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Research papers

Plot-based experimental study of raindrop detachment, interrill wash and erosion-limiting degree on a clayey loessal soil

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ABSTRACT

Better understanding of raindrop detachment, interrill wash and erosion-limiting degree in interrill processes is critical for accurately modelling interrill erosion and implementing proper anti-erosion strategies. Simulated rainfall experiments were conducted on a clayey loessal soil at three rainfall intensities (42, 60 and 90 mm h^{-1}), five slope gradients (7°, 10°, 15°, 20° and 25°) and rainfall duration of 40 min. Results showed that raindrop detachment rate initially decreased rapidly within a few minutes and then reached a relative steady state during rainfall. The initial and steady raindrop detachment rate increased with increased rainfall intensity. Interrill wash rate peaked early and then decreased to a relative constant rate during the rainfall. The initial, maximum and steady interrill wash rate increased with increased rainfall intensity and slope gradient. Erosion-limiting degree (*ELD*), defined as the ratio of interrill wash rate to raindrop detachment rate, ranged from 10.99% to 35.70% under experimental conditions, indicating that interrill erosion system was transport-limited. The *ELD* decreased with rainfall intensity and increased linearly (R^2 = 0.90) with slope gradient. The higher the rainfall intensity, the stronger the transport-limiting in interrill erosion processes; the steeper the slope gradient, the weaker the transport-limiting in interrill erosion processes. Raindrop detachment is the dominant process in detaching soil particles, whereas interrill flow contributes to washing out detached sediments. The findings of this study, especially *ELD*, largely improved the understanding of interrill erosion processes.

1. Introduction

Interrill erosion is considered one of the major processes contributing to soil and water quality degradation; it is identified as a complex and dynamic combination of two sub-processes: detachment and transport by rain splash and thin surface flow (Ellison, 1945, 1947; Meyer, 1981; Foster, 1990; Wan et al., 1996; Wan and Elswaify, 1998). Identification of these sub-processes laid a solid foundation for studying interrill erosion processes and their mechanism in detail (Meyer and Wischmeier, 1969; Owoputi and Stolte, 1995; Zhang and Wang, 2017). In addition, the improved accuracy of soil erosion models and proper implementation of hillslope anti-erosion strategies to diminish interrill erosion damage depend on the profound understanding of interrill sub-processes. Thus, more attention should be paid to detachment and transport dynamics during the interrill erosion processes.

Rainfall intensity, slope gradient, and soil properties are the main factors that influence splash and interrill erosion. Many studies were conducted to describe splash or interrill erosion processes under different experimental conditions (Meyer, 1981; Quansah, 1981; Assouline and Ben-Hur, 2006; Issa et al., 2006; Fu et al., 2011; Liu et al., 2015; Shen et al., 2016; Wu et al., 2017). In most cases, both rainfall intensity and slope gradient have a positive effect on splash or interrill wash erosion (Nearing et al., 1989; Assouline and Ben-Hur, 2006; Shen et al., 2016; Wu et al., 2017), and rainfall intensity often plays a more important role (Shen et al., 2016; Wu et al., 2017). Different results have been obtained in some cases. Such as, Bradford and Foster (1996) found that as slope gradient increased, splash increased for five soil treatments and decreased for other three treatments. Surface seal

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development, water depth and interaction between rainfall and flow during rainfall events also affect and even control interrill erosion processes. Surface seal development can reduce soil infiltration rate and increase the shear strength of soil surface, thus influencing the splash and interrll wash processes (Poesen, 1984; Moore and Singer, 1990). Warrington et al. (2009) found that the degree of seal development also affected the particle size distribution of the eroded sediment. Arjmand Sajjadi and Mahmoodabadi (2015) found that soil infiltration rate increased with increasing slope gradient and rainfall intensity under unsteady state rainfall conditions because of less development of surface seal. Mutchler and Hansen (1970) and Moss and Green (1983) showed that both detachment and transportation of soil particles by raindrop impact are greatly affected by water depth. Kinnell (1993) found that flow depth not only affects the stress applied to the soil surface under interrill flow, but also controls which particles can be lifted in the flow, both of them influence the interrill erosion process. Asadi et al. (2007) found that the interaction between rainfall and flow has a positive effect on the interrill erosion process under their experimental conditions, similar results were reported by Singer et al. (1981), Foster (1982) and Hao et al. (2019). Rouhipour (1997) and Rouhipour et al. (2006) showed that the interaction between rainfall and flow changed with the stream power of flow, and they found a negative interaction for one soil and a positive interaction for the other soil.

A few studies have investigated the interrill erosion process by partitioning it into its sub-components, i.e. splash and interrill wash, and by comparing the magnitude of splash and interrill wash sediments to evaluate their relative importance in interrill erosion processes (Young and Wiersma, 1973; Luk, 1979; Sutherland et al., 1996; Mermut, 1997; Wan and Elswaify, 1998; Van Dijk et al., 2003; Issa et al., 2006; Fu et al., 2011; Mahmoodabadi and Sajjadi, 2016; Wu et al., 2018). Young and Wiersma (1973) evaluated the relative importance of rain splash and interrill flow in interrill erosion process on a low slope (9%) using three different soils; they observed that soil detachment was mainly accomplished by rain splash, and interrill flow was the main transporting agent. Luk (1979) measured the total splashed and washed losses from a $30.5 \times 30.5\,cm^2$ plot and discovered that splash detachment combined with wash transport was the dominant erosion process in interrill areas. Sutherland et al. (1996) discovered that both downslope splash sediments and total splash (lateral + down + top) sediments were higher than that of wash sediments under slope gradients from 5° to 20°. Mermut (1997) observed that the amounts of splashed soil sediments were much higher (10–20 times) than that of interrill wash sediments. Van Dijk et al. (2003) also identified that splash was more dominant than wash under slope gradients of 0°, 5°, 15° and 40° under natural rainfalls, and wash transport accounted for 8%–22% of splash transport. However, other studies showed the opposite results, indicating that wash loss is higher than splash detachment loss in the interrill processes (Fox and Bryan, 2000; Mahmoodabadi and Sajjadi, 2016). Fox and Bryan (2000) observed that downslope splash erosion never accounted for more than 20% of the total erosion. Mahmoodabadi and Sajjadi (2016) concluded that wash load was much higher than splash load (the ratio of wash load to splash load ranged from 543 to 109) at all slope gradients and rainfall intensities in their study. In addition, Wan et al. (1996) noted that wash dominated interrill sediment transport at low slope gradients (< 9%), whereas downslope splash transport was dominant at high slopes (> 9%). Bryan (1979) concluded that splash detachment loss was higher than wash loss for grey luvisol but less than the wash loss for calcareous loess soil. Wu et al. (2018) reported that interrill erosion rate was higher than splash detachment rate in most cases, indicating that overland flow possesses sufficient power to detach soil in addition to washing out the loose materials detached by rainfall, especially at high rainfall intensities or steep slope gradients. Overall, the differences among the results of the studies above indicate that the relative importance of splash detachment and interrill wash in interrill erosion processes varies with soil texture and experimental conditions (measurement of splash sampling, experimental setups, rainfall properties, slope gradients, etc.).

When studying the rainfall-induced interrill erosion processes at a plot scale under laboratory conditions, a buffer area surrounding the central test area is important and necessary to be designed into the experimental plot, which equalise the opportunity for splash both onto and off the test area (Bradford and Foster, 1996; Agassi and Bradford, 1999; Wu et al., 2018). However, most experimental plots in the aforementioned studies had no buffer area, which affects an exact observation of the raindrop detachment rate and interrill wash rate during rainfall time, and thus affects an accurate modelling of interrill erosion process. In addition, no previous work has gained insights into raindrop detachment and interrill wash dynamics simultaneously in interrill erosion processes on clayey loessal hillslopes in the Loess Plateau of China. Moreover, little research has defined and studied the erosion-limiting degree in the interrill erosion process, especially in the Loess Plateau of China.

Therefore, the objectives of this study were as follows: (i) to investigate temporal changes in raindrop detachment rate and interrill wash rate under different rainfall intensities and slope gradients on a clayey loessal soil; and (ii) to identify the erosion-limiting degree under different rainfall intensities and slope gradients.

2. Materials and methods

2.1. Study area and test soil

The study area is located in Tianshui in Gansu Province, which is in the southern part of the Loess Plateau, China, featuring an average annual temperature of 11.5 °C, a mean annual precipitation of 500 mm and a hilly and gully landform. The test soil was collected from a 0–25 cm upper depth of a farming layer. The soil is clayey loessal soil. The absolute particle size distribution (i.e. dispersed particle size distribution) consisted of 24.46% clay (diameter: < 0.002 mm), 68.52% silt (diameter: 0.002–0.05 mm) and 7.02% sand (diameter: > 0.05 mm), and its effective particle size distribution (i.e. undispersed particle size distribution) consisted of 9.39% particles with < 0.002 mm diameter, 46.35% particles with 0.002–0.05 mm diameter and 44.26% particles with > 0.05 mm diameter. The organic matter content in the test soil is $9.13\,g\,kg^{-1}$.

2.2. Experimental setups

The study was conducted in the Simulated Rainfall Hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau at the Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resources. Simulated rainfall was generated by two groups of lateral spraying nozzles. The rainfall simulator used for experimental events could apply rainfall intensities ranging from $30\,mm\,h^{-1}$ to $180\,mm\,h^{-1}$, with a height of 16 m above the soil surface. Tap water (electrical conductivity = $0.7\,dS\,m^{-1}$) was used to supply the water source of simulated rainfall.

A soil erosion pan similar to that used by Bradford and Foster (1996) but with a slight modification in design was used in this study; the pan could measure raindrop detachment and interrill wash processes separately and simultaneously. The soil erosion pan was constructed with metal frames measuring 140 cm (length) × 120 cm (width) × 25 cm (depth), integrating the test area, buffer areas and two splash troughs. Firstly, the test area (60 cm width, 80 cm length and 25 cm depth) was placed at the centre of the soil erosion pan. A slot along the lower end of the test area was designed to collect runoff and interill wash sediments. Secondly, 30 cm-wide soil buffer areas surrounded the test area; they were filled with soil in the same manner as the test area to equalise the opportunity for splash both onto and off the test area. Thirdly, two

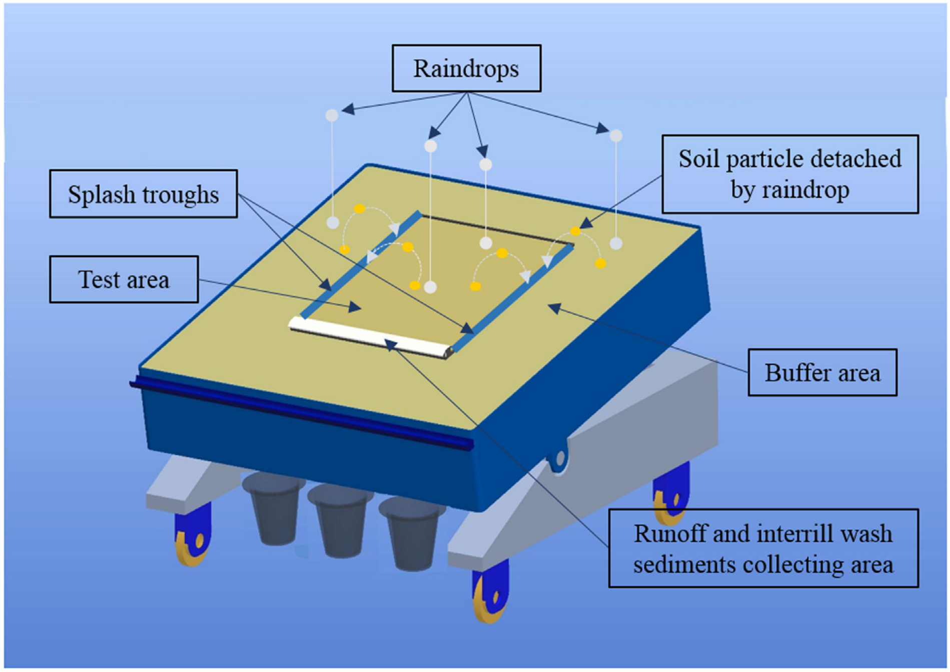

Fig. 1. Soil erosion pan used in this study.

splash troughs (3.5 × 80 cm) were located along both sides of the test area and were used to collect raindrop detachment sediments. The image of the soil erosion pan used in this study is presented in Fig. 1.

2.3. Experimental treatments

The soil used in this study was air-dried after it was collected from the study area, and plant residues and pebbles were removed from the soil by passing it through a 5 mm sieve. The soil was then evenly mixed and compacted in the soil pan. A 5 cm-thick layer of sand was placed as filter at the bottom of the soil pan to simulate a drainage system. Then, four 5 cm-thick soil layers were placed on top of the sand layer, with a porous jute sheet used to separate the sand layer and the soil layer. Before adding the next layer, each soil layer was lightly raked to reduce any discontinuities between layers. The soil was compacted to an appropriate bulk density of 1.20 g cm^{-3}, which is almost equal to that of soil under natural conditions. The antecedent soil moisture was gravimetrically set at about 14% for each run.

Three rainfall intensities (42, 60 and 90 mm h^{-1}) and five slope gradients (7°, 10°, 15°, 20° and 25°) were designed. This study was a two-factor factorial experiment (3*5) in a completely randomised design at two replications, with a total of 30 simulation events. The duration of simulation approximated 40 min, and no rills occurred during rainfall time. For each run, raindrop detachment sediments, runoff and interill washed sediments were collected within 3 min after runoff at 1 and 2 min intervals for the first two samples and 3 min intervals for the remaining samples. In total, 14 sets of samples were collected in each run. The raindrop detachment sediments, runoff and interill washed sediments for each time interval were weighed and oven-dried at 105 °C for about 24 h. Once dry, all the sediments were weighed again to calculate the raindrop detachment rate and interrill wash rate.

2.4. Data calculation

Raindrop detachment rate (kg m^{-2} s^{-1}) is defined as the weight of splashed sediments per unit area per unit time. Interrill wash rate (kg m^{-2} s^{-1}) is defined as the weight of sediments transported by interrill flow per unit area per unit time. Raindrop detachment load (kg m^{-2} s^{-1}) is defined as the mean raindrop detachment rate for an individual rainfall experiment event under each combination of rainfall intensity and slope gradient. Similarly, interrill wash load (kg m^{-2} s^{-1}) is defined as the mean interrill wash rate for an individual rainfall experiment event under each combination of rainfall intensity and slope gradient.

In addition, erosion-limiting degree (*ELD*, %) is defined in this study and is calculated by the following equation:

$$ELD = \frac{Ir}{Sr} \times 100\% \tag{1}$$

where *ELD* is the erosion-limiting degree (%), *Ir* is the interrill wash rate (kg m^{-2} s^{-1}), and *Sr* is the raindrop detachment rate (kg m^{-2} s^{-1}). The related explanation was as follows. The erosion-limiting phenomenon was widely noticed in the erosion processes, especially in the interrill erosion processes. Several methods were used to distinguish the transport-limited and detachment-limited processes of interrill erosion in previous studies, such as Mahmoodabadi and Sajjadi (2016), Wu et al. (2018), Zhang et al. (2017) and Zhang et al. (2018). The distinguishing method mentioned in the study of Wu et al. (2018) was used in the present study. According to this method, when the interrill wash rate is lower than the raindrop detachment rate, the interrill erosion process is defined as a transport-limited erosion process, and when the interrill wash rate is higher than the raindrop detachment rate, the interrill erosion process is defined as a detachment-limited erosion process (Wu et al., 2018). On the basis of this concept, further calculations were conducted to reveal the *ELD*s under different rainfall intensities and slope gradients by using Eq. (1). $ELD < 1$ means that the interrill erosion process is transport-limited, and the lower the *ELD* value, the less the erosion-limiting degree, and the stronger the transport-limiting in interrill erosion processes. While $ELD > 1$ means that the interrill erosion process is detachment-limited, and the higher the *ELD* value, the more the erosion-limiting degree, and the weaker the transport-limiting in interrill erosion processes.

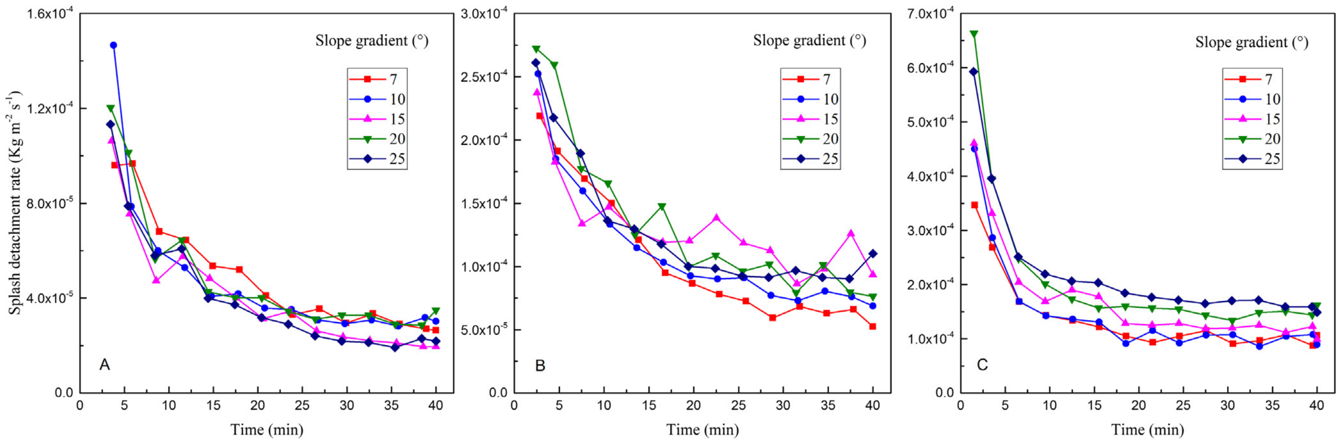

Fig. 2. Temporal variations of raindrop detachment rate under different slope gradients at low rainfall intensity (A: 42 mm h^{-1}), moderate rainfall intensity (B: 60 mm h^{-1}) and high rainfall intensity (C: 90 mm h^{-1}).

3. Results

3.1. Temporal changes in raindrop detachment rate

Fig. 2 shows the temporal changes in raindrop detachment rate with rainfall time under different slope gradients (7°, 10°, 15°, 20° and 25°) and rainfall intensities (42, 60 and 90 mm h^{-1}). Variations in raindrop detachment rate with rainfall time under different slope gradients and rainfall intensities were almost the same. For all slope gradients and rainfall intensities, splash detachment rate initially decreased rapidly within a few minutes and then reached a relative steady state during rainfall time. The initial and steady raindrop detachment rates increased with the increase in rainfall intensity. The ratios of average initial and steady raindrop detachment rate among rainfall intensities of 42, 60 and 90 mm h^{-1} were 1:2.13:4.31 and 1:3.07:4.51, respectively. The variations of initial and steady raindrop detachment rates with slope gradient were different under different rainfall intensities. Under rainfall intensities of 60 and 90 mm h^{-1}, the initial and steady raindrop detachment rate increased with increase of slope gradient and can be described by power equations (Fig. 3). However, slope gradient had no significant influence on the initial and steady raindrop detachment rate under the rainfall intensity of 42 mm h^{-1} (Fig. 3).

3.2. Temporal changes in interrill wash rate

Interrill wash is produced by interrill flows. The flow rate, water depth, velocity, stream power and shear stress of interrill flow ranged from 0.31 to 0.96 mm min^{-1}, 0.08 to 0.17 mm, 0.05 to 0.14 m s^{-1}, 0.01 to 0.05 W m^{-2} and 0.10 to 0.34 Pa, respectively, under different combinations of rainfall intensity and slope gradient.

Fig. 4 shows the temporal changes in interrill wash rate with rainfall time under different slope gradients (7°, 10°, 15°, 20° and 25°) and rainfall intensities (42, 60 and 90 mm h^{-1}). A similar variation in interrill wash rate with rainfall time occurred under different slope gradients, whereas a different tendency was observed in interrill wash rate among different rainfall conditions. For the low and moderate rainfall intensities (42 and 60 mm h^{-1}, respectively), the dynamic changes in interrill wash rate with rainfall time can be divided into three stages: 1) rapid increase stage, 2) gradual decline stage and 3) relatively steady stage (Fig. 4A and B). When rainfall intensity increased to 90 mm h^{-1}, the interrill wash rate decreased sharply in the first few minutes and then reached a relative steady state after approximately 12 min (Fig. 4C). The initial, maximum and steady interrill wash rates increased with the increase in rainfall intensity. The ratios of average initial, maximum and steady interrill wash rate among rainfall intensities of 42, 60 and 90 mm h^{-1} were 1:2.94:14.06, 1:2.50:9.17 and 1:2.31:2.58, respectively. The initial, maximum and steady interrill wash rate increased linearly with the increase in slope gradient (Fig. 5). Overall, a higher rainfall intensity led to higher initial and peak interrill wash rate and earlier peak and steady stages, as well as in a steeper slope gradient.

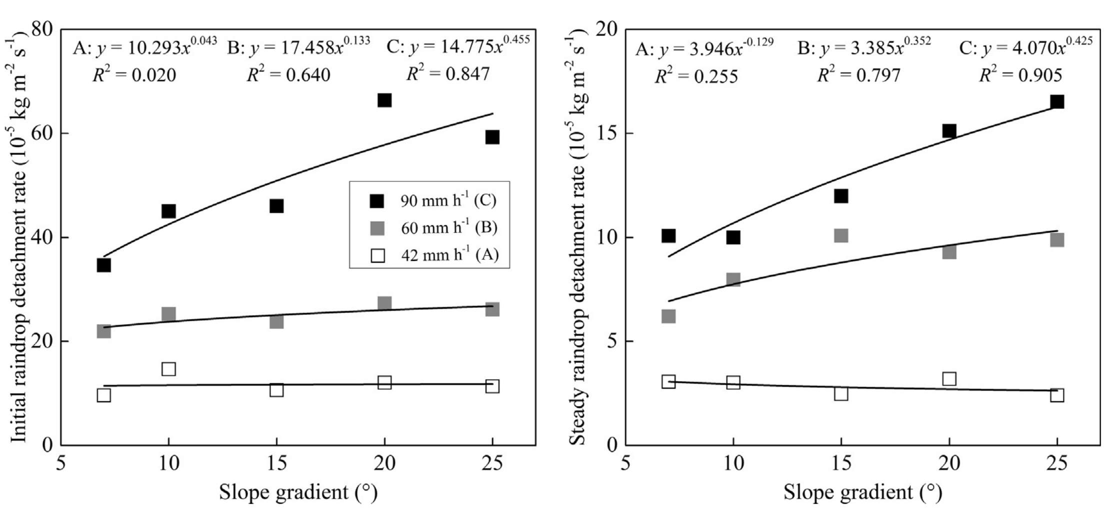

Fig. 3. Variations of initial raindrop detachment rate and steady raindrop detachment rate with slope gradient under different rainfall intensities.

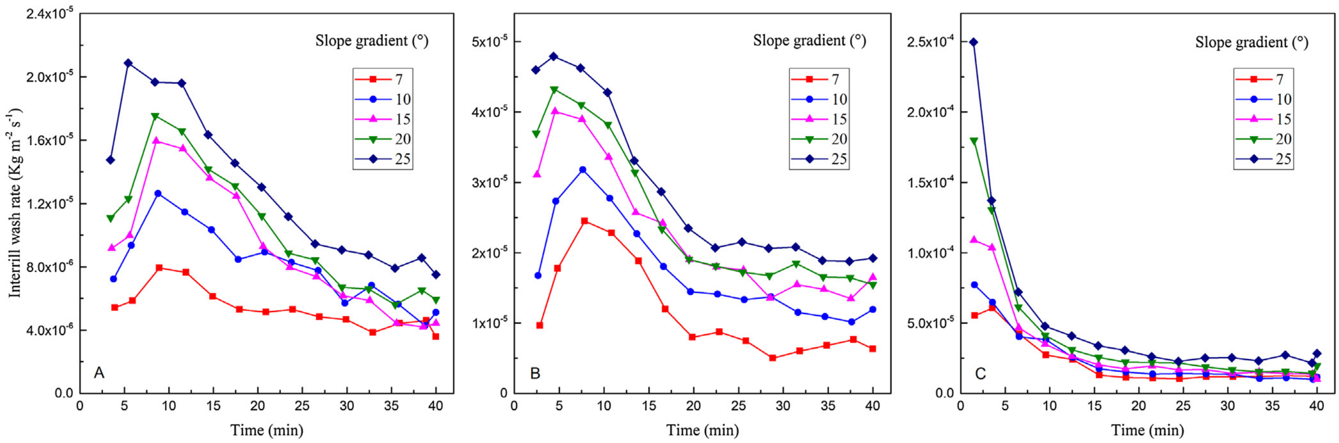

Fig. 4. Temporal variations of interrill wash rate under different slope gradients at low rainfall intensity (A: 42 mm h^{-1}), moderate rainfall intensity (B: 60 mm h^{-1}) and high rainfall intensity (C: 90 mm h^{-1}).

3.3. Erosion-limiting degrees (ELDs) at different rainfall intensities and slope gradients

Fig. 6 shows the *ELD*s at different rainfall intensities and slope gradients. For the mean value in an individual rainfall event, the *ELD*s at different slope gradients ranged from 12.30% to 35.70%, with an average value of 22.98%, under the low rainfall intensity (42 mm h^{-1}). Under moderate rainfall intensity (60 mm h^{-1}), the *ELD*s at different slope gradients ranged from 10.99% to 22.57%, and the average value was 17.22%. The *ELD*s ranged from 14.40% to 20.13%, yielding an average value of 16.58%, at a rainfall intensity of 90 mm h^{-1} under different slope gradients. It is shown that all values of *ELD*s were less than 1, which indicated that the raindrop detachment rate was higher than the interrill wash rate at all slope gradients and rainfall intensities, and the interrill erosion processes were transport-limited processes in this study (*ELD* range: 10.99%–35.70%, average *ELD*: 18.93%). The findings also showed that with increasing rainfall intensity, the *ELD*s decreased, thereby indicating that the higher the rainfall intensity, the lower the *ELD* and the stronger the transport-limiting in the interrill erosion processes. Moreover, the *ELD*s increased with increasing slope gradient, and the relationship between *ELD* and slope gradient can be described by a linear equation ($R^2 = 0.90$, $P < 0.05$) (Fig. 7). The steeper the slope gradient, the higher the *ELD* and the weaker the transport-limiting in the interrill erosion processes.

4. Discussion

The dynamic changes in raindrop detachment rate with rainfall time (Fig. 2), where detachment rate initially decreased rapidly within a few minutes and then reached a relative steady state during rainfall time, may be explained by the following: (1) the development of surface water film reduced the impact of raindrop (Wan et al., 1996; Mermut, 1997); (2) continued raindrop impact facilitated the sealing of the surface and increased the near-surface bulk density and resistance to detachment, thus, raindrop detachment rate decreased to a relative balance state between the resistance of the soil surface and erosive force of raindrop detachment (Bradford et al., 1987; Sutherland et al., 1996; Fox and Bryan, 2000; Rienzi et al., 2013; Wang and Shi, 2015); and (3) particles that fell back to the surface as a result of gravity produced a layer of pre-detached particles, providing a degree of protection against the detachment of particles from the underlying soil (Kinnell, 2005). The dynamic changes in interrill wash rate with rainfall time (Fig. 4), where erosion peaked early in rainfall times and then decreased to a final relative steady state, may be accounted by the storage quantities of transportable particles on soil surface. In the first few minutes of rainfall, large amounts of loose and fine soil particles were observed on the soil surface and were available to be washed by interrill runoff. As rainfall continued, loose particles that remained on the soil surface became increasingly coarse and were difficult to wash away. Besides, due to the coarse soil particles remained on the soil surface, the resistance of interrill runoff increased and the path of runoff become more complicated, resulting in a low interrill wash rate.

In this study, a steeper slope gradient or higher rainfall intensity resulted in higher initial, peak and steady erosion (raindrop detachment and interrill wash) rates. The effects of rainfall intensity on raindrop detachment rate could be attributed to the different raindrop energies under different rainfall intensities; this energy was used to overcome the bonds that hold particles in the soil surface and may also be used in

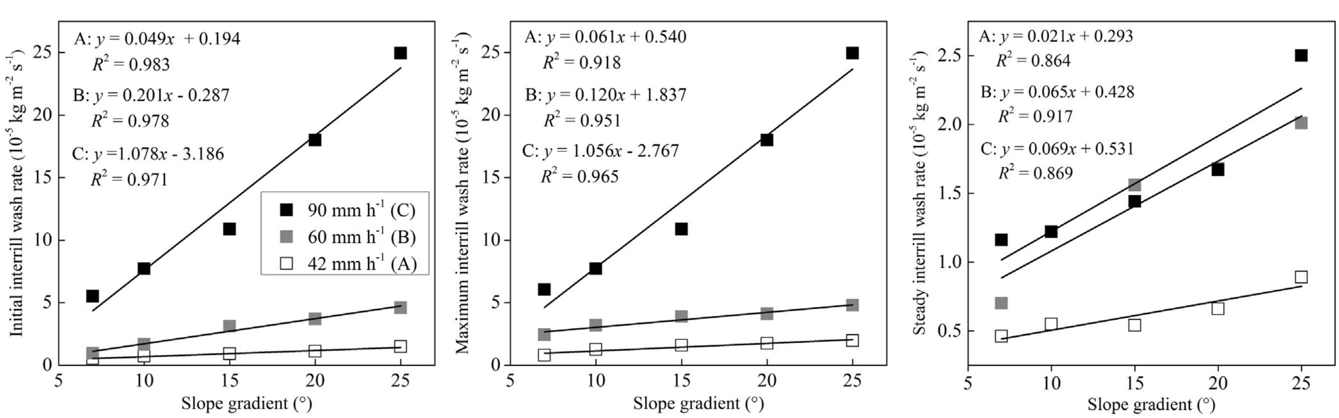

Fig. 5. Variations of initial interrill wash rate, maximum interrill wash rate and steady interrill wash rate with slope gradient under different rainfall intensities.

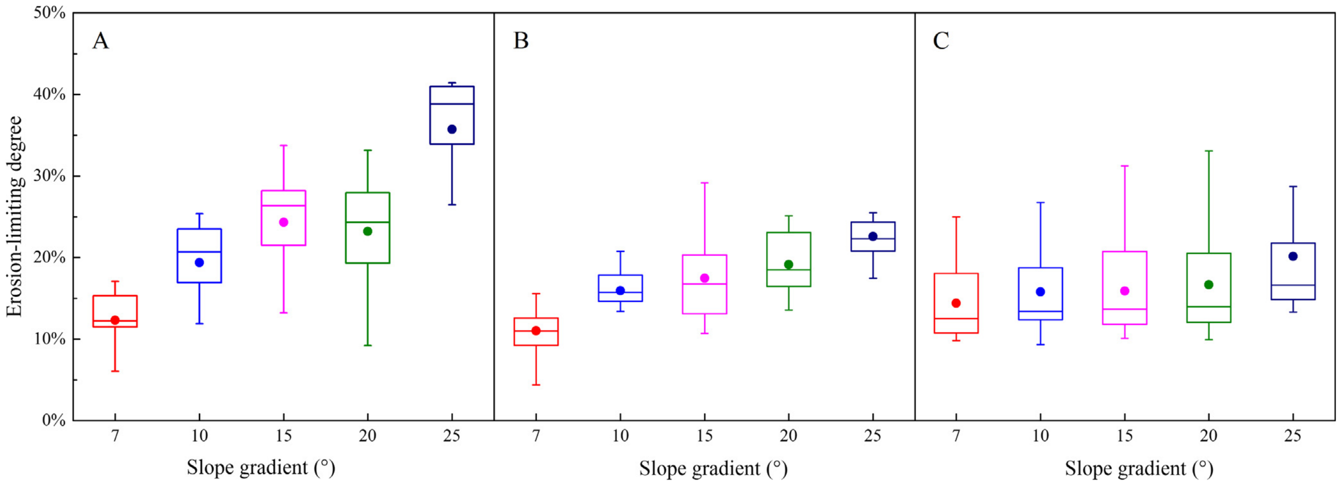

Fig. 6. Box-plots of erosion-limiting degree at low rainfall intensity (A: 42 mm h^{-1}), moderate rainfall intensity (B: 60 mm h^{-1}) and high rainfall intensity (C: 90 mm h^{-1}).

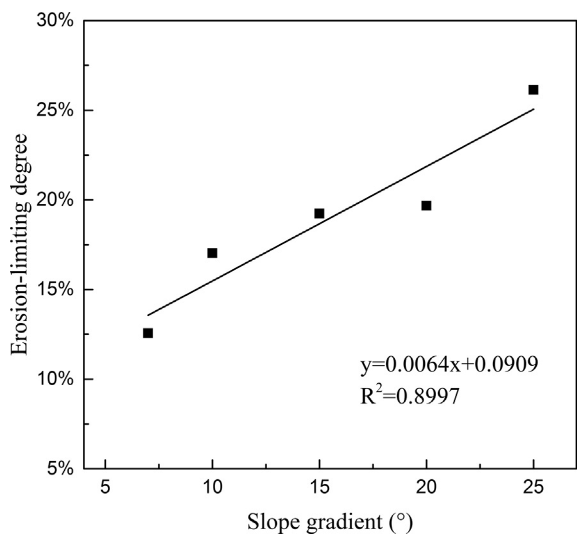

Fig. 7. Relationship between erosion-limiting degree and slope gradient.

transporting the detached particles away from the drop impact site (Kinnell, 2005). A higher rainfall intensity leads to higher raindrop energy. Thus, a large magnitude of raindrop detachment rate was reached in this study. Similar results were reported by Mermut (1997) and Mahmoodabadi and Sajjadi (2016). The effects of rainfall intensity on interrill wash rate were attributed to the increased runoff energy with increasing rainfall intensity, which enhanced the mixing of the surface soil with the water layer and enhanced the sediment transport capacity of interrill flow (Kinnell, 2012; Liu et al., 2015; Zhang et al., 2018). Positive effects of slope gradient on raindrop detachment and interrill wash rate were observed in this study. These results can be explained by the positive influence of slope gradient on raindrop splash angle, movement status of interrill flow (e.g. flow velocity) and instability of soil particles on slopes. Similar results were reported by Van Dijk et al. (2003), Fu et al. (2011) and Mahmoodabadi and Sajjadi (2016). However, under low rainfall intensity (42 mm h^{-1}), raindrop detachment rates showed no significant difference with increasing slope gradient, possibly because the soil used in this study was well aggregated and featured low erodibility. Under low rainfall intensity, the raindrop energy was inadequate to detach considerable soil particles although the slope gradients were steep enough.

Results indicated that the raindrop detachment rate was greater than the interrill wash rate at all rainfall intensities and slope gradients in this study. The *ELD*s ranged from 10.99% to 35.70%, with an average value of 18.93%, which is similar to previous studies (Luk, 1979; Truman and Bradford, 1995; Sutherland et al., 1996; Mermut, 1997). *ELD*s < 1 also indicated that raindrop detachment is the dominant mechanism in detaching soil particles, whereas interrill flow contributes to washing out the detached sediments. However, other studies showed opposite views, such as those of Fox and Bryan (2000), Mahmoodabadi and Sajjadi (2016) and Wu et al. (2018). Fox and Bryan (2000) revealed that downslope splash erosion never accounted for more than 20% of total erosion. Mahmoodabadi and Sajjadi (2016) concluded in their study that wash load was much higher than splash load (the ratio of wash load to splash load ranged from 543 to 109) at all slope gradients (0.5%, 2.5%, 5%, 10% and 20%) and rainfall intensities (57 and 80 mm h^{-1}). The difference between the results of our study and those of others may be accounted for the differences in test soil texture and experimental conditions (measurement of splash sampling, experimental setup, rainfall properties and slope gradient). In addition, Wu et al. (2018) showed that the interrill erosion rate was higher than the raindrop detachment rate in most cases, indicating that overland flow possesses sufficient power to detach soil in addition to washing out the loose materials detached by rainfall. The opposite views between this study and that of Wu et al. (2018) were attributed to the test soil texture (because of the same experimental setup, measurement of splash and wash sampling between this study and that of Wu et al. (2018)). Although the soils used in this study and those in Wu et al. (2018) were both loessal soil, their properties varied remarkably. Our soil was well aggregated with high clay (24.46%) and organic matter (9.13 g kg^{-1}) contents and was difficult to erode. By contrast, in the study of Wu et al. (2018), the soil was highly erodible and susceptible to erosive forces, and it could easily turn into mud at high moisture, resulting in easy detachment by overland flow, especially in steep slope gradients or at high rainfall intensities. This diversity further highlighted the significant influence of soil texture on interrill erosion processes.

*ELD*s increased linearly ($R^2 = 0.90, P < 0.05$) with increasing slope gradient. This finding may be explained as follows. With the increase in slope gradient, not only the normal component of raindrop impact force, raindrop impact force multiplied by the cosine of slope, was decreased and interrill flow power increased, but also the components along the slope of raindrop impact force, raindrop impact force multiplied by the sine of slope, increased, which make interrill flow has much more power to wash soil particles than raindrop to detach soils. Therefore, although both interrill wash load and raindrop detachment load increased with increasing slope gradient, interrill wash load increased more than raindrop detachment, thus resulting in increased

ELD. These results imply that interrill wash is more sensitive to slope gradient than splash detachment is. The *ELD*s decreased gradually with increasing rainfall intensity. This finding may be explained as follows. With the increase in rainfall intensity, the impact force of raindrop, such as velocity, diameter and kinetic energy, and soil detachability for raindrop impact increased. With the increase in rainfall intensity, interrill flow power, such as flow rate, velocity and stream power increased, but detached soil particle transportability for interrill flow remained unchanged. This caused the lower increase in interrill wash load compared with that of splash detachment with increasing rainfall intensity, thereby indicating that splash detachment is more sensitive to rainfall intensity than interrill wash is.

5. Conclusion

Raindrop detachment rate, interrill wash rate and *ELD* under different rainfall intensities (42, 60 and 90 mm h^{-1}) and slope gradients (7°, 10°, 15°, 20° and 25°) were investigated on a clayey loessal soil.

Raindrop detachment rate decreased rapidly in the first few minutes and then reached a relative steady state during rainfall time. The initial and steady raindrop detachment rate increased with the increase in rainfall intensity, and ratios of their average values were 1:2.13:4.31 and 1:3.07:4.51 among rainfall intensities of 42, 60 and 90 mm h^{-1} respectively. The initial and steady raindrop detachment rate increased as slope gradient increased and can be described with power function under 60 and 90 mm h^{-1} rainfall intensities. Interrill wash rate peaked early and then decreased to a relative constant rate during the rainfall. The initial, maximum and steady interrill wash rate increased as rainfall intensity increased, and ratios of their average values were 1:2.94:14.06, 1:2.50:9.17 and 1:2.31:2.58 among rainfall intensities of 42, 60 and 90 mm h^{-1}, respectively. The initial, maximum and steady interrill wash rate increased linearly with the increase in slope gradient.

The *ELD*s ranged from 10.99% to 35.70%, which explained that interrill erosion system was transport-limited, raindrop detachment was the dominant process in detaching soil particles and interrill flow contributed to washing out the detached sediments. The *ELD*s decreased gradually with increasing rainfall intensity and increased linearly with increasing slope gradient, which indicated that the higher the rainfall intensity, the stronger the transport-limiting in interrill erosion processes, and the steeper the slope gradient, the weaker the transport-limiting in interrill erosion processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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