Soil erosion processes on row sideslopes within contour ridging systems

Q.J. Liu a,⁎, H.Y. Zhang a,b, J. An a, Y.Z. Wu a

⁎ Corresponding author. Tel.: +86 13562990782; fax: +86 539 8766700.
E-mail address: liuqianjin@lyu.edu.cn (Q.J. Liu).

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1. Introduction

Contour ridging is an effective tillage practice for controlling soil erosion and increasing crop yield (Barton et al., 2004; Quinton and Catt, 2004; Shi et al., 2004; Stevens et al., 2009). In contour ridge systems, the seedbed is mounded above the natural surface to increase soil temperature and moisture, enhance soil depth, control pests and weeds, and increase crop yield (Gupta et al., 1990; Hathfield et al., 1998; Lal, 1990; Wang et al., 2008; X.H. Shi et al., 2012; Z.H. Shi et al., 2012). By increasing the soil surface roughness, contour ridging results in rainwater ponding in the furrow area, which reduces runoff velocity, increases infiltration, and reduces soil erosion (Lal, 1990; Liu and Huang, 2013; Liu et al., 2011; Quinton and Catt, 2004). In addition, nutrients (e.g., nitrogen and phosphorus) in runoff are retained better in contour ridge tillage compared with up- and downslope tillage (Barbosa et al., 2009; Ma et al., 2010; Stevens et al., 2009).

Although the functions of contour ridges in soil conservation have been widely acknowledged, they remain uncertain due to the variations of field slope and microtopographic relief. When the field slope is steep enough so that the ridge top is below the furrow on the upper side of the ridge, the soil conservation capacity of the contour ridge is lost (USDA-ARS, 2008). Due to the microtopographic relief of sloped land, it is impossible to perfectly align the ridge with the contour. Thus, depression areas will be formed in the furrows when the contour ridges are moulded (Cui et al., 2007; Griffith et al., 1990). During a rainfall event, runoff from ridge sideslopes and furrows will accumulate in these depressions. When the ponded rainwater exceeds the storage within a contour row, it overflows the ridge. Rill erosion occurs when the shear stress of this overflow exceeds ridge stability. At this point, the dominant form of erosion transitions from interrill to rill erosion (USDA-ARS, 2008). The rill erosion increases the probability of contour failure. After contour failure, the concentrated rainwater will enhance...
soil erosion with high erosive power (Flanagan and Livingston, 1995; Hatfield et al., 1998; USDA-ARS, 2008). Serious soil erosion induced by contour failure is a common phenomenon in sloped land in North China (Fig. 1).

Soil erosion on the row sideslope is affected by the length and steepness of the row sideslope (Kinnell, 2000; Meyer and Harmon, 1987). The length of the row sideslope positively affects soil erosion (per unit of area) when small rills develop where the hydraulic shear of flowing water is sufficient to denude soil particles from the soil matrix (Kinnell, 2000; Meyer and Harmon, 1987). Another case is when the erosion process is dominated by raindrop detachment and flow transport rather than raindrop detachment and raindrop-induced flow transport, because the system of raindrop detachment and flow transport has sufficient hydraulic shear to entrain the raindrop-detached particles, while raindrop induced flow transport only operates in shallow flow through the combined action of raindrops (Kinnell, 2000). In addition, Meyer and Harmon (1987) observed that soil erosion slightly increased and soil cohesiveness decreased as the slope increased from 5 to 30%.

The contour ridge system is a combination of ridges, adjacent furrows, and the topography of the field where it is implemented. Thus, erosion is affected by geomorphological factors other than the length and steepness of the row sideslope. For example, contour ridge height is an important factor that influences soil erosion in ridge tillage systems. Greater amounts of runoff are stored between taller ridges, which results in greater infiltration and lower runoff and sediment yield (USDA-ARS, 2008). The contour ridge height and width can be used to determine the length of the row sideslope. The existing row grade in a contour ridge system will result in several depressions where runoff is concentrated. A slight row grade may result in severe ephemeral gully erosion (USDA-ARS, 2008). In addition to the microtopographic features mentioned above, field slope strongly influences the runoff and erosion processes on sloped land (USDA-ARS, 2008). The influences of these factors (especially field slope or ridge height) on soil erosion in contour ridge systems have been studied already during the development of the USLE (Wischmeier and Smith, 1978) and RUSLE (Renard et al., 1997) soil erosion models. In the RUSLE2 user guide (USDA-ARS, 2008), the soil conservation benefit of field slope on soil erosion is described as a concave curve, increasing from no effect to greatest benefit and then decreasing to no effect with the rise of the field slope. The field slope at which the greatest benefit occurs is related to ridge height (USDA-ARS, 2008). Ridge height has a negative effect on soil erosion and is considered as a subfactor to the support practice factor (P) in the RUSLE2 model (USDA-ARS, 2008). However, the quantitative influences of microtopography indices (e.g., row grade and field slope), ridge geometry indices (e.g., ridge height and width) and their interactions during different rainfall intensities on the sideslope erosion of rows remain unclear. Thus, understanding this soil erosion process and its influencing factors will improve our knowledge regarding soil erosion and will potentially improve soil conservation practices using contour ridge systems. This study addresses the influence of combination of different topographical features and their interactions on the erosion process of contour ridge systems. The specific objectives of this study were to (i) reveal the processes of interrill and rill erosion on row sideslopes; and (ii) interpret the effects and interactions of microtopography, ridge geometry and rainfall intensity on runoff and sediment yield.

2. Materials and methods
2.1. Experimental design

In order to analyze the effects on soil erosion on row sideslopes, 32 rainfall simulation experiments were conducted. Five different factors were analyzed in this study, including two microtopography indices (row grade, RG, and field slope, FS), two ridge geometry indices (ridge height, H, and ridge width, W), and rainfall intensity (RI) in two levels (Table 1). The two levels of row grade, ridge height and width were determined according to a previous field investigation. The effects and first-order interactions of the five factors were arranged in an L_{16}(2^{5}) orthogonal array created by the Taguchi method. Under this method, the effect and interaction of factors can be calculated and the significance tested using statistical software (e.g., SPSS), and the optimal parameters and their levels can be determined. An important advantage of the Taguchi method is that the overall testing time and experiential costs can be significantly minimized compared with a full factorial design, especially when the number of factors and levels increase (Sadeghi et al., 2012). In this experiment, all treatments were replicated twice.

2.2. Experiment plots

In order to analyze row grade and field slope simultaneously, a new type of experimental plot was designed for this study. The experimental plot consisted of a box including two stainless steel cassettes (80 cm wide and 160 cm long) that were hinged together, which could be filled with soil (Fig. 2). By rotating the screw (a) with one apex fixed on the cassette boundary and another apex fixed on the chassis, the box could be lifted up or down to simulate different row grades between 0° and 15°. The field slope along the plot was obtained from 0° to 20° by rotating the screw fixed under the two stabilizer blades (b).

A sandy brown soil that developed from granite with a sand content of 71.2% (Table 2) was used in this study. The soil collected from the plow layer was air dried before passing through a 10.0 mm sieve. The soil of the plow pan was simulated by packing the soil at a depth of 20 cm (in four 5 cm layers) to a bulk density of 1.6 g cm\(^{-3}\) (the measured bulk density in the field). The soil packed into the plot was kept in the same weight in a given row grade treatments by adjusting the levels of the furrow bottoms at a bulk density of 1.2 g cm\(^{-3}\).

![Fig. 1. Erosion induced by contour failure in the field (typical slope land in North China).](image-url)
For example, the furrow bottom level should be raised to contain more soil in the case of diminished ridge volume (e.g., if the ridge height was decreased under a certain ridge width), and vice versa. Before ridge formation, the ridge geometry in a cross section was drawn on the plot wall above the furrow bottom line. The crest point of the ridge cross section was located by offsetting the point at the upper 1/3rd of the ridge width segment vertically to the designed height, and the side line was obtained by joining the crest point to the two endpoints of the ridge width segment. Following the sketches of ridge cross section, the ridges were formed with a bulk density of 1.2 g cm⁻³.

To prevent the impacts of runoff and sediment disturbances in the upper areas (c) of the row sideslopes on soil erosion in the lower areas (d), two plastic plates (e) were inserted into the surface of the row sideslopes at a depth of approximately 2 cm. The vertical sides of these plates were fixed to the adjacent plot wall after the ridge was formed. Two outlets (f) were fixed in the plot wall to allow runoff from the upper area (c) to flow out. In addition, an outlet (g) was fixed in the junction of the two cassettes and above the furrow bottom to collect the runoff and sediments that were generated from the lower area (d).

### 2.3. Rainfall simulation experiments

The simulated rainfall experiments were performed at the Shandong Provincial Key Laboratory of Soil Conservation and Environmental Protection. Rainfall intensities (39 ± 0.3 mm h⁻¹ and 61 ± 0.6 mm h⁻¹) with a homogeneity coefficient of >0.89 were obtained in a trough rainfall simulator using a Veejet 80100 nozzle (Xie et al., 2008; Zhang et al., 2007). To settle the soil surface and reduce its variability, a 60 min pre-rain with a rainfall intensity of 20 mm h⁻¹ was performed 12 h before each experiment. The initial ridge height was 2 cm greater than designed because the ridge height decreased during the pre-rain. The rainfall duration was set to 50 min to ensure that contour failure occurred in most of the treatments.

The runoff was collected with previously weighted plastic buckets at 1 min intervals during each rainfall event until rill erosion occurred [as shown in Fig. 3(B)]. Next, the collected samples were immediately weighed on an electronic scale and dried in a forced-air oven at 105°C, and, subsequently, the sediment mass was quantified. The water mass was obtained by subtracting the sediment weight from the mixed sample weight, and the runoff volume was calculated. The total runoff and sediment yields were obtained by adding the entire runoff and sediment yields from the rainfall until rill cut through the entire row sideslope.

#### 2.4. Data treatment

When the row grade was adjusted, the section area of the plot could change, which could influence the soil erosion and induce a difference. Therefore, a constant of 0.9455, which corresponded to the ratio of the 10° and 5° row grade plots areas, was used to calibrate the runoff for the 10° row grade plot. It was assumed that the difference area was located at the upper board of the ridge, where interrill erosion occurred; therefore, runoff in these small areas was considered linearly related to the erosion area. The sediment yields were calibrated according to the power function (Eq. (1)) that was established from the measured runoff and sediment data.

\[
S = 5E - 0.99Q^{2.64} \\
R^2 = 0.75
\]  

(1)

Where S represents sediment yield per min (g min⁻¹); Q represents runoff per min (ml min⁻¹); and n represents the number of the observed data groups (16).

Runoff and sediment yield per min were expressed as Q and S, respectively, and were used in the following statistical analyses. The main effects analysis was used to determine how the average dependent variables changed when a factor increased from level 1 to 2 (Eq. (2)) (Jeff Wu and Hamada, 2009). If the main effect was positive,
then the effect of this factor on the dependent variable was positive (and vice versa). In addition, the greater the absolute value of the change, the greater the effect of the factor.

\[
ME(A) = z(A_2) - z(A_1).
\]

Where \(ME(A)\) represents the main effect of factor \(A\); \(z(A_2)\) is the average of the \(z_i\) values observed at \(A_2\); and \(z(A_1)\) is the average of the \(z_i\) values observed at \(A_1\).

The interactions of a pair of factors were calculated using Eq. (3) (Jeff Wu and Hamada, 2009).

\[
INT(A, B) = \frac{1}{2} (z(A_2B_2) + z(A_1B_1)) - \frac{1}{2} (z(A_2B_1) + z(A_1B_2)).
\]

Where \(INT(A, B)\) represents the interaction value of factors \(A\) and \(B\) (the positive and negative values indicate the interaction is positive or negative); and \(z(A_2B_2)\) denotes the average of the values with both \(A\) and \(B\) at the two levels.

ANOVA was conducted in SPSS 20 to quantify the effects and interactions of these factors (Sadeghi et al., 2012).

3. Results

3.1. Soil erosion process phases

Fig. 3, which shows photos taken in experiment No. 1, and Table 3 depict the rainwater and soil erosion status during a rainfall event. After simulated rainfall begins, the Horton flow runoff is generated during the first 1 or 2 min because even the lowest rainfall intensity of 39 ± 0.3 mm h\(^{-1}\) was greater than the infiltration rate. As shown in Fig. 3(A), the runoff accumulated in the low areas of the furrows, and overfl ow occurred when the amount of rainwater exceeded the storage capacity of the furrow. The surface soil on the row sideslopes was denuded and waterfalls formed a few minutes after overfl ow. Headwater erosion occurred at these waterfalls and proceeded until a rill was formed that cut through the surface (Fig. 3B).

The runoff and sediment yields in the time series for experiment No. 1 are shown in Fig. 4. Before overfl ow, the runoff and sediment yields from the lower sideslopes of the down-slope end ridges were measured. As shown in Fig. 4, the runoff and sediment increased before remaining relatively steady before the occurrence of overfl ow at 21 min. After overfl ow run out, the runoff and sediment yield increased until an extreme value was reached, which was associated with ridge collapse at 29 min. Therefore, two phases were determined during the rainfall event before ridge collapse, including interrill erosion (\(P_1\)) and rill erosion (\(P_2\)) (Fig. 4).

3.2. Runoff, sediment yield and duration before contour failure

The runoff, sediment yield and duration of the interrill and rill erosion periods in the 16 treatments (with two replications) were measured, and the mean values for the two replicates were calculated (Table 3). In treatment No. 4 (which had lower row and land slope and a greater ridge width and height during low rainfall intensity), the runoff, sediment duration and of the rill erosion period was zero because no overfl ow or rill erosion occurred. Treatment No. 4 had the longest interrill erosion duration (50 min), while treatment No. 10 had the longest observed rill erosion period (21 min). The shortest interrill and rill erosion durations were observed in experiments No. 14 (6 min) and No. 3 and 8 (4.5 min), respectively. The rill erosion period accounted for 72.3% of the overall time. The sediment yield in the interrill erosion period varied from 2.9 g (No. 5) to 64.6 g (No. 8), and the greatest runoff was observed in treatment No. 4 (7905.9 ml). During the rill erosion period, the maximum runoff and sediment yields were observed in experiments No. 10 (12780.8 ml) and No. 12 (410.9 g).

### Table 3

The L\(_{16}(2^{15})\) orthogonal array and the experimental results\(^a\).

<table>
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<th>Experiment no.</th>
<th>RG</th>
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<th>W</th>
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<th>Runoff (ml)</th>
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<td>3753.5</td>
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\(P_1\), interrill erosion period; \(P_2\), rill erosion period.

\(RG\), row grade; \(FS\), field slope; \(H\), ridge height; \(W\), ridge width; \(RI\), rainfall intensity.

\(^a\) The presented sediment yields, runoff values and durations are the mean values measured in the two replications.
respectively. In the interrill erosion period, 44.2% of the entire runoff was observed, and 55.8% of the total runoff occurred in the rill erosion period. The rill erosion period accounted for 87.0% of the overall sediment yield, and the interrill erosion accounted for 72.3% of the experimental period.

3.3. Factor effects on soil erosion

The effects of the different factors and their interactions on the duration (T), runoff (Q), and sediment yield (S) are given in Tables 4 and 5. Table 4 lists the effect and interaction of these factors, where a positive value indicates the impact is positive, and vice versa. Table 5 shows the significance testing results for the effects and interactions of these factors.

The duration of interrill erosion (T1) was significantly affected (p < 0.01) by ridge height, field slope and rainfall intensity with contributions of 46.8, 31.8 and 9.5%, respectively (Table 5). Only the ridge height positively affected the duration (15.7, in Table 4). The rainfall intensity had the most significant negative (−4.3, in Table 4) effect on the duration of rill erosion with a contribution of 21.3% (Table 5), and row grade had a positive effect (3.4, 13.4%). A positive interaction was observed between row grade and ridge width (RG * W) (3.3, 12.4%), and between ridge height and rainfall intensity (H * RI) (3.0, 10.5%).

Because the duration of interrill erosion (T1) dominated the entire period (T12), the factors affecting T12 were similar to those of T1. The runoff per min during the interrill erosion period (Q1) was positively affected by ridge width (33.1%), rainfall intensity (28.7%), and ridge height (16.6%). Regarding runoff per min during rill erosion period Q2, the ridge width had the greatest positive effect (181.0, 21.3%), while the ridge height had a negative effect (−152.9) with a contribution of 15.1%. The Q2 was also affected by the positive interaction of H * RI (8.8%) and the negative interaction of FS * RI (8.8%). The runoff per min during the entire period (Q12) was mainly positively affected by ridge width (50.1%), and negatively affected by ridge height (14.5%).

The sediment yield per min in the interrill erosion period (S1) was significantly and positively affected by rainfall intensity (17.0%), ridge width (14.8%) and field slope (8.3%). Ridge width had a positive interaction with rainfall intensity (RI * W) and field slope (FS * W) (contributions of 8.8 and 8.5%, respectively). Row grade not only exerted a positive main effect on sediment yield per min during the rill erosion period (S2) (14.7, 19.7%) but had a significant positive interaction with ridge width and rainfall intensity (12.1, 12.8% and 7.8, 4.6%, respectively), while rainfall intensity had a lower contribution (12.3%). The sediment yield per min during the entire period (S12) was mainly affected by the positive effect of the row grade (17.5%), followed by the positive effects of ridge width (15.1%) and RG * W (10.6%).

4. Discussion

4.1. Interrill erosion and its influencing factors

Interrill erosion involves the raindrop detachment and shallow flow transportation processes and is a major threat to the sustainability of natural ecosystems (Dlamini et al., 2011; Meyer and Harmon, 1987).

Table 4

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<th>T12</th>
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<th>Q2</th>
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<td>42.4</td>
<td>0.2</td>
<td>1.5</td>
<td>−0.9</td>
</tr>
<tr>
<td>H * W</td>
<td>1.8</td>
<td>−2.4</td>
<td>−0.6</td>
<td>4.9</td>
<td>−80.0</td>
<td>−15.9</td>
<td>−0.5</td>
<td>−2.7</td>
<td>−2.4</td>
</tr>
<tr>
<td>FS * RI</td>
<td>1.5</td>
<td>0.3</td>
<td>1.7</td>
<td>18.5</td>
<td>−118.1</td>
<td>−21.4</td>
<td>0.5</td>
<td>−0.3</td>
<td>2.0</td>
</tr>
<tr>
<td>RG * W</td>
<td>0.7</td>
<td>−1.7</td>
<td>−1.0</td>
<td>12.7</td>
<td>−58.6</td>
<td>5.5</td>
<td>0.4</td>
<td>7.8</td>
<td>3.8</td>
</tr>
</tbody>
</table>

*mean interactions, e.g., RG * FS denotes the interaction of RG and FS.

RG, row grade; FS, field slope; H, ridge height; W, ridge width; RI, rainfall intensity.

T1, T2, the durations of the interrill and rill erosion periods, respectively; Q1, Q2, the runoff per min for the interrill and rill erosion periods, respectively.

S1 and S2, the sediment yield per min for the interrill and rill erosion periods, respectively; T12, Q12 and S12, the duration, runoff per min and the sediment yield per min for the entire period, respectively.
Interrill erosion is affected by rainfall intensity, slope gradient and length, surface roughness and cover, soil properties, soil water regimes, and their interactions (Fox and Bryan, 2000; Gabriels, 1999; Quansah, 1981; Römken et al., 2002; Shi et al., 2010).

In this experiment, ridge width, rainfall intensity and their interactions positively affected runoff and sediment per min (Tables 4 and 5). This finding indicates that increasing the ridge width may lead to more runoff and sediment yield for a given rainfall intensity. When the ridge width increases, the row-sideslope length increases and the steepness decreases, meaning more and less soil erosion in unit time and area, respectively (Kinnell, 2000; Meyer and Harmon, 1987). However, the sediment and runoff indices used in this study were only in units of time (min) and were not standardized by area. Therefore, greater length of the row sideslope and erosion area caused the increased runoff and sediment yield, and the reduction effect of decreased steepness was counteracted. In addition, the ridge width interacted with the rainfall intensity and field slope and affected the sediment yield and runoff per min positively, which indicated that ridge width played a critical role in the interrill erosion period.

Ridge height significantly and positively affected the runoff per min. This affect potentially resulted from the increased row-sideslope length, steepness and erosion area with increasing ridge height. However, the sediment yield per min was not significantly affected by ridge height, which indicated that the erosion process was detachment limited (Meyer and Harmon, 1987). Because the field slope increased from 5° to 10°, it had a negative effect on runoff generation, though the effect was not significant at p < 0.01. This result may have been due to the steepness of the row sideslopes potentially exceeding the critical slope, at which point the increasing trend of runoff generation begins to decline with increasing slope (Hu and Jin, 1999; Jin, 1995). However, the value of the critical slope could not be determined because only two factor levels were designed in this experiment. As the field slope increased, the soil cohesiveness decreased (Meyer and Harmon, 1987). Therefore, the field slopes significantly and positively affected the sediment yield per min.

4.2. Rill erosion and its influencing factors

Rill erosion occurs when the shear stress of the concentrated flow exceeds the critical shear stress of the soil surface (Govers et al., 2007; Lei et al., 2008; Owoputi and Stolte, 1995). Soil erosion dramatically increases during the development of rills (Cerdan et al., 2002; X.H. Shi et al., 2012; Z.H. Shi et al., 2012). Rill erosion accounts for approximately 70% of soil erosion from upland areas in the Loess Plateau of China (Zheng and Tang, 1997). The influencing factors on rill erosion include field slope and length (Polyakov and Nearing, 2003; Zhang et al., 2008). In this study, the difference of the factors on runoff and sediment yield per min was obvious, although the ridge width and rainfall intensity both had significant positive impacts on runoff and sediment yield per min. The ridge height significantly and negatively affected runoff per min but did not significantly affect sediment yield per min. This negative influence on runoff can be enhanced by increasing the ridge height (USDA-ARS, 2008), which would increase the infiltration.

Rainfall intensity significantly and positively interacted with ridge height and width, which indicated that a large ridge sideslope and high rainfall intensity would lead to more runoff. In contrast, the negative interaction of field slope and rainfall intensity indicates a smaller runoff increase rate under high rainfall intensities on steeper slopes relative to gentle slopes. However, the cause of this result remains unclear and requires further investigation. Row grade significantly and positively affected sediment yield per min because greater row grades resulted in deeper headcutting by narrow turbulence, which increased sediment yield (Shi et al., 2013; Wirtz et al., 2012). In addition, headcutting may occur more frequently along the longer rills that occur in the wider ridges during high rainfall intensities. Therefore, row grades positively interacted with ridge width and rainfall intensity, thus affecting sediment yield per min.

4.3. Overall runoff and sediment yield and their influencing factors

The runoff and sediment yields per min over the entire period were affected by different factors. The runoff per min was mainly influenced by ridge geometry, including ridge width and height with contributions of 50.1 and 14.5%, respectively (Table 5). The effects of rainfall intensity on runoff per min were determined from their interactions with ridge height. Only the ridge height negatively affected runoff, perhaps because a greater ridge height may result in greater water infiltration across a longer period of interrill erosion relative to rill erosion.

Microtopographic relief factors played an important role in the sediment yield per min. Row grade and its interaction with ridge width and rainfall intensity significantly and positively contributed 17.5, 10.6 and 6.1%, respectively. In addition, ridge width and rainfall

Table 5
Effects of the factors on the duration, runoff and sediment yield per min based on ANOVA analysis.

<table>
<thead>
<tr>
<th>Items</th>
<th>T1</th>
<th>T2</th>
<th>T12</th>
<th>Q1</th>
<th>Q2</th>
<th>Q12</th>
<th>S1</th>
<th>S2</th>
<th>S12</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG</td>
<td>0.003</td>
<td>3.3</td>
<td>0.000</td>
<td>13.4</td>
<td>0.256</td>
<td>0.0</td>
<td>0.138</td>
<td>0.4</td>
<td>0.095</td>
</tr>
<tr>
<td>FS</td>
<td>0.000</td>
<td>3.1</td>
<td>0.041</td>
<td>0.9</td>
<td>0.000</td>
<td>33.4</td>
<td>0.122</td>
<td>0.5</td>
<td>0.000</td>
</tr>
<tr>
<td>H</td>
<td>0.000</td>
<td>46.8</td>
<td>0.000</td>
<td>5.8</td>
<td>0.000</td>
<td>32.8</td>
<td>0.000</td>
<td>16.6</td>
<td>0.000</td>
</tr>
<tr>
<td>W</td>
<td>0.000</td>
<td>1.6</td>
<td>0.071</td>
<td>0.7</td>
<td>0.000</td>
<td>2.6</td>
<td>0.000</td>
<td>33.1</td>
<td>0.000</td>
</tr>
<tr>
<td>RI</td>
<td>0.000</td>
<td>9.5</td>
<td>0.000</td>
<td>21.3</td>
<td>0.000</td>
<td>23.3</td>
<td>0.000</td>
<td>28.7</td>
<td>0.000</td>
</tr>
<tr>
<td>RG-FS</td>
<td>0.000</td>
<td>0.8</td>
<td>0.000</td>
<td>11.4</td>
<td>0.142</td>
<td>0.1</td>
<td>–</td>
<td>–</td>
<td>0.177</td>
</tr>
<tr>
<td>RG-H</td>
<td>0.001</td>
<td>6.0</td>
<td>0.000</td>
<td>2.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.006</td>
</tr>
<tr>
<td>FS-H</td>
<td>0.000</td>
<td>0.8</td>
<td>0.000</td>
<td>4.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.002</td>
</tr>
<tr>
<td>RI-W</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.001</td>
</tr>
<tr>
<td>RG-W</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.001</td>
</tr>
<tr>
<td>FS-W</td>
<td>0.000</td>
<td>0.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.002</td>
</tr>
<tr>
<td>H-RI</td>
<td>0.000</td>
<td>1.9</td>
<td>0.000</td>
<td>10.6</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.159</td>
</tr>
<tr>
<td>H-W</td>
<td>0.001</td>
<td>1.6</td>
<td>0.000</td>
<td>6.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.000</td>
</tr>
<tr>
<td>FS-RI</td>
<td>0.006</td>
<td>0.4</td>
<td>–</td>
<td>–</td>
<td>0.024</td>
<td>0.4</td>
<td>0.011</td>
<td>2.2</td>
<td>0.000</td>
</tr>
<tr>
<td>RG-RI</td>
<td>0.151</td>
<td>0.0</td>
<td>0.002</td>
<td>2.9</td>
<td>0.192</td>
<td>0.1</td>
<td>0.070</td>
<td>0.9</td>
<td>0.033</td>
</tr>
<tr>
<td>Error</td>
<td>0.7</td>
<td>4.5</td>
<td>1.8</td>
<td>6.1</td>
<td>6.8</td>
<td>7.3</td>
<td>23.9</td>
<td>24.9</td>
<td>10.7</td>
</tr>
</tbody>
</table>
intensity interactions had a significant and positive effect. By comparing the sediment yield in the interrill and rill erosion periods, it can be observed that the latter period contributed the most sediment yield. Therefore, the influencing factors for the overall sediment yield per min were in accordance with those factors that influenced the sediment yield per min in the rill erosion period.

4.4. Duration of the phases and their influencing factors

The duration of the interrill and rill erosion can be used as an index for assessing the soil conservation potential of contour ridge systems. The soil conservation capacity of a contour ridge increases as the duration increases. During the interrill period, the soil erosion mainly include the generation of runoff and sediment from the row sideslopes and runoff accumulation in the furrow, and therefore, little sediment is transported out of the ridge systems. The rill erosion duration, determined by the soil strength and erosive power of the concentrated flow, was obviously shorter than that of the interrill erosion. In the interrill erosion process, when the rill cuts through the row sideslopes, contouring failure will occur within a few minutes.

The extension of the interrill erosion period was mainly obtained by raising the ridge height because ridge height had a significant positive effect, with a contribution of 46.8% (Tables 4 and 5). The increase of field slope and rainfall intensity will shorten the duration because less rainfall water can be stored (USDA-ARS, 2008) and runoff accumulation can be accelerated in furrows (Assouline and Ben Hur, 2006). The overall duration of the interrill and rill erosion (T_{12}) was affected by the same influencing factors that affected the interrill erosion period, although the duration of the rill erosion period was influenced by other factors, such as row grade, field slope and ridge width interactions, and rainfall intensity and ridge height interactions. Therefore, reducing the field slope and using high ridges could prolong the time to contour failure.

5. Summary and conclusions

The erosion process on row sideslopes was divided into periods of interrill and rill erosion. The sediment yield mainly resulted from rill erosion. During the interrill erosion period, the ridge width, which changed the erosion area, and the rainfall intensity, which changed the net rainfall, positively affected runoff and sediment yield per min. Ridge height significantly and positively affected runoff but not sediment yield because the erosion was detachment limited. Field slope positively affected sediment yield due to reduced soil cohesive ness, and negatively affected duration, as less water can be stored with increasing field slope. Runoff and sediment yield (per min) during the rill and interrill erosion periods were significantly influenced by ridge width and rainfall intensity. In addition, row grade increased sediment yield in the rill erosion period due to deeper headcutting.

The entire duration of the erosion process was dominated by the interrill erosion period, which was also shown under similar influencing factors. However, the overall sediment yield was dominated by the rill erosion period. Thus, the factors influencing rill erosion also influenced the overall erosion from the experimental plots. Prolonging the duration of the two erosion periods, especially the interrill erosion period, would increase the soil conservation capacity of the contour ridge system. In addition, adopting taller ridges and reducing field slopes may be useful for decreasing the risk of contour failure.

In this experiment, the soil erosion on row sideslopes was studied at a plot scale before contour failure. Therefore, additional processes may occur under field conditions that require further investigation. For example, a taller ridge height confers greater soil conservation capacity, but if contour failure occurs, the stored rainfall in the deeper furrow may have a higher waterhead and thus greater erosive power, indicating more soil erosion. Here, the maximum rainfall duration was designed to be 50 min, and Horton flow was generated under a rainfall intensity of 39 ± 0.3 mm h^{-1}. If the rainfall intensity is lower and the duration of the rain events longer, will the interrill erosion period become longer and offer better soil conservation? This may not be always the case. Under this circumstance, soil may be saturated with water, and seepage may occur that could lead more soil erosion. Further research should also address the effects and interactions with other factors that could not be considered in this study, such as slope length, size of the field, vegetation, plant roots, and soil texture, in order to fully understand the processes of erosion in contour ridging systems.

Acknowledgments

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References


