The Directional Components of Splash Erosion at Different Raindrop Kinetic Energy in the Chinese Mollisol Region

Splash erosion is an important process of hillslope erosion. However, there is little information available in the literature to show how rainfall physical parameters affect the directional components of splash erosion. Therefore, the objectives of this study were to investigate the effects of rainfall physical parameters (rainfall intensity [RI], raindrop kinetic energy [KE], and raindrop diameter) on the directional components (upslope, lateral, downslope) of splash erosion characteristics in the Chinese Mollisol region. A specially designed soil pan, which can measure the directional components of splash erosion, was subjected to designed rainfall intensities of 50 and 100 mm h⁻¹ and varying raindrop KE. The results showed that the total splash erosion (downslope plus upslope plus lateral splash erosion), directional components of splash erosion, and net splash erosion (downslope minus upslope erosion) on hillslopes significantly increased as RI and raindrop KE increased (p < 0.05). Furthermore, splash erosion from downslope, lateral slope, and upslope contributed 32.2, 26.3, and 14.5%, respectively, of total splash erosion. Additionally, raindrop KE and raindrop median volume diameter ($D_{50}$) were the key indicators affecting both total and net splash erosion. The equations between total and net splash erosion with both parameters of raindrop KE and raindrop $D_{50}$ were fitted. The cross validation results showed that the two equations had acceptable accuracy. Therefore, preventing raindrop impact by using conservation tillage methods, such as retaining crop residue or mulch cover, can effectively reduce splash erosion in the Mollisol region of Northeast China.

Abbreviations: KE, kinetic energy; RI, rainfall intensity.
pression for splash erosion as a function of raindrop fall velocity, raindrop diameter, and RI. Bubenzer and Jones (1971) found that splash erosion rates were defined as a function of raindrop momentum and the number of raindrops. Morgan (1982) proposed that soil detachment by raindrops could be described as a traditional power function of raindrop KE. Salles et al. (2000) noted that multiplying the raindrop diameter by its velocity provided the best rainfall physical parameter for explaining splash detachment. Fernández-Raga et al. (2010) and Schooten et al. (2011) analyzed the role of various rainfall physical parameters in explaining splash erosion. Generally, raindrop KE is accepted as the best predictor of rainfall erosivity that can define the ability of raindrops to detach soil particles (Hamad et al., 2006; Fernández-Raga et al., 2010).

Rainfall simulators are generally used in soil erosion studies. In laboratory settings, there are four methods to alter raindrop KE. 1. Changing RI for the same rainfall simulator can form different raindrop size distributions and momentums (Abd Elbasit et al., 2010; Mekasha et al., 2016), but this method cannot distinguish the effects of RI or raindrop KE on soil erosion. 2. Changing rainfall simulator systems can produce different raindrop size distributions and momentums even at the same RI (Bradford and Huang, 1993). Due to differences in design principle for different rainfall simulators, this method cannot distinguish the effects of raindrop KE or rainfall simulator systems on soil erosion. 3. Eliminating raindrop KE through covering the soil surface by nylon net (or something else) under the same RI for the same rainfall simulator system (An et al., 2012; Wang et al., 2014). While this method greatly reduces soil erosion, it cannot be used to assess the process by which raindrop KE reduction affected soil erosion. 4. Changing the raindrop falling height at the same RI for the same rainfall simulator system (Mamedov et al., 2000) can maintain the same raindrop size distribution and \( D_{90} \) while changing the KE. This is the most effective method to distinguish the effects of raindrop KE and RI on soil erosion. Therefore, this study used the fourth method to investigate the effects of raindrop KE on splash erosion.

The Mollisol region in Northeast China, which has been cultivated as farmland, is considered to be essential for crop production (Xu et al., 2010). The thickness of the Mollisols has decreased by a depth of 30 to 50 cm due to large-scale cultivation and soil erosion since the 1950s (Zhang et al., 2007; Wang et al., 2009; Fang et al., 2012). Soil erosion studies in this region have been conducted for several years (Cheng et al., 2008; Xu et al., 2010). Splash erosion is one of the principal erosion processes in the Mollisol region. It has been reported that the key factor affecting soil erosion in the Mollisol region is raindrop impact. When raindrop impact was eliminated by nylon nets, soil erosion decreased by 72.3 to 96.2% on Mollisol hillslopes (An et al., 2012). Essentially all residues are removed from the fields after harvest, and cropland is left fallow without any cover during October to April in the Chinese Mollisol region (Xu et al., 2010), which leaves the soil surface vulnerable to raindrop splash erosion. How rainfall physical parameters (RI, raindrop KE, and raindrop diameter) affect the directional components (upslope, lateral, and downslope) of splash erosion is still unclear in this region. Although the role of rainfall physical parameters on splash erosion has been reported (Bubenzer and Jones, 1971; Meyer, 1981; Quansah, 1981; Poesen, 1985; Fernández-Raga et al., 2010), little information is available on distinguishing the effects of RI and raindrop KE on splash erosion at the same rainfall amounts. Thus, it is imperative to study the effects of rainfall physical parameters on splash erosion characteristics, as this would provide guidance about current cropland management for local farmers in the Chinese Mollisol region.

Therefore, a laboratory experiment was designed to investigate how rainfall physical parameters affected the directional components (upslope, lateral, and downslope) of splash erosion in the Chinese Mollisol region. The objectives of this study were (i) to investigate the effects of rainfall physical parameters on directional components of splash erosion characteristics, (ii) to select the key rainfall physical parameters affecting total and net splash erosion, and (iii) to fit and validate the equations between total and net splash erosion with rainfall physical parameters.

**MATERIAL AND METHODS**

**Experimental Materials**

The experimental study was conducted 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-sprinkle rainfall simulator system was used to apply rainfall, which could simulate natural rainfall size distribution, and rainfall uniformity reached 85% (Chen and Wang, 1991). The rainfall simulator system included two nozzles, and the designed rainfall intensities were precisely achieved by adjusting the aperture of the nozzle orifice and the water pressure (Fig. 1). The aperture of the nozzle orifice ranged from 3 to 15 mm, which can produce rainfall intensities of 30 to 165 mm h⁻¹. The water pressure was adjusted by the variable-frequency drive (VFD). The diameters of the simulated rainfall ranged from 0.2 to 3.0 mm, and 85% of the raindrop diameters were <1.0 mm, which is similar to the raindrop size distribution of natural rainfall (Chen and Wang, 1991).

The experiments were conducted in a slope-adjustable soil pan made from steel, which was 50 cm long, 50 cm wide, and 40 cm deep, with holes (5 mm) at the bottom to facilitate drainage (Fig. 1). The soil pan used in this study was modified from the soil pan designed by Bradford and Huang (1993), which could separately measure the directional components of splash erosion and sediment transport by runoff (sheet erosion) on hillslopes. The slope gradient ranged from 0 to 35° with adjustment intervals of 0.1°. A 50-cm-long, 3.5-cm-wide, and 1.5-cm-deep runoff collector was installed at the outlet of the soil pan, which was elevated 5 mm above the soil surface to allow for runoff sampling. Two 50-cm-long, 3.5-cm-wide, and 40-cm-deep lateral splash collectors were attached to each side of the soil pan. The 57-cm-long, 3.5-cm-wide, and 40-cm-deep downslope splash collector was attached to the lower end of the
runoff collector (Fig. 1). The upslope splash collector was identical to the downslope splash collector and was attached to the upper edge of the soil pan. Splash erosion was washed into the collector with a sprinkler and then collected through a plastic water tube at the bottom of the collector. The splash collectors were surrounded by four buffer areas. The splash boards are approximately 80 cm tall, with a height of 40 cm above the soil surface.

The soil used in this study was a Mollisol (US soil taxonomy) consisting of 3.3% sand (>50 μm), 76.4% silt (2–50 μm), 20.3% clay (<2 μm), and 23.8 g kg⁻¹ soil organic matter. The pH was 5.92, determined in water using a 1:2.5 solid/water ratio (weight basis). The pipette method and the potassium dichromate oxidation external heating method (Liu, 1996) were used to determine the soil texture and soil organic matter content, respectively. The tested soil was collected at a depth of 0 to 20 cm in the Ap horizon of a maize field in Liuji Town (44°43' N, 126°11' E), Yushu City, Jilin Province, in the center of the Mollisol region in Northeast China. The tested soil water content at field capacity was 28.0%. Foreign matter, such as large organic debris and gravel, was removed manually; however, the soil was not passed through a sieve.
Experimental Setup and Procedures

Soil erosion is generally caused by the high-intensity and short-duration rainstorms in the Mollisol region of Northeast China (maximum 10-min rainfall intensity ≥ 0.71 mm min−1, 42.6 mm h−1). In some cases, the momentary RI reaches 103.2 mm h−1 (Zhan et al., 1998). Thus, the representative rainfalls in this study were set to 50 and 100 mm h−1. Cui et al. (2007) reported that when the slope gradient was greater than 7° in the Chinese Mollisol region, soil erosion became more severe. Therefore, a 7° slope was used in this study.

To achieve different raindrop kinetic energies, we altered the raindrop falling heights at the same RI while maintaining the raindrop size distribution and median diameter drop size. Previous laboratory studies noted that if the raindrop falling height was >4.3 m, the fall velocities of the raindrops could reach 80% of their terminal velocities; when the raindrop falling height was approximately 7 to 8 m, 95% of the raindrops could reach their terminal velocities (Laws, 1941; Gunn and Kinzer, 1949). In China, Chen and Wang (1991) noted that when the raindrop falling height was 6.5 m, the raindrops (>2 mm) could not reach their terminal velocities for the side-sprinkle rainfall simulator; when the raindrop falling height was 11 m, the raindrops (0–6 mm) could reach their terminal velocities. Thus, based on previous studies, five raindrop falling heights of 3.5, 5.5, 7.5, 9.5, and 11.5 m were set. All experiments were replicated four times, and fresh soil was used for each replication.

Before packing the soil pan, the soil moisture content of the tested soil was determined and used to calculate how much soil was needed to pack the soil pan and obtain the target bulk density. First, a 20-cm-thick layer of sand was packed at the bottom of the soil pan, which allowed for free drainage of excess water. Then, a plow pan with a depth of 10 cm and a tillage layer with a depth of 10 cm were placed over the sand layer to simulate typical cropland soil conditions. The bulk densities for the plow pan and the tillage layer were 1.35 and 1.20 g cm−3, respectively. During the packing process, the plow pan and the tillage layer were both packed in 5-cm increments. After packing each soil layer, the surface was lightly raked, and the water needed to obtain field capacity for each packed soil layer was uniformly sprayed to the soil layer with a sprinkler. Subsequently, the next soil layer was packed. The aim of separately packing each soil layer was to reduce the nonuniformity of the soil surface. After packing the soil pan, manual tillage with a special rake made of steel (8-cm width and 10-cm till depth) was performed to a depth of approximately 10 cm along the contour line before spraying water. After plowing and adding water, the soil pan was allowed to settle for 24 h. The soil surface was covered with a plastic sheet to prevent soil moisture evaporation.

Before running experiments, RI was calibrated to confirm that it reached the target RI and met the experimental requirements. All experimental treatments had the same run time of 30 min.

Measurements of Raindrop Kinetic Energy

To determine raindrop KE, the raindrop size distribution and its fall velocity must be measured. The raindrop diameters were measured by using the color spot method (Hall, 1970; Dou and Zhou, 1982). In addition, the raindrop diameters were measured at 5-min intervals during each run, with three replications each time for a total of 18 samples to eliminate the uncertainty of raindrop size distribution and fall velocity for each treatment. The methods were as follows. A 1:10 mixture of eosin and talcum powder (w/w basis) was painted on the medium-speed qualitative filter paper (diameter = 15 cm). The color spots could be obtained when the filter papers were exposed to rainfall for extremely short time intervals. The filter paper was scanned, and then four pairs of mutually perpendicular diameter drops for each rainfall diameter were measured by the ruler function of ImageJ software (National Institute of Mental Health), with a 0.001-mm measurement accuracy.

The raindrop diameter, \( d \) (mm), was calculated as

\[
d = 0.356D^{0.711}
\]

where \( D \) is the color spot diameter (mm).

The terminal velocities of the raindrops under natural rainfall conditions were calculated using

\[
V = \begin{cases} \frac{0.496}{d} & \text{for } d < 1.9 \text{ mm} \\ \frac{0.712}{d} & \text{for } d \geq 1.9 \text{ mm} \\ \end{cases}
\]

However, raindrops could not reach their terminal velocities under simulated rainfall. Thus, the raindrop terminal velocity under simulated rainfall, \( \nu_t \) (m s\(^{-1}\)), was calculated as (Zheng and Gao, 2000)

\[
\nu_t = V \sqrt{1 - \exp \left( -\frac{2g}{V^2} H \right)}
\]

where \( V \) is the raindrop terminal velocity under natural rainfall (m s\(^{-1}\)), \( g \) is the gravitational acceleration (9.8 m s\(^{-2}\)), and \( H \) is the raindrop falling height (m).

The individual raindrop KE, \( \epsilon_i \) (J), was calculated using

\[
\epsilon_i = \frac{1}{2} m_i \nu_t^2
\]

where \( m_i \) is the mass of individual drops (g). In addition, the mass of the raindrops was calculated from the diameter measured using the color spot method by assuming a spherical drop shape.

The total KE, \( \epsilon_{sum} \) (J), was calculated as

\[
\epsilon_{sum} = \sum_{i=1}^{n} \epsilon_i
\]

where \( n \) is the total number of raindrops.

The rainfall depth, \( P \) (mm), was calculated as
where \( p \) is the density of water (deionized water was applied, 1.0 g cm\(^{-3}\)), and \( S \) is the sampling area of the filter paper (m\(^2\)).

The unit kinetic energy per unit surface and precipitation amount, \( KE \) (J m\(^{-2}\) mm\(^{-1}\)), was calculated as

\[
KE = \frac{E_{\text{sum}}}{PS}
\]

where \( P \) is the rainfall depth (mm), and \( S \) is the sampling area of the filter paper (m\(^2\)).

The characteristics of rainfall in this study are shown in Table 1.

For each treatment, splash samples were collected in 2-L buckets, which were measured at 6-min intervals for 50 mm h\(^{-1}\) RI, and at 3-min intervals for 100 mm h\(^{-1}\) RI. These samples were weighed and allowed to sit so that the suspended sediments would settle out. The clear supernatant was decanted, and the remaining sediment was oven-dried at 105°C and weighed to calculate the sediment yield.

In this study, the total, lateral, and net (downslope minus upslope) splash erosions were calculated as follows:

\[
S_T = S_u + S_d + S_l + S_r
\]

\[
S_u = \frac{1}{2}(S_l + S_r)
\]

\[
S_N = S_d - S_u
\]

where \( S_T \) is total splash erosion (g), \( S_u \) is upslope splash erosion (g), \( S_d \) is downslope splash erosion (g), \( S_l \) is left splash erosion (g), \( S_r \) is right splash erosion (g), \( S_{ul} \) is lateral splash erosion (g), and \( S_N \) is net splash erosion (g).

### Data Analysis

Using SPSS 16.0 software (SPSS Inc.), ANOVA was conducted to examine significant differences in total, net, and directional components (upslope, lateral, downslope) of splash erosion among different raindrop kinetic energies at the same RI. For the results of multiple comparisons, the LSD procedure was used and the values were statistically significant at the 95% confidence level. The method of independent-sample \( t \) test was used to identify the differences between two rainfall intensities and the differences between the left and right splash erosion at the same raindrop KE and the same RI. A correlation matrix of the Pearson correlation coefficient was used to analyze the correlations between total and net splash erosion with rainfall physical parameters.

A surface fitting tool was applied using the Matlab R2010b software (MathWorks Inc.). The relationships of total and net splash erosion with rainfall physical parameters were fitted.

### Table 1. The characteristics of rainfall produced by the rainfall simulator system used in this study.

<table>
<thead>
<tr>
<th>Rainfall intensity (mm h(^{-1}))</th>
<th>Raindrop median volume diameter* (mm)</th>
<th>Raindrop falling height (m)</th>
<th>Raindrop terminal velocity* (m s(^{-1}))</th>
<th>Raindrop kinetic energy (J m(^{-2}) mm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.01 (0.04)§</td>
<td>3.5</td>
<td>3.17 (0.14)¶</td>
<td>6.48 (1.06) •</td>
</tr>
<tr>
<td>100</td>
<td>1.16 (0.03)</td>
<td>3.5</td>
<td>3.51 (0.28)c**</td>
<td>7.67 (0.16) **</td>
</tr>
<tr>
<td>§ Means followed by different letters in the same column are significantly different among different raindrop kinetic energies at the same rainfall intensity at ( p &lt; 0.05 ). ** Values at 100 mm h(^{-1}) rainfall intensity are significantly greater than those at 50 mm h(^{-1}) rainfall intensity at ( p &lt; 0.05 ) according to an independent-sample ( t )-test.</td>
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</table>

During the specific implementation process, the trust region method was applied (Wen et al., 2015), and the physical meaning of the equations was considered.

The three-dimensional surface figures of raindrop KE and raindrop \( D_{50} \) with total and net splash erosion were plotted using SigmaPlot 12.5 software (Systat Software).

To ensure the independence of the splash erosion data used to establish and validate the equations, three-fourths of the data were randomly selected to establish the equations and the remaining one-fourth of the data were used to validate the equations. The determination coefficient (R\(^2\)) and the Nash–Sutcliffe simulation efficiency (E\(_{NS}\)) (Nash and Sutcliffe, 1970) were generally used to evaluate the prediction accuracy. The R\(^2\) value indicates the strength of the relationship between observed and simulated splash erosion. The E\(_{NS}\) value indicates how well the plot of the observed vs. the simulated splash erosion fits the 1:1 line. If the values of R\(^2\) and E\(_{NS}\) are close to 1, the model prediction is considered to be perfect; however, if the values of R\(^2\) and E\(_{NS}\) are close to 0, the model prediction is considered to be poor. Typically, when R\(^2\) > 0.6 and E\(_{NS}\) > 0.5, the equation prediction is acceptable or satisfactory (Santhi et al., 2001).

### RESULTS AND DISCUSSION

**Total Splash Erosion**

Total splash erosion significantly increased as RI increased (\( p < 0.05 \)) (Table 2). When RI increased from 50 to 100 mm h\(^{-1}\), total splash erosion significantly increased by 4.4 to 10.4 times.
Values at 100 mm h−1 rainfall intensity are significantly greater than those at 50 mm h−1 rainfall intensity at increased from 7.75 to 9.83 J m−2 mm−1, total splash erosion different raindrop falling heights at 100 mm h−1, KE and raindrop falling height was 3.5 m, as RI increased from 50 to 100 mm h−1 rainfall intensity were mainly affected by the mechanical breakdown by raindrop impact (Le Bissonnais, 1996). In addition, soil detachment and transport by raindrop impacts were energy consumption processes (Rouhipour et al., 2006). The influence of raindrop impact on splash erosion was related to the effect of the soil surface in dissipating raindrop KE. For lower KE, a large amount of energy was dissipated at the raindrop impact moment, and there was insufficient energy for detaching soil particles (Moss et al., 1980). With the increase of raindrop impact energy, there was sufficient energy for soil detachment and transport.

As raindrop falling height decreased from 11.5 to 3.5 m, KE at rainfall intensities of 50 and 100 mm h−1 decreased 34.1 and 47.0%, respectively, and total splash erosion decreased 80.1 and 86.5%, respectively (Table 2). Previous studies (Meyer and Mannering, 1963; Wang et al., 2014; Ma et al., 2015) have indicated that if KE is dissipated either by some artificial means or vegetative canopy, soil erosion could be greatly reduced. An et al. (2012) noted that when raindrop impact was eliminated by nylon nets, soil erosion decreased by 72.3 to 96.2% on Mollisol hillslopes. The key factor affecting soil erosion in the Chinese Mollisol region was raindrop impact (Wen et al., 2015). Besides, there was not any residue cover on cropland after harvest from October to April in the Chinese Mollisol region (Xu et al., 2020). Hence, to prevent the effects of raindrop impact on soil surface, effective soil conservation measures, such as cover crops and crop residue retention (Zhang et al., 2009), should be implemented instead of current cropland management measures in the Mollisol region of Northeast China.

The relationships between total splash erosion and KE at rainfall intensities of 50 and 100 mm h−1 (Fig. 2) were power functions ($R^2 = 0.91$ and 0.88, respectively), which was consis-

<table>
<thead>
<tr>
<th>Table 2. The directional components of splash erosion, net splash erosion, and total splash erosion at rainfall intensities of 50 and 100 mm h−1.</th>
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<tbody>
<tr>
<td><strong>Raindrop kinetic energy</strong></td>
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<tr>
<td>J m−2 mm−1</td>
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<tr>
<td>6.48</td>
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<tr>
<td>6.77</td>
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<tr>
<td>7.75</td>
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<td>8.59</td>
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<tr>
<td>9.83</td>
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<tr>
<td>7.67</td>
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<tr>
<td>8.52</td>
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<tr>
<td>10.23</td>
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<tr>
<td>12.85</td>
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<td>14.47</td>
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</table>

*Values at 100 mm h−1 rainfall intensity are significantly greater than those at 50 mm h−1 rainfall intensity at p < 0.05 according to an independent-sample t-test. **Values at 100 mm h−1 rainfall intensity are significantly greater than those at 50 mm h−1 rainfall intensity at p < 0.01 according to an independent-sample t-test. †Means with standard deviations in parentheses. Means followed by different letters in the same column are significantly different in splash erosion among different raindrop kinetic energies at the same rainfall intensity at p < 0.05 according to the LSD test. ‡The letter A in the same row indicates that there is no significant difference between the left slope and right slope splash erosion at the same raindrop kinetic energy and the same rainfall intensity at p < 0.05 according to an independent-sample t-test.
tent with the results of previous studies (Meyer, 1981, Morgan, 1982). By studying two types of soil under variable RI, Free (1960) noted that the power equation exponents were 0.9 and 1.46 for sandy and loam soil, respectively. Bubenzer and Jones (1971) found that the equation exponents ranged from 1.34 to 1.77 for soils with textures from silty clay to loamy sand. Quansah (1981) identified the equation exponents as 0.84 to 1.06, 1.16, and 1.35 for sand, clay loam, and clay soil, respectively. Sharma et al. (1991) noted that the equation exponents ranged from 0.77 to 2.10 and 0.84 to 1.54 for seven soils ranging in texture from clay to sandy loam at the matrix potential of −0.1 kPa (near saturation) and −1.0 kPa, respectively. The equation exponents in the present study were 2.79 and 1.96 for 50 and 100 mm h⁻¹ RI, respectively. The equation exponent values were different from previous studies. This may be related to the content of soil organic matter, which affected the soil erodibility.

The Directional Components of Splash Erosion

There were significant differences in the contributions of the directional components (upslope, lateral, downslope) of splash erosion to total splash erosion at the same raindrop KE ($p < 0.05$) (Table 3). Splash erosion from upslope, downslope, and lateral slope (left or right slope) averaged 14.5, 32.2, and 26.3% of total splash erosion, respectively. Furthermore, the downslope splash erosion accounted for an average of 60.4% of the sum of the left and right splash erosion. This was quite different from the result of Bradford and Huang (1993); they assumed the downslope splash erosion was equal to the sum of the left splash plus the right splash. Thus, downslope and lateral splash erosion were very important components of total splash erosion. This might be due to the effects of gravity. When the soil surface had a slope, gravity was a driving force for the downslope and a resistance force for the upslope, respectively. Thus soil particles splashed downslope traveled further than those splashed upslope, which resulted in greater mass loss downslope. Fu et al. (2011) also presented evidence that gravity caused more soil particles to move downslope. For lateral splash, gravity was a driving force and a resistance force. In addition, the contribution of lateral splash erosion to total splash erosion was significantly greater than that of upslope splash erosion to total splash erosion and significantly lower than that of downslope splash erosion to total splash erosion.

### Table 3. Contributions of the directional components of splash erosion to total splash erosion.

<table>
<thead>
<tr>
<th>Raindrop kinetic energy</th>
<th>Contribution to total splash erosion</th>
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<tbody>
<tr>
<td></td>
<td>Upslope (%)</td>
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<tr>
<td>50 mm h⁻¹ rainfall intensity</td>
<td>6.48</td>
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<td></td>
<td>6.77</td>
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<td></td>
<td>7.75</td>
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<td>8.59</td>
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<td>9.83</td>
</tr>
<tr>
<td>100 mm h⁻¹ rainfall intensity</td>
<td>7.67</td>
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<td>8.52</td>
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<td>12.85</td>
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<td>14.47</td>
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</table>

† Means with standard deviations in parentheses. Means followed by different lowercase letters in the same column are significantly different among different raindrop kinetic energies at the same rainfall intensity at $p < 0.05$ according to the LSD test; means followed by different uppercase letters in the same row are significantly different among the contributions of upslope, downslope, and lateral slope splash erosion to total splash erosion at the same raindrop kinetic energy and the same rainfall intensity at $p < 0.05$ according to the LSD test.

![Fig. 2. Relationships between total splash erosion and raindrop kinetic energy at rainfall intensities of (a) 50 and (b) 100 mm h⁻¹ ($n = 20$).](image-url)
total splash erosion \( (p < 0.05) \) (Table 3). Thus, lateral splash erosion played a significant role in supplying detached particles to adjacent areas.

The directional components of splash erosion significantly increased with increasing RI \( (p < 0.05) \) (Table 2). As RI increased from 50 to 100 mm h\(^{-1}\), splash erosion from the upslope, downslope, and lateral slope significantly increased 4.5 to 12.5, 4.9 to 13.4, and 3.8 to 10.4 times, respectively \( (p < 0.05) \) (Table 2). When the raindrop falling height was 11.5 m, splash erosion from the upslope, downslope, and lateral slope at 100 mm h\(^{-1}\) RI were 8.4, 8.0, and 7.9 times greater than those at 50 mm h\(^{-1}\) RI \( (p < 0.05) \), respectively. In addition, when raindrop falling height was 3.5 m, upslope, downslope, and lateral slope splash erosion at 100 mm h\(^{-1}\) RI were 5.5, 5.9, and 4.8 times greater than those at 50 mm h\(^{-1}\) RI, respectively \( (p < 0.05) \).

Splash erosion from the upslope, downslope, and lateral slope significantly increased as raindrop KE increased at the same RI \( (p < 0.05) \) (Table 2). The relationships between the directional components of splash erosion and KE at rainfall intensities of 50 and 100 mm h\(^{-1}\) were described by power functions (Fig. 3). At 50 mm h\(^{-1}\) RI, when KE was increased from 8.59 to 9.83 J m\(^{-2}\) mm\(^{-1}\), upslope splash erosion significantly increased \( (p < 0.05) \). When KE was increased from 6.48 to 6.77 J m\(^{-2}\) mm\(^{-1}\) and from 8.59 to 9.83 J m\(^{-2}\) mm\(^{-1}\), downslope splash erosion significantly increased \( (p < 0.05) \). There were significant differences in lateral splash erosion among different raindrop KE \( (p < 0.05) \). Furthermore, at 100 mm h\(^{-1}\) RI, when KE was increased from 7.67 to 8.52 J m\(^{-2}\) mm\(^{-1}\) from 10.23 to 12.85 J m\(^{-2}\) mm\(^{-1}\), upslope splash erosion significantly increased \( (p < 0.05) \). There were significant differences in downslope and lateral splash erosion among different raindrop KE \( (p < 0.05) \). In addition, at 50 mm h\(^{-1}\) RI, when KE increased 1 J m\(^{-2}\) mm\(^{-1}\), splash erosion from the downslope, lateral slope, and upslope averages increased 17.3, 13.8, and 7.0 g m\(^{-2}\) h\(^{-1}\), respectively. At 100 mm h\(^{-1}\) RI, when KE increased 1 J m\(^{-2}\) mm\(^{-1}\), splash erosion from the downslope, lateral slope, and upslope averages increased 75.3, 67.3, and 32.2 g m\(^{-2}\) h\(^{-1}\), respectively.

The directional components of splash erosion responded differently as KE increased (Fig. 3). When KE was lower than 8 J m\(^{-2}\) mm\(^{-1}\), splash erosion slowly increased with an increase of KE. Conversely, when KE was greater than 8 J m\(^{-2}\) mm\(^{-1}\), splash erosion greatly increased with an increase of KE. Kinnell (2005) noted that raindrop detachment occurred only when the KE exceeded a threshold value to overcome the bonding effects that hold particles in the soil surface. Thus, there existed a threshold KE for initiating splash erosion, below which the KE might not cause soil erosion (Wang et al., 2014).

**Net Splash Erosion**

Net splash erosion also significantly increased with increasing RI \( (p < 0.05) \) (Table 2). When RI increased from 50 to 100 mm h\(^{-1}\), net splash erosion significantly increased 5.4 to 13.5 times \( (p < 0.05) \). When raindrop falling height was 11.5 m, net splash erosion at 100 mm h\(^{-1}\) RI was 7.7 times greater than that at 50 mm h\(^{-1}\) RI \( (p < 0.05) \). Additionally, when raindrop falling height was 3.5 m, net splash erosion at 100 mm h\(^{-1}\) RI was 6.4 times greater than that at 50 mm h\(^{-1}\) RI \( (p < 0.05) \).

Net splash erosion significantly increased as raindrop KE increased at the same RI \( (p < 0.05) \) (Table 2). The relationships between net splash erosion and KE at rainfall intensities of 50 and 100 mm h\(^{-1}\) (Fig. 4) were power functions \( (R^2 = 0.83 \text{ and } 0.79, \text{ respectively}) \). At 50 mm h\(^{-1}\) RI, when KE was increased from 8.59 to 9.83 J m\(^{-2}\) mm\(^{-1}\), net splash erosion significantly increased \( (p < 0.05) \). In addition, at 100 mm h\(^{-1}\) RI, when KE was increased from
7.67 to 8.52 J m$^{-2}$ mm$^{-1}$ from 10.23 to 12.85 J m$^{-2}$ mm$^{-1}$, net splash erosion significantly increased ($p < 0.05$). Moreover, when KE increased 1 J m$^{-2}$ mm$^{-1}$, net splash erosion increased 1.9 to 19.8 g m$^{-2}$ h$^{-1}$ and 5.4 to 107.4 g m$^{-2}$ h$^{-1}$ at rainfall intensities of 50 and 100 mm h$^{-1}$, respectively. The results also showed that net splash erosion was largely affected by the changes in KE, especially at greater KE ranging from 7.93 to 14.56 J m$^{-2}$ mm$^{-1}$. In the present study, lateral splash erosion was balanced from the left and right splash erosion; thus, the net effect of the left and right splash erosion would be offset (Table 2), which was similar with the field study (Singer and Le Bissonnais, 1998; Fox and Bryan, 2000). However, lateral splash may play a significant role in the magnitude of the net splash erosion by increasing the supply on the surface of readily transportable material, which still needs further investigation.

### Correlations between Total and Net Splash Erosion with Rainfall Physical Parameters

A correlation matrix of the Pearson correlation coefficient was used to analyze the correlations between total and net splash erosion with each rainfall physical parameter (Table 4). Raindrop KE, RI, raindrop $D_{50}$ and $V_m$ were taken into account. The correlations between total and net splash erosion with rainfall physical parameters decreased as follows: KE > $D_{50}$ > RI > $V_m$.

Based on the correlation matrix, the correlation coefficient of total and net splash erosion with KE and $D_{50}$ was >0.8. Thus, KE and $D_{50}$ were the key indicators for evaluating total and net splash erosion.

### Equation Fitting between Total and Net Splash Erosion with Rainfall Physical Parameters

To ensure the independence of the splash erosion data used to fit and validate the equations, 30 samples were randomly selected from 40 samples to establish the equation. The remaining 10 samples were used to validate the equations. The relationships of total and net splash erosion with KE and $D_{50}$ were established as follows:

$$S_T = 0.14 KE^{2.65} D_{50}^{0.54}, \quad R^2 = 0.80, \quad n=30, \quad p<0.05 \quad [11]$$

$$S_N = 0.05 KE^{2.33} D_{50}^{1.38}, \quad R^2 = 0.76, \quad n=30, \quad p<0.05 \quad [12]$$

where $S_T$ is total splash erosion (g), $S_N$ is net splash erosion (g), KE is raindrop kinetic energy (J m$^{-2}$ mm$^{-1}$), and $D_{50}$ is the raindrop median volume diameter (mm).

The three-dimensional surface of KE, $D_{50}$ and splash erosion was plotted in Fig. 5 and 6. Equations [11] and [12] demonstrated that the effects of KE on total and net splash erosion were greater than those of $D_{50}$ (Hammad et al. 2006) and Fernández-

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$S_T$</th>
<th>$S_N$</th>
<th>KE</th>
<th>RI</th>
<th>$D_{50}$</th>
<th>$V_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_T$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_N$</td>
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<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KE</td>
<td>0.905**</td>
<td>0.889**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RI</td>
<td>0.775**</td>
<td>0.746**</td>
<td>0.565**</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>0.817**</td>
<td>0.817**</td>
<td>0.905**</td>
<td>0.472**</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$V_m$</td>
<td>0.669**</td>
<td>0.658**</td>
<td>0.877**</td>
<td>0.301</td>
<td>0.860**</td>
<td>1</td>
</tr>
</tbody>
</table>

** $p < 0.01$.
Raga et al. (2010) noted that KE was a better parameter for explaining splash erosion than other rainfall physical parameters. Values calculated by Eq. [11] and [12] were cross-validated with observed values not used in Eq. [11] and [12] development. The determination coefficient ($R^2$) and Nash–Sutcliffe simulation efficiency ($E_{NS}$) of Eq. [11] were 0.81 and 0.79, respectively. The observed and simulated values of total splash erosion were in close agreement (Fig. 7). The $R^2$ and $E_{NS}$ values of Eq. [12] were 0.72 and 0.83, respectively (Fig. 8). Both $R^2$ values of the two equations were greater than 0.6, indicating that the correlation between the predicted and observed splash erosion was acceptable (Nash and Sutcliffe, 1970). Besides, both $E_{NS}$ values of the two equations were greater than 0.5, indicating a satisfactory agreement for the model validation (Santhi et al., 2001). Thus, Eq. [11] and [12] are suitable for total and net splash erosion predictions in the Mollisol region of Northeast China, respectively.

CONCLUSIONS

Rainfall simulation studies focusing on splash erosion at two rainfall intensities (50 and 100 mm h$^{-1}$) and a range of raindrop KE varied by changing raindrop falling heights were conducted to investigate the effects of rainfall physical parameters (RI, raindrop KE, and raindrop diameter) on the directional components (upslope, lateral, downslope) of splash erosion characteristics. The results showed that splash erosion on hillslope increased as RI and raindrop KE increased.
from 50 to 100 mm h\(^{-1}\), total and net splash erosion significantly increased by 4.4 to 10.4 and 5.4 to 13.5 times, respectively (\(p < 0.05\)); upslope, downslope, and lateral slope splash erosion significantly increased by 4.5 to 12.5, 4.9 to 13.4, and 3.8 to 10.4 times, respectively (\(p < 0.05\)). Additionally, downslope, lateral slope, and upslope splash erosion accounted for 32.2, 26.3, and 14.5% of total splash erosion, respectively. Both raindrop KE and raindrop \(D_{50}\) were the key indicators for evaluating total and net splash erosion. Moreover, the relationships between total and net splash erosion with raindrop KE and raindrop \(D_{50}\) were established, and the results by cross-validation indicated that the equation had satisfactory prediction accuracy. Both equations indicated that the effects of raindrop KE on total and net splash erosion were obviously greater than those of raindrop \(D_{50}\). Thus, raindrop KE is the key factor affecting splash erosion on hillslopes. To prevent soil detachment by raindrop impacts, it is necessary to take soil conservation measures, such as retaining crop residue on the surface, to reduce splash erosion in the black soil region, Northeast China. Geomorphology 169:142–150. doi:10.1016/j.geomorph.2012.04.019


