aggregates decreased except for 10° slope under 100 mm h$^{-1}$ rainfall intensity (Table 3). There was no significant difference in the loss percentage of the >0.25 mm aggregates between the treatments with and without RI at 5° slope; while for 10° slope under 100 mm h$^{-1}$ rainfall intensity, the loss percentage of the >0.25 mm aggregates with RI significantly greater than that without RI. For the treatments with RI, the loss percentage of the >0.25 mm aggregates decreased with rainfall intensity increased from 50 to 100 mm h$^{-1}$ at 5° slope. However, at 10° slope, the loss percentage of the >0.25 mm aggregates size increased with an increase of rainfall intensity. Slope gradient of 5° was relatively gentler, runoff transportation capacity was limited (Sutherland et al., 1996); while at 10° slope, runoff was of sufficiently energetic to transport the larger size aggregates. Besides, high rainfall intensity and steep slope gradient led to a greater soil aggregate loss. Rainfall intensity affected soil aggregate size distribution as a result of the raindrop kinetic energy, which detached all aggregate sizes. Slope gradient influenced the soil aggregate size distribution by transported the broken aggregates which were detached by raindrop impact.

After eliminating raindrop impact, the loss percentage of >0.25 mm aggregates generally showed an increasing trend, except for the treatment of 10° under 100 mm h$^{-1}$ rainfall intensity. Because the elimination of raindrop impact reduced the raindrop kinetic energy and runoff entrainment capacity, which prevented soil aggregate breakage. Beuselinck et al. (2002) and An et al. (2012) noted that when raindrop impact was eliminated, flow depth and flow velocity were both reduced. Thus, after eliminating raindrop impact, there was a weakened effect of raindrop impact on soil aggregate breakage, and runoff did not have sufficient energy to detach the >0.25 mm aggregates. For the treatments without RI, the loss percentage of >0.25 mm aggregates decreased with an increase of rainfall intensity, with a reduction rate of 58.0–83.4%. With an increase of slope gradient, the loss percentage of >0.25 mm aggregates (>2, 1–2, 0.5–1, and 0.25–0.5 mm) increased, but there was no significant increase between 5 and 10° slope gradient. These results showed that eliminating raindrop impact reduced slope gradient impacts on aggregate size distribution.

For the treatments with RI, the loss percentage of >0.25 mm aggregates was less than that in the tested soil, with an average reduction of 63.9%. In particular, the values of 0.5–1 and 0.25–0.5 mm aggregates were 77.3% and 76.7% lower than those in the tested soil, respectively. The loss percentage of >2 and 1–2 mm aggregates for the treatment of 5° slope under the 50 mm h$^{-1}$ rainfall intensity was 10.0% and 1.5% lower than those in the tested soil, respectively. As rainfall intensity increased from 50 to 100 mm h$^{-1}$ rainfall intensity, the loss percentage of >2 and 1–2 mm aggregates were 55.0% and 85.3% lower than those in the tested soil. However, for the treatment of 10° slope under 100 mm h$^{-1}$ rainfall intensity, the loss percentages of >2 and 1–2 mm aggregate were 1.7 and 0.6 times higher than those in the tested soil, respectively. The reason was that an increase in rainfall intensity or slope gradient, causing greater sediment concentration and a higher runoff rate, enhanced hillslope erosion, and resulted in greater breakage of soil aggregates.

For the treatments without RI, the loss percentage of >0.25 mm aggregates was less than that in the tested soil, with an average reduction of 72.4%. In particular, the percentage of the total sediment mass represented by the 0.5–1 and 0.25–0.5 mm sizes decreased 79.2% and 82.1%, respectively. This indicated that the loss percentage of soil aggregates in the intermediate size ranges (0.5–1 and 0.25–0.5 mm) resulted from the high abrasion rate of the larger aggregates due to runoff. This result was similar to that reported by Martinez-Mena et al. (2000), who noted that the aggregate size of the sediment was finer than that of the matrix soil. A comparison of the aggregate size distribution between the sediment and the original soil indicated the existence of transport selectivity in the rainfall process.

## 4. Conclusions

The effect of raindrop impact contributed 86.8% of soil loss. Compared with the treatments with RI, the each size aggregate loss was significantly reduced for the treatments without RI, with reduction rates of 45.1% to 99.4%. The contributions of raindrop impact to the >2, 1–2, 0.5–1 and 0.25–0.5 mm soil aggregate loss were 89.7%, 89.1%, 84.2%, 79.1%, and 88.7%, respectively. Raindrop impact played an important role on soil erosion and soil aggregate loss. As rainfall intensity and slope gradient increased, soil loss caused by raindrop impact and runoff detachment increased. For the treatments with RI, the >0.25 mm soil aggregate loss decreased 52.8% at 5° slope with an increase of rainfall intensity; while it increased 13.7 times at 10° slope. As slope gradient increased, the >0.25 mm soil aggregate loss increased 1.0 times at the 50 mm $h^{-1}$ rainfall intensity; and it siginicatly increased 59.9 times at the 100 mm $h^{-1}$ rainfall intensity. For the treatments without RI, the >0.25 mm soil aggregate loss caused by runoff detachment significantly increased as slope gradient changed from 5 to 10°. The loss percentage of >0.25 mm aggregates generally showed an increased trend after eliminating raindrop impact, except for the treatment of 10° slope under 100 mm $h^{-1}$ rainfall intensity. As rainfall intensity increased from 50 to 100 mm $h^{-1}$, the loss percentage of >0.25 mm aggregates decreased at 5° slope; while it showed an opposite trend at 10° slope for the treatments with RI. For the treatments without RI, the loss percentage of >0.25 mm aggregates decreased with an increase of rainfall intensity, with a reduction rate of 58.0–83.4%, and there was no significant increased in the loss percentage of >0.25 mm aggregates between 5 and 10° slope.

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