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Rainfall and inflow effects on soil erosion for hillslopes dominated by sheet erosion or rill erosion in the Chinese Mollisol region

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Abstract: Erosion agents and patterns profoundly affect hillslope soil loss characteristics. However, few attempts have been made to analyze the effects of rainfall and inflow on soil erosion for hillslopes dominated by sheet erosion or rill erosion in the Chinese Mollisol region. The objective of this study was to discuss the erosive agent (rainfall or inflow), hillslope erosion pattern (sheet erosion or rill erosion) and slope gradient effects on runoff and soil losses. Two soil pans (2.0 m long, 0.5 m wide and 0.5 m deep) with 5° and 10° slopes were subjected to rainfall (0 and 70 mm h^{-1}) and inflow (0 and 70 mm h^{-1}) experiments. Three experimental combinations of rainfall intensity (RI) and inflow rate (IR) were tested using the same water supply of 70 mm by controlling the run time. A flat soil surface and a soil bed with a straight initial rill were prepared manually, and represented hillslopes dominated by sheet erosion and rill erosion, respectively. The results showed that soil losses had greater differences among treatments than total runoff. Soil losses decreased in the order of RI70+IR70 > RI70+IR0 > RI0+IR70. Additionally, soil losses for hillslopes dominated by rill erosion were 1.7-2.2 times greater at 5° and 2.5-6.9 times greater at 10° than those for hillslopes dominated by sheet erosion. The loss of <0.25 mm soil particles and aggregates varying from 47.72%-99.60% of the total soil loss played a dominant role in the sediment. Compared with sheet erosion hillslopes, rill erosion hillslopes selectively transported more microaggregates under a relatively stable rill development stage, but rills transported increasingly

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more macroaggregates under an active rill development stage. In conclusion, eliminating raindrop impact on relatively gentle hillslopes and preventing rill development on relatively steep hillslopes would be useful measures to decrease soil erosion and soil degradation in the Mollisol region of northeastern China.

Keywords: Runoff; Soil loss; Slope gradient; Rill erosion; Mollisol region;

Introduction

The Mollisol region plays an important role in the food supply and agricultural sustainability in China (Ou et al. 2017). However, soil erosion in this region has become increasingly severe since the Mollisol land has been widely cultivated from the 1950s (Zhang et al. 2007; Liu et al. 2011). The soil erosion area is 216,600 km^2 based on the first nationwide water resources survey of China in 2010-2012, which accounts for ~20.0% of the total area of the Mollisol region. Soil erosion degrades the soil on-site and results in environmental problems due to deposition in areas off-site from the source field (Pelt et al. 2017). Hillslopes with long slope lengths and gentle slope gradients are the major sloping croplands, which generate severe topsoil erosion resulting in deposition at the toe of slopes in the Mollisol region (Xu et al. 2010). Once the topsoil is carried away, agricultural development is adversely influenced (Liu et al. 2013; Yao et al. 2017). Thus, preventing soil erosion is critical to protecting valuable Mollisol resources.

Many factors such as the erosive agent (rainfall or runoff), the hillslope erosion pattern (sheet erosion or rill erosion), and the topography (slope length and slope gradient) affect soil erosion characteristics. Rainfall is an important agent of soil erosion due to its potential to breakdown of aggregates, detachment of soil particles, runoff production (Oliveira et al. 2013). Runoff determines how much of the detached material is transported on hillslopes (Strohmeier et al. 2016). Sheet erosion caused mostly by raindrop detachment with transport by shallow flow is a great threat for many developing countries and affects cultivated soils (Kinnell 2005; Descroix et al. 2008). Rills commonly provide the dominant transport network on a hillslope erosion period (Shen et al. 2015; He et al. 2016). Furthermore, the topography is also one of the most important factors influencing soil erosion in the Chinese Mollisol region, and the slope gradient receives more attention than the slope length under the indoor simulated experiments due to the limitations of laboratory space (e.g., Cui et al. 2007; Lu et al. 2016). Although studies on the factors influencing soil erosion have been carried out for several years (Xu et al. 2010; Nearing et al. 2017), few attempts have been made to systematically analyze the effects of the erosive agent, hillslope erosion pattern, and topography on soil erosion in the Chinese Mollisol region. Therefore, deeper insight into the soil erosion mechanism obtained by adjusting the influencing factors on the hillslopes of this region is essential.

Soil degradation by water is a three-phase process that consists of the detachment of soil particles by either raindrop impact or surface water flow from the soil mass, the transport of detached particles, and deposition of eroded sediment (Vaezi et al. 2017). The sediment leaving an eroding area is a combination of primary soil particles and secondary or soil aggregates (Asadi et al. 2007). Soil aggregates have an important effect on soil fertility and soil erosion (Legout et al. 2005). Soil erosion results in a loss of soil organic matter which fosters a breakdown in soil aggregates and increase in the erosion of particles and aggregates (Barthes and Roose 2002; Barral et al. 2007). Although the Mollisol in northeastern China is considered one of the most fertile soils in China because of its rich organic matter content (Xu et al. 2010), the problem of soil particle and aggregate loss cannot be ignored (Liu et al. 2011).

The loss of soil particles and aggregates is mainly affected by both the detachment and breakdown of raindrop impact and runoff transport during hillslope erosion processes (Ma et al. 2014; Vaezi et al. 2017). Rainfall usually breaks macroaggregates into microaggregates and runoff selectively transports the finer particles (Issa et al. 2006; Jiang et al. 2013). Asadi et al. (2007) have demonstrated that the particles between 0.1 and 0.5 mm appear to resist transportation. Lu et al. (2016) have noted that the contributions of raindrop impact to the >0.25 and <0.25 mm soil aggregate loss are between 79.1% -89.7%. However, the transport effects of sheet flow (Hairsine and Rose 1992a) and rill flow (Hairsine and Rose 1992b) on the particle size distribution of the eroding sediment are still unclear.

There is still a gap in understanding the intrinsic mechanism of soil erosion in the Chinese Mollisol region, although the magnitude of the gap might vary. Therefore, a laboratory study focusing on the soil erosion characteristics of the Mollisol region was conducted under controlled experimental conditions. The objective of this study was to analyze the effects of the erosive agent (i.e., rainfall and inflow), hillslope erosion pattern (i.e., sheet erosion and rill erosion) and slope gradient on the total runoff, soil loss, runoff rates, sediment concentration, soil particle and aggregate size distributions. An understanding of soil erosion processes is not only useful for soil erosion prediction models but also important for the prevention of soil erosion on the Mollisol hillslopes of northeastern China.

1 Materials and Methods

1.1 Experimental equipment and materials

The study was carried out in the rainfall simulation laboratory of the Scientific Research Base of Soil and Water Conservation (43°52′N, 125°21′E) in Jilin Agricultural University, which is located in the typical Mollisol region of northeastern China. Two slope-adjustable soil pans, 2.0 m long, 0.5 m wide and 0.5 m deep, with holes (2 cm aperture) at the bottom to facilitate water discharge were used to run the experiments. The rainfall experiments were conducted with a downward-facing sprinkler rainfall simulator system set at 6 m height above the floor, and the drop uniformity was >90%. The inflow experiments were completed with the overflow tank used for supplying the inflow water, which was attached to the upper end of the soil pan. A schematic representation of the experimental setup including the inflow supply device was shown by Wen et al. (2015). The water used in experiments came from groundwater, the pH was 7.12 and its turbidity was less than 1 NTU.

The soil used in this study was black soil that was classified as Mollisol in the US Soil Taxonomy (Nearing et al. 2017). The particle size distribution was 10.2% sand (>50 μm), 9.6% silt (50-2 μm), and 80.2% clay (<2 μm), while the content of soil organic matter was 25.6 g kg^{-1}. The tested soil was collected from 0–20 cm in the Ap horizon of a well-drained site in the croplands of Jilin Agricultural University. The soil was not passed through any sieve to maintain its natural state but was freed of clods greater than 8 mm and undecomposed plant residues (Asadi et al. 2007).

1.2 Experimental design

The designed 70 mm h^{-1} rainfall intensity was close to the maximum rainfall within 1 h recorded for a 50-year recurrence period, which was obtained from precipitation data for 1983-2012 at the Changchun national benchmark weather station (Liu et al. 2014). The inflow rate was the same as the rainfall intensity based on the area of soil bed. A total water supply of 70 mm during each treatment was maintained. Thus, three experimental variations of rainfall intensity (RI) and inflow rate (IR) were tested, and the run time was 60 or 30 min (Table 1). The designed slope gradients were 5° and 10° according to the topographic features of the Chinese Mollisol region (Wen et al. 2015). Hillslopes dominated by sheet erosion and rill erosion were selected because they are two common and severe soil erosion patterns in the region (Liu et al. 2010; Guo et al. 2015). The hillslope dominated by sheet erosion was a flat soil surface. The hillslope dominated by rill erosion was a soil bed with a prepared straight initial rill (100 cm-long, 10 cm-wide and 5 cm-deep) located 80-180 cm from the top of the hillslope (Figure 1). The prepared straight initial rill was similar to that used in the study by Strohmeier et al. (2014). Each treatment was conducted two times.

Table 1 Experimental design of rainfall simulation laboratory under different rainfall intensity (RI) and inflow rate (IR)

Slope	RI (mm h^{-1})	IR (mm h^{-1})	Variation of RI and IR	Time (min)
5°	70	0	RI70+IR0	60
	0	70	RI0+IR70	60
	70	70	RI70+IR70	30
10°	70	0	RI70+IR0	60
	0	70	RI0+IR70	60
	70	70	RI70+IR70	30

Figure 1 Test soil pan with hillslopes dominated by sheet erosion (a) and rill erosion (b).

1.3 Experimental procedures

The soil pan was first packed with a 5-cm-thick layer of sand at the bottom for free drainage of excess water. A plow pan with a depth of 15 cm and a tilth layer with a depth of 20 cm were placed over the sand layer to simulate the cropland condition. The bulk densities of the plow pan and the tilth layer were 1.35 and 1.20 g cm^{-3}, respectively. During the packing process, both the plow pan and tillage layer were packed in 5-cm increments, and each packed soil layer was raked lightly before the next layer was packed to ensure uniformity and continuity in the soil structure. The detailed process of packing a soil pan is described in Shen et al. (2015).

To maintain consistent soil moisture, a prerain with a rainfall intensity of 30 mm h^{-1} was performed on the soil pan until surface flow occurred. Then, the soil pan was covered with a plastic sheet and allowed to stand for 24 h prior to the experiment. The average soil moisture contents before each experiment were 31.9%±1.8% for all hillslopes dominated by sheet erosion and 32.9%±1.7% for all hillslopes dominated by rill erosion.

The designated rainfall intensity, inflow rate or a combination of the two factors was applied to the soil pans. The runoff samples were measured at 1 or 2 min intervals for the whole run time after runoff occurred for different experimental treatments. Next, 3 runoff samples were successively passed through a column of six sieves of 5, 2, 1, 0.5 and 0.25 mm diameter to quantify the soil particle and aggregate losses in the sediment (Lu et al. 2016). The sediment samples were weighed and then oven-dried at 105°C to calculate soil particle and aggregate losses.

1.4 Data analysis

Statistical analysis was performed using the SPSS 19.0 software (SPSS Inc., Chicago, IL, USA). Analysis of variance (ANOVA) was conducted to examine significant differences in the runoff, soil loss and sediment size fractions. For multiple comparisons, the method of least significant differences (LSD) was applied at the 95% confidence level.

2 Results and Discussion

2.1Runoff rates and sediment concentration

Runoff rates were mainly affected by

hydrological characteristics and hillslope conditions (Xin et al. 2016; Xu et al. 2018). The trends in runoff rates for all treatments were similar and could be divided into an increasing stage and a relatively stable stage (Figure 2). The magnitudes and fluctuations of runoff rates for treatments with rainfall were significantly greater than those for treatments without rainfall on hillslopes under the same hillslope patterns and slope gradients. The treatments (RI70+IR70) that involved both rainfall and inflow produced the maximum runoff rates and the strongest fluctuations, especially during the relatively stable stage. This effect was due to the increases in raindrop impact and runoff on the hillslope (Lu et al. 2016; Vaezi et al. 2017). For the RI0+IR70 sheet flow treatment, water flowed across the surface as shallow flow, and changes in runoff rates depended solely on fluctuations in sheet flow (Tayfur and Kavvas 1994) caused by blockages by large soil particles and aggregates (Wen et al. 2015).

As the slope gradient increased from 5° to 10°, the runoff rate increasing stage lasted for a longer time, and the relatively stable stage showed stronger fluctuations (Figure 2). In comparing treatments for hillslopes dominated by sheet erosion and rill erosion, the latter showed a longer increasing stage and a relatively stable stage with stronger fluctuations. As we know, hillslope conditions, such as the slope gradient and microtopography, affect runoff rates (e.g., Strohmeier et al. 2014). The runoff rates were different for treatments at different slope gradients or for treatments on hillslopes dominated by sheet erosion and rill erosion in the Chinese Mollisol region.

The sediment concentration versus the water supply is plotted in Figure 3, which was used to analyze the effects of rainfall and inflow on soil erosion for hillslopes dominated by sheet erosion and rill erosion. The magnitudes of and fluctuations in the sediment concentration for

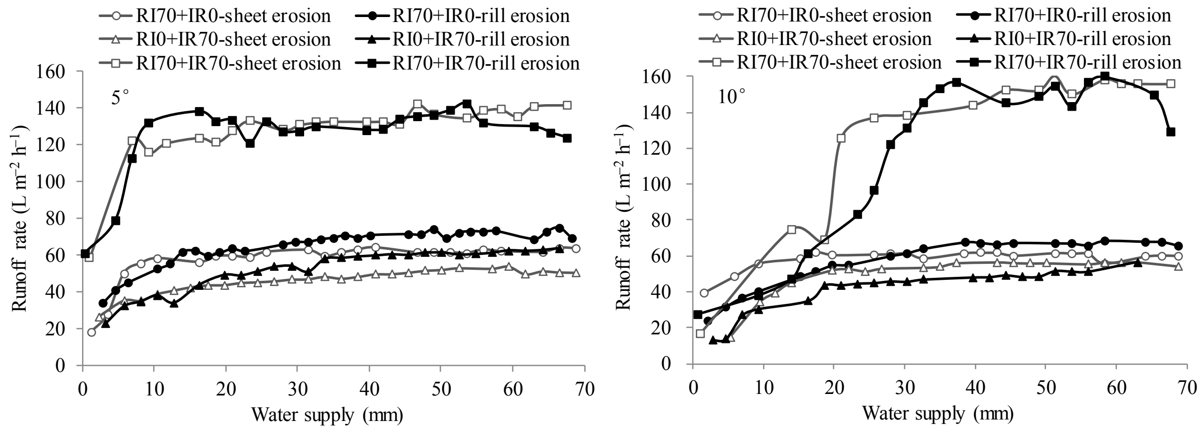

Figure 2 Runoff rates versus water supply for different variations of rainfall intensity and inflow rate for hillslopes dominated by sheet erosion and rill erosion with slopes 5° and 10°, respectively.

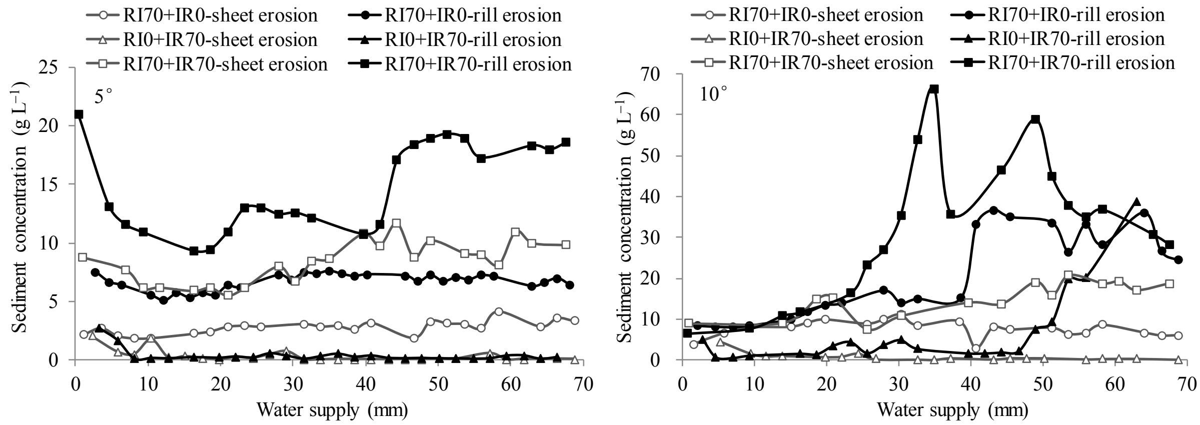

Figure 3 Sediment concentration versus water supply for different variations of rainfall intensity and inflow rate for hillslopes dominated by sheet erosion and rill erosion with slopes 5° and 10°, respectively.

treatments with added rainfall were significantly greater than those for treatments without rainfall on hillslopes under the same hillslope erosion patterns and slope gradients. Treatments (RI70+IR70) involving both rainfall and inflow produced the maximum sediment concentration and strongest fluctuations. The maximum value reached 66.2 g L^{-1}. This result indicated that rainfall had an important effect on soil erosion, which was similar to that obtained by Wen et al. (2015).

Most sediment concentration for treatments with a slope of 10° were greater than those for treatments with a slope of 5° except for the RI0+IR70 treatments on hillslopes dominated by sheet erosion (Figure 3). This result indicated that the slope gradient also had an important effect on soil erosion and that rainfall participation could strengthen the slope gradient effect. Furthermore, with regard to RI0+IR70, there was no significant difference in sediment concentration between the 5° and 10° treatments for hillslopes dominated by sheet erosion. This result showed that inflow on different slope gradient treatments for hillslopes dominated by sheet erosion had relatively small effect on soil erosion.

Most sediment concentration for treatments on hillslopes dominated by rill erosion were significantly greater than those for treatments on hillslopes dominated by sheet erosion with slopes of 5° and 10° (Figure 3). It is worth noting that the RI0+IR70 treatment on a hillslope dominated by rill erosion with a slope of 10° produced a relatively greater sediment concentration after 50 mm of water was supplied. The maximum value reached 38.8 g L^{-1}, which was significantly greater than those in other RI0+IR70 treatments. The results indicated that rills on hillslopes could accelerate soil erosion, which was similar to results obtained in other regions (e.g., Bryan and Rockwell 1998; Shen et al. 2016). Additionally, rill erosion would strengthen the effects of inflow on soil erosion among different slope gradient treatments.

2.2 Total runoff and soil loss

There were no significant differences in total runoff among treatments with rainfall (RI70+IR0 and RI70+IR70) on the 5° and 10° hillslopes dominated by sheet erosion and rill erosion, respectively (Table 2). This similarity was due to using the same amount of prerain and the same total water supply. This result was similar to those of previous related studies of sheet erosion in the Chinese Mollisol region (e.g., Wen et al. 2015). However, there were significant differences in total runoff for treatments with and without added rainfall because of raindrop impact effects (Lu et al. 2016; Vaezi et al. 2017). The total runoff for treatments with added rainfall was 1.2-1.4 and 1.2-1.5 times greater than that without rainfall on hillslopes dominated by sheet erosion and rill erosion, respectively. The results indicated that rainfall showed significant effects on the total runoff, but slope gradients and hillslope erosion patterns (sheet erosion and rill erosion) had slight effects on the total runoff.

Soil losses among treatments showed greater differences in amount than the total runoff (Table 2). The soil losses decreased in the order of RI70+IR70 > RI70+IR0 > RI0+IR70. The RI70+IR70 treatments produced the highest soil losses under the same total water supply, with values even greater than the sum of RI70+IR0 and RI0+IR70. When the rainfall intensity increased from 0 to 70 mm h^{-1}, soil losses increased by 45.2-47.0 times at 5° and 7.3-16.7 times at 10° on hillslopes. When the inflow rate increased from 0

Table 2 Total runoff and soil loss for different variations of rainfall intensity (RI) and inflow rate (IR) for hillslopes dominated by sheet erosion and rill erosion with slopes 5° and 10°, respectively.

Slope	Variation of RI and IR	Hillslope dominated by sheet erosion		Hillslope dominated by rill erosion	
		Total runoff (mm)	Soil loss (g m^{-2} h^{-1})	Total runoff (mm)	Soil loss (g m^{-2} h^{-1})
5°	RI70+IR0	60.5a	192.9e	62.5a	421.1d
	RI0+IR70	43.7bc	11.6f	51.0b	19.3f
	RI70+IR70	62.4a	526.3c	62.1a	905.2b
10°	RI70+IR0	57.0a	454.6cd	56.2a	1154.6b
	RI0+IR70	47.8b	33.3f	37.6c	230.5e
	RI70+IR70	58.6a	554.9c	57.6a	1692.7a

Notes: Values in the columns for total runoff or soil loss followed by different letters (i.e., a to f) are significantly different at p <0.05 according to the LSD test. n = 2.

to 70 mm h⁻¹, soil losses increased by 2.1-2.7 times at 5° and 1.2-1.5 times at 10° on hillslopes. With increasing rainfall intensity, both rainfall erosivity and runoff erosivity on hillslopes increased (Meshesha et al. 2016). However, with increasing inflow rate, only runoff erosivity on hillslopes increased. Although both soil losses increased correspondingly, the former was significantly greater than the latter. The results showed that rainfall induced greater effects on soil losses than inflow for hillslopes in the Chinese Mollisol region. Additionally, the increment effects of both rainfall and inflow on soil losses decreased with increasing slope gradients because of interference from the topography. Therefore, eliminating raindrop impact by using proper soil conservation measures such as residue coverage, no-till residue management system, etc. (Xu et al. 2010; Yang et al. 2011; Fang and Sun 2017) on relatively gentle hillslopes would be effective to protect the precious Mollisol resource.

For the same variations of RI and IR, soil losses in treatments for hillslopes dominated by rill erosion were 1.7-2.2 times greater at 5° and 2.5-6.9 times greater at 10° than those in treatments for hillslopes dominated by sheet erosion (Table 2). Soil detachment occurred by several processes, predominantly the hydraulic forces of raindrop impact and shear forces of concentrated flow in rills (Polyakov and Nearing 2003). Furthermore, rill channels transported sediment particles both detached from the inter-rill areas and from the wetted perimeter of the rill (Bewket and Sterk 2003; Bruno et al. 2008). Therefore, once rills occurred on the hillslope, soil erosion rapidly increased, which was consistent with previous related studies (e.g., Di Stefano et al. 2013; Shen et al. 2016). The rill effects on soil losses increased with increasing slope gradients from 5° to 10°. Because the slope gradient was one of the most important factors influencing soil erosion in northeastern China (Cui et al. 2007; Lu et al. 2016), preventing rill development is a necessary measure to decrease soil erosion on relatively steep hillslopes in the Chinese Mollisol region.

2.3 Soil particle and aggregate size distributions of the eroding sediment

The proportion of the >0.25 mm soil particles and water-stable aggregates in the tested soil reached 46.19%, which illustrated that the tested soil had a good aggregate structure (Table 3). There were significant differences in the proportions of soil particle and aggregate losses between >0.25 mm (i.e., >5, 2-5, 1-2, 0.5-1 and 0.25-0.5 mm) and <0.25 mm soil particles and aggregates in the sediment. Specifically, the loss of <0.25 mm soil particles and aggregates in proportion to the total soil loss was highest for all treatments, varying from 47.72%-99.60%. This loss occurred because the finer particles and aggregates were more easily transported than coarse particles and aggregates (Koiter et al. 2017), and the size distribution of the sediment was very similar to that of the original soil (Asadi et al. 2007). This result showed that the loss of <0.25 mm soil particles and aggregates played a dominant role in soil loss in the Mollisol region, which was similar to the results of previous related studies (e.g., Lu et al. 2016).

Table 3 Distribution of sediment gradation for different variations of rainfall intensity (RI) and inflow rate (IR) for hillslopes dominated by sheet erosion and rill erosion with slopes 5° and 10°, respectively.

Slope	Variation of RI and IR	Losses proportion on hillslope dominated by sheet erosion (%)						Losses proportion on hillslope dominated by rill erosion (%)					
		>5 mm	2-5 mm	1-2 mm	0.5-1 mm	0.25-0.5 mm	<0.25 mm	>5 mm	2-5 mm	1-2 mm	0.5-1 mm	0.25-0.5 mm	<0.25 mm
5°	RI70+IR0	0b	1.83d	12.85b	12.18a	8.64b	64.50b	0b	0.01e	0.12d	0.15d	0.12e	99.60a
	RI0+IR70	0b	0e	0d	0d	0e	100.00a	0b	0e	0d	0d	0e	100.00a
	RI70+IR70	0b	3.08c	13.20b	8.86b	5.83c	69.03b	0b	5.86b	17.55a	10.37ab	7.91b	58.31c
10°	RI70+IR0	0b	4.62c	14.91a	12.21a	8.42b	59.84bc	0b	0.81de	1.82d	2.76c	1.69d	92.92a
	RI0+IR70	0b	0e	12.02b	11.74a	8.04b	68.20b	0b	7.03b	11.09b	11.84a	10.22ab	59.82bc
	RI70+IR70	0b	4.88c	7.81c	14.40a	13.86a	59.05c	0.39a	16.90a	18.62a	8.62b	7.75b	47.72d
Contrast values of the tested soil		2.63	13.62	13.89	8.17	7.88	53.81	2.63	13.62	13.89	8.17	7.88	53.81

Notes: Values in the columns for the same sediment size fraction followed by different letters (i.e., a to e) are significantly different at $p < 0.05$ according to the LSD test. $n = 3$.

The soil losses for treatments without rainfall were significantly less than those for treatments with rainfall on hillslopes under the same hillslope patterns and slope gradients (Table 2). Thus, soil particle and aggregate losses were so small that all losses were <0.25 mm soil particles and aggregates in the sediment with a slope of 5°, and the losses showed significant differences in the proportions of each sediment size fraction of soil particle and aggregate loss to the total soil loss with a slope of 10° compared with those in the other treatments without rainfall (Table 3). This result indicated that the rainfall impact affected the distribution of soil particle and aggregate gradation by affecting the breakdown of soil aggregates (Lado et al. 2004).

As the slope gradient increased from 5° to 10°, the loss of <0.25 mm soil particles and aggregates in proportion to the total soil loss decreased, but the loss of >0.25 mm soil particles and aggregates increased in the sediment (Table 3). This change occurred because the slope gradient was one of the important factors affecting the sediment size distributions (Asadi et al. 2007) by decreasing soil stability and increasing runoff erosivity. The result indicated that the slope gradient affected the distribution of soil particle and aggregate gradation and was conducive to the migration of large soil particles and aggregates, which further influenced soil fertility and soil degradation.

On the basis of a comparison of the treatments for hillslopes dominated by sheet erosion and rill erosion, there were significant differences in the proportion of each sediment size fraction of soil particle and aggregate loss to the total soil loss (Table 3). The loss of <0.25 mm soil particles and aggregates in the sediment was highest in all treatments, followed by the 1-2 and 0.5-1 mm soil particles and aggregates for hillslopes dominated by sheet erosion, but followed by the 0.5-1 and 1-2 mm soil particles and aggregates for hillslopes dominated by rill erosion. Furthermore, with regard to the RI70+IR0 treatments, the proportions of <0.25 mm soil particle and aggregate lost to the total soil loss were 59.84%-64.50% for hillslopes dominated by sheet erosion, and the values were 92.92%-99.60% for hillslopes dominated by rill erosion. The rainfall impact (i.e., slaking and raindrop impact) was mainly used to split macroaggregates into microaggregates. The thin sheet flow selectively transported these microaggregates for hillslopes dominated by sheet erosion. However, both the thin sheet flow and rill flow selectively transported the microaggregates for hillslopes dominated by rill erosion (Jiang et al. 2013; Shen et al. 2016). Thus, rill erosion hillslopes lost more microaggregates than sheet erosion hillslopes under the condition of only rainfall. Additionally, rill erosion showed obvious selective transport of finer sediment particles at the relatively stable stage of rill development.

With regard to the RI70+IR70 treatments, the proportions of <0.25 mm soil particle and aggregate lost to the total soil loss were 59.05%-69.03%, which did not show significant differences compared with the RI70+IR0 treatments for hillslopes dominated by sheet erosion (Table 3). However, the proportions of <0.25 mm soil particle and aggregate lost to the total soil loss were 47.72%-58.31%, which were significantly less than those for the RI70+IR0 treatments for hillslopes dominated by rill erosion. This difference was due to the wholesale migration of soil particles and aggregates by the undercutting erosion of headcuts, headward erosion of rill heads and sidewall collapse erosion during rill development (Shen et al. 2015). The other main reason was that the breakage of soil aggregates by raindrop impact was decreased or eliminated (Vaezi et al. 2017) since the runoff depths in rills were 3-4 times greater than the raindrop diameters (Palmer 1965; Ghadiri and Payne 1981). Therefore, the runoff transport, friction and perturbation among macroaggregates were the major factors resulting in soil aggregate losses for hillslopes dominated by rill erosion under the condition of both rainfall and inflow. This result illustrated that rill erosion showed uneven or non-selective transport of finer sediment particles during the active stage of rill development, which was similar to the result obtained by Proffitt et al. (1993).

3 Conclusions

Simulations carried out using Mollisols demonstrated the effects of rainfall and inflow on soil erosion for hillslopes dominated by sheet erosion and rill erosion with slopes of 5° and 10° in the Chinese Mollisol region. It was found that the total runoff values for treatments with rainfall were 1.2-1.4 and 1.2-1.5 times greater than those with no added rainfall on hillslopes dominated by sheet erosion and rill erosion, respectively. Compared with the soil losses for the total runoff, those between treatments showed greater differences. Soil losses decreased in the order of RI70+IR70 > RI70+IR0 > RI0+IR70. Furthermore, soil losses for hillslopes dominated by rill erosion were 1.7-2.2 times greater at 5° and 2.5-6.9 times greater at 10° than those for hillslopes dominated by sheet erosion. Rainfall, hillslope erosion patterns (sheet erosion and rill erosion) and slope gradients had large effects on runoff rates, sediment concentration, and soil particle and aggregate losses in the sediment. The loss of <0.25 mm soil particles and aggregates in proportion to the total soil loss was highest for all treatments, varying from 47.72%-99.60%. Rill erosion hillslopes lost more coarse soil particles and microaggregates than sheet erosion hillslopes under the condition of only rainfall. The runoff transport, friction and perturbation among macroaggregates were the major factors resulting in soil particle and aggregate losses for hillslopes dominated by rill erosion under the condition of both rainfall and inflow. This result illustrated that whether rill erosion selectively transported different sediment size fractions depended most on the degree of rill development and stability. Therefore, eliminating raindrop impacts by using proper soil conservation measures such as residue coverage, etc. on relatively gentle hillslopes would be effective at protecting the precious Mollisol resource; preventing rill development would be a necessary measure to decrease soil erosion on relatively steep hillslopes in the Chinese Mollisol region.

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