The effect of row grade and length on soil erosion from concentrated flow in furrows of contouring ridge systems

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\begin{abstract}
Concentrated flow in furrows may lead to serious rill erosion in production systems where ridges are mulched with plastic film in contouring ridges. Studying the effect of influential factors on soil erosion in such systems could improve our understanding on erosion process and take appropriate control treatments. Considering a furrow with mulched ridges on both sides as a width-limited eroding rill, an in situ field experiment was conducted to analyze the effect of row grades and row lengths on soil erosion. Soil erosion indices, including runoff, runoff modulus, sediment concentration, soil loss, and soil loss modulus were monitored. Row grade and length exerted significant effect on all indices at \( p < 0.01 \). The relationship of sediment concentration, soil loss, soil loss modulus and row grade could be fitted by exponential functions (\( R^2 > 0.950, p < 0.01 \)) with the exponents expressed as second-order polynomial functions. Functions from the convex curves of these exponential functions, the critical row grade at which the maximum values occurred were interpreted as 10\%. With row grade increasing, erosion presented a detachment-limited process. The relationship between row length and soil erosion indices could be modeled by different exponential functions (\( R^2 > 0.830, p < 0.01 \)): two-parameter exponential function for runoff, modulus of runoff and modulus of soil loss; Box Lucas model for sediment concentration; and second-order polynomial function for soil loss. Based on the results, we suggest that avoiding the row grade of 10\% and row length < 5 m could reduce soil loss in the contouring ridges where plastic film covers ridges and irrigation is used to supply water into furrows.
\end{abstract}

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1. Introduction

Contour ridges have been used widely to control soil erosion in wet areas and to maintain soil moisture in dry and semi-dry areas (Hatfield et al., 1998; Gupta et al., 1990; Lal, 1990). Soil erosion processes and mechanisms in contour ridge systems have garnered increasing attention because the effectiveness of controlling soil erosion can be influenced by ridge height decay and contouring failure (Hatfield et al., 1998; USDA-ARS, 2008a; Liu et al., 2014a). Because of the microtopography, it is hard to make the ridge along the contour precisely (Griffith et al., 1990; Liu et al., 2014a). Therefore, rainwater can flow in furrows and erode the soil, then accumulate in local depressions in the furrows, where the eroded soil may deposit. Sediment deposition in the furrows in turn reduces relative ridge height and water storage, which diminishes the effectiveness of contour ridge systems (Hatfield et al., 1998; USDA-ARS, 2008a). When the accumulated flow exceeds the water storage capacity of the furrows, overflow occurs and induces ephemeral gully erosion. Soil loss from ridge-furrow systems is an important sediment source in the formation of ephemeral gullies if contouring failure occurs. The soil lost from upper ridge-furrow areas could comprise 40\% of the total soil loss in catchments where ephemeral gullies form (Cui et al., 2007).

Row grade is a key factor influencing soil loss in slope land (Renard et al., 1997; USDA-ARS, 2008a; Wischmeier and Smith, 1978). In the Revised Universal Soil Loss Equation, version 2 (RUSLE2) the row grade could be set as absolute row grade (i.e., a decrease in elevation over a distance along the furrows, hereinafter referred to as “row grade” in the following text) and relative row grade (the ratio of row grade to average steepness of overland flow...
path) (USDA-ARS, 2008b). Although the row should only be used in special cases where the ridges and furrows are well defined and runoff flows along the furrows, it could give more accuracy than relative row grade. In most physical-process erosion models, including the Water Erosion Prediction Project (WEPP) and the Limburg Soil Erosion Model (LISEM), the runoff accumulation paths are calculated through the D8 method (a widely used method for determining flow direction) without consideration of flow paths and contribution areas that could be changed by row grade (Flanagan and Livingston, 1995; Wilson et al., 2007; Pieri et al., 2014). Based on a fine resolution digital elevation model, Takken et al. (2001a) merged the tillage orientation to field slope to derive flow paths. Under these flow paths, Takken et al. (2001b) modeled soil losses more accurately than under the flow paths derived from D8 method. However, the manner in which row grade affects the soil loss process in ridge-furrow systems has not been studied to date.

Row length, also called furrow length, i.e., the length along the furrow and ridge, controls the contribution area of local depressions in furrows. The WEPP model uses row length, together with field slope, ridge height, and row grade, to determine when the overtopping flow from ridges occurs. If overflow occurs, the model adjusts the parameters or activates the watershed version of WEPP to model ephemeral gully erosion (Laffan et al., 1991; Flanagan and Livingston, 1995). If the rows are oriented parallel to the field slope, the effect of row length on soil erosion is similar to that of rill length, with the rows considered as eroding rills. The influence of rill length on soil erosion has been investigated in both the laboratory and field (Wirtz et al., 2012, 2013; Guzmán et al., 2015). In consideration of the random fluctuations of rill width, laboratory studies mainly were conducted on a limited-width rill bed into which a constant-flow discharge was supplied (Lei et al., 2001, 2008; Polyakov and Nearing, 2003; Chen et al., 2015). Because the soil matrix was in a saturated condition during these experiments, the runoff developed to a stable state and sediment concentration also attained a near maximum value. Under these conditions, Lei et al. (2001) and Polyakov and Nearing (2003) proved the exponential relationship between sediment concentration and rill length induced from the first-order detachment and transport coupling equation proposed initially by Foster and Meyer (1972). Through interpreting the relationships of sediment concentration, soil detachment, sediment load, and rill length, the soil erodibility and critical shear stress were determined (Lei et al., 2008).

However, in the field, these trends or relationships may differ from laboratory results because of soil heterogeneity, initial soil moisture, rill width changes, and the complex subprocess of soil erosion. Wirtz et al. (2012, 2013) measured three sections in eroding rills and found that sediment concentration mostly increased when rill length increased. Guzmán et al. (2015) suggested that when the furrow length increases, sediment contribution would decrease. These few results do not provide enough information for soil erosion modeling or management practices. How row length affects sediment concentration and soil loss in situ needs further research.

To improve crop yield, plastic film has been used together with contouring ridges in an effort to retain moisture and heat in the soil under the plastic film mulching, and to adjust the soil microenvironment to be more suitable to microbial activities (Ramakrishna et al., 2006; Zhang et al., 2012; Zhou et al., 2012). With biodegradable technology advancing and costs decreasing, plastic film has been used more widely (Kasirajan and Ngouajio, 2012). Plastic film could change the soil erosion process because ridges are mulched while furrows are uncovered in contouring ridge systems (Zhang et al., 2012). With the impermeable plastic mulching, the ridge is protected from splash erosion but rainwater can quickly flow into the adjacent furrows and form concentrated flows, leading to rill erosion in furrows (Ruidisch et al., 2013; Zhang et al., 2014). In previous studies in north China, rill erosion in furrows with mulched ridges was found to be more serious than in those where ridges were not mulched. With the adoption of mechanized tillage devices, uncovered furrows have an approximately uniform width, similar to the limited-width rills investigated by Lei et al. (2001) or Polyakov and Nearing (2003). With knowledge from these laboratory experiments, soil erosion in contouring ridge systems with plastic film mulching could be studied in depth.

The objectives of this study were: (i) to analyze the effect and interaction of row grade and length on soil erosion in furrows with plastic film covering the adjacent ridges; and (ii) to interpret the relationships between sediment concentration, soil loss, and runoff.

2. Materials and methods

2.1. Experimental site and land management

The experiment was conducted in the Shuanghe watershed (35° 38′ 07″ N, 118° 06′ 52″ E), belonging to the Yimeng Mountain area in north China. This area is predominately characterized by the temperate continental Monsoon climate, with an average annual temperature of 13.4 °C and an average annual precipitation of 760 mm, of which 60–65% falls in summer. Generated from acidic granite and gneiss, the soil belongs to brown soil characterized by a bulk density of 1.2 g cm⁻³, a low pH of ~5.6, and high sand content (Table 1). Corn (Zea mays), peanuts (Arachis hypogaea), and sweet potatoes (Ipomoea batatas) are the main crops. Most croplands are located on slopes, and some distributed in valley areas. Contour ridging is the main cultivation method employed in this region. The up and down tillage method may lead to serious soil erosion, but it is still be used by a small number of farmers because contouring failure may occur under high-intensity rainfall in contour ridges and reforming the collapsed contouring ridges is a hard work.

The site used for this experiment had a field slope of 11°. The land had been cultivated with peanuts for 4 years. After the peanut harvest in late September of 2014, the land was plowed and raked in a local tradition. The ridge (55-cm wide) was formed and mulched with black plastic (0.015-mm thickness), leaving furrows (25-cm wide) uncovered. After a rainfall event of 13 mm on September 29, the site was covered with greenhouse film to

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Table 1
Soil characteristic of plough layer soil used for field experiments.

<table>
<thead>
<tr>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
<th>Gravel (%)</th>
<th>Bulk density (g cm⁻³)</th>
<th>Organic matter (g kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>29.9</td>
<td>68.7</td>
<td>20.8</td>
<td>1.2</td>
<td>5.1</td>
</tr>
</tbody>
</table>

*a The soil texture was classified based on the USDA soil classification system.*
maintain soil moisture during the experimental period. This rainfall event also made the soil to hydrate and settle naturally (Fig. 1).

2.2. Experimental design

A field investigation performed in September 2014 showed that the ridge-furrow orientation off contour line varied greatly because of the local microtopography; however, nearly 80% of the orientation was in a range of 5°–45°. A furrow with a grade of 5° was difficult to observe visually, and a grade greater than 45° was always formed by down slope tillage. We therefore chose five ridge-furrow orientations (i.e., 9°, 18°, 27°, 36°, and 45°) in this study. Considering the field slope of 11° and these five orientations, five row grades were determined as 3, 5.9, 8.7, 11.3 and 13.6%. According to local field investigation, the eroded rill length in furrows ranged from 0 to about 6 m. Hence, we chose six row lengths (i.e., 1, 2, 3, 4, 5, and 6 m), and considered the furrows as eroding rills. A full factorial design was used to arrange the five-level factor of row grade and six-level factor of row length into 30 treatments. All these treatments were repeated twice, therefore, a total of 60 runs were performed.

Different discharge rates have been used in previous studies. Franti et al. (1999) used 3.2 to 12.8 L s⁻¹ to model the high-discharge concentrated flow in field conditions. Lei et al. (2001) used 3 to 12 L min⁻¹ and Polyakov and Nearing (2003) used 6 and 9 L min⁻¹ in a laboratory setting. Here, based on pre-experimental data, a discharge rate of 8 l min⁻¹ was chosen. This rate would induce rill erosion in the lowest row grade (9°) and longest row length (6 m), but would not destroy the ridge and furrow systems with the highest row grade (45°) and shortest row length (1 m). This set of effects was desirable to prevent failure of the riddings caused by a flow path through the ridges, rather than in the furrows.

2.3. Experimental processes

The flow was supplied by a pump with a constant power. Before each run, the flow discharge was calibrated to 8 L min⁻¹. Flow from the outlet tube was energy-dissipated by a baffler and irrigated into the furrow freely and evenly (Fig. 1). At the end of each furrow, a V-shaped runoff gathering pit was inserted into the soil with the bottom about 10 cm lower than the furrow surface (Fig. 1). Runoff was collected in 50-L plastic buckets at 2-min intervals from runoff generation to the gathering pit. At the beginning of the second minute during each 2-min interval, a sample was collected in a 0.5-L bottle used for sediment content analysis. The buckets and bottles were weighed immediately in the field. Each run continued until the weights of runoff became stable. Samples in the bottles were dried in the oven at 105°C for 12 h.

2.4. Data analysis

According to the time at which the runoff containing sediment became stable in time, we chose to use data collected within the first 30 min. The significance tests of effects of row grade and row length on runoff, sediment concentration, and soil loss were performed using SPSS version 16.0. Based on the results of ANOVA analysis, the contribution of these factors and their interactions were calculated according to Eq. (1). The curve fitting and contour map were produced using the software Origin version 8.0.

\[
CT = (SS - MSE \times df)/SST
\]  

(1)

Table 2

<table>
<thead>
<tr>
<th>Items</th>
<th>Sediment concentration (gL⁻¹)</th>
<th>Runoff (L)</th>
<th>Soil loss (kg)</th>
<th>Runoff modulus (Lm⁻²s⁻¹)</th>
<th>Soil loss modulus (gmm⁻²s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sig.</td>
<td>CT (%)</td>
<td>Sig.</td>
<td>CT (%)</td>
<td>Sig.</td>
</tr>
<tr>
<td>RG</td>
<td>0.000</td>
<td>46.0</td>
<td>0.000</td>
<td>15.7</td>
<td>0.000</td>
</tr>
<tr>
<td>RL</td>
<td>0.000</td>
<td>29.1</td>
<td>0.000</td>
<td>62.5</td>
<td>0.000</td>
</tr>
<tr>
<td>RG × RL</td>
<td>0.000</td>
<td>15.0</td>
<td>0.014</td>
<td>7.0</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>9.9</td>
<td></td>
<td>0.014</td>
<td>14.7</td>
<td>0.000</td>
</tr>
<tr>
<td>Main effect</td>
<td>75.1</td>
<td>78.2</td>
<td>72.2</td>
<td>98.9</td>
<td>75.7</td>
</tr>
</tbody>
</table>

CT, the contribution of a factor change on the variance of the dependent variable. RG, row grade; FL, row length; RG × RL, interaction of row grade and length. Main effect, the effect of RG and RL, and their interaction not included.
where \( CT \) is contribution (\%), \( SS \) is sum of squares, \( MSE \) is mean squares of error, \( df \) is degrees of freedom, and \( SST \) is total sum of squares.

3. Results

3.1. Effects and interactions of row grade and row length on soil erosion

Table 2 shows the ANOVA analysis results of the effects and contributions of row grade and row length on sediment concentration, amount and modulus of soil loss, and runoff. Experimental errors contribute 0.8\% to 14.7\%, which indicates that changes in row grade and row length could explain 85.3\% to 99.2\% of the variance of these soil erosion indices. With respect to sediment concentration, soil loss, and soil loss modulus, row grade has a larger effect than row length, with contributions of 41.5–56.5\%. Row length has a greater influence on runoff and runoff modulus, with contributions of 62.5\% and 98.6\%, respectively. The main effect of row grade and row length is 72.2\% to 98.9\%, meaning that soil erosion can be explained mostly with these two factors considered independently. The interaction of row grade and row length is significant on sediment concentration, soil loss amount,
and soil loss modulus, but not on runoff and runoff modulus at 
$p < 0.01$.

### 3.2. Soil erosion at different row grades

The runoff, sediment concentration, and soil loss in furrows at different row grades are plotted in Fig. 2. The runoff shows no obvious trend as row grade increases (Fig. 2a). The average runoff of different row lengths shows that runoff is higher at 8.7% and lower at 5.9%. Most of the sediment concentrations, except for the 3-m row length, increase first then decrease as row grade increases (Fig. 2b). Because the sediment concentration could hardly reach zero, even with a decreasing trend after reaching maximum values, the exponential function, whose exponent is a second-order polynomial, is applied here to fit the changing trend of the average sediment concentration ($R^2 = 0.958, p < 0.01$). Row grade exerts a similar effect on soil loss as on sediment concentration and can also be described as an exponential curve with $R^2 = 0.988 (p < 0.01)$ (Fig. 2c). To compare runoff and soil loss in rows of different length, the modulus of each is calculated and plotted as shown in Fig. 2d (runoff) and Fig. 2e (soil loss). Row grade has a similar effect on soil loss modulus as on soil loss, whereas it has no obvious effect on runoff modulus, with low $R^2$ and high $p$ values. From these exponential functions, the row grade at which the maximum values occur can be calculated as 10.8% for sediment concentration, 10.6% for soil loss, and 10.5% for soil loss modulus.

![Figure 2a](image1.png)  
**a**  
$$y = 231.181 e^{-0.075x}$$  
$$R^2 = 0.987 \ p < 0.01$$  

![Figure 2b](image2.png)  
**b**  
$$y = 104.417 (1-e^{-0.303x})$$  
$$R^2 = 0.958 \ p < 0.01$$  

![Figure 2c](image3.png)  
**c**  
$$y = \exp(-0.041x^3+0.413x+1.575)$$  
$$R^2 = 0.831 \ p < 0.01$$  

![Figure 2d](image4.png)  
**d**  
$$y = 810.517 e^{0.572x}$$  
$$R^2 = 0.967 \ p < 0.01$$  

![Figure 2e](image5.png)  
**e**  
$$y = 16.637 e^{-0.205x}$$  
$$R^2 = 0.985 \ p < 0.01$$

*Fig. 3. Soil erosion indices in different row lengths. The equation in each figure represents the average of five row grades in six row lengths.*
3.3. Soil erosion in different row lengths

Fig. 3 shows the change in runoff, sediment concentration, and soil loss with increasing row length. Runoff shows a two-parameter exponential decreasing trend, and $R^2$ for the average runoff at different row grades reaches as high as 0.987 ($p < 0.01$) (Fig. 3a). Sediment concentration increases continuously except for that at row grade of 3%. The change in average sediment concentration can be modeled by an exponential function, the Box Lucas model (Eq. (2)), with $R^2 = 0.958$ ($p < 0.01$) (Fig. 3b).

$$c = A(1 - e^{-\beta x})$$

where $c$ is sediment concentration (g L$^{-1}$), $A$ and $\beta$ are regression coefficients, $x$ is downslope rill distance (m).

Soil loss presents a convex curve with an increase in row length, and can be modeled using the exponential function with a second-order polynomial as its exponent ($R^2 = 0.831$, $p < 0.01$) (Fig. 3c). The critical row length at which the maximum soil loss occurs is 5.0 m. As row length increases, the average modulus of runoff and soil loss presents a decreasing trend towards zero, which fits well using the exponential functions in Fig. 3d and e, respectively. Comparing the modulus curves of runoff and soil loss, they can be interpreted that, at all row lengths, row grade has more effect on runoff than on soil loss.

Fig. 4. Contour maps for soil erosion indices controlled by row grade and length. The indices are as follows: a, runoff; b, sediment concentration; c, soil loss; d, runoff modulus; e, soil loss modulus.
loss, which is indicated by the intervals of the curve groups in Figs. 3d and 4e: larger intervals mean greater effect.

3.5. Soil erosion indices controlled by both row grade and length

Fig. 4 shows the contour map of soil erosion indices under row grade and length. From Fig. 4a–e, it can be seen that runoff trends toward the highest value area when row length approaches zero at row grade of 10% (Fig. 4a and d). Sediment concentration and soil loss have similar distribution: both have a higher area around row length of 4–6 m. The most serious soil loss accrues at a slightly shorter row length (4–5 m) than sediment concentration (5–6 m) (Fig. 4b and c). As for the modulus of runoff and soil loss, they have a higher value at a shorter row length around a row grade of 10%.

4. Discussions

4.1. Interpretation of row grade effect

Row grade and ridge height are two major variables for modeling soil loss in contour ridge systems (Lafflen et al., 1991). In the RUSLE2 model, row grade is considered to the greatest extent and it has a power-function effect on the Manning’s n of the vegetation rows, the ridge height subfactor values of cover-management (C factor) and the contouring subfactor of support practice (P factor) (USDA-ARS, 2008a). Under two-gradient experiments, Liu et al. (2014a, b) found that row grade has a positive significant effect on runoff and soil loss at row side slopes, but has no significant effect on them when contouring failure occurs. In addition, they considered row grade to have a greater effect on soil loss than on runoff, and the effect on soil loss presented a convex curve (Liu et al., 2015).

This field study suggests that row grade has a greater effect on soil loss than runoff (Table 2). Sediment concentration, soil loss amount, and soil loss modulus presented a convex trend with increasing row grade. Although the study by Liu et al. (2015) and the present study were conducted under different conditions, the former conditions under seeding in the laboratory and this study under drainage conditions in the field, row grade in both studies presents a convex effect. Further, row grade reached a similar critical grade for soil loss, 10.6%, and for soil loss modulus, 10.5%, after which soil erosion tends to decrease (Figs. 2c and 3e). The critical slope about 40° was observed in the Boise River watershed by Renner (1936) and was mathematically proven by Horton (1945). The increasing trend of soil loss occurring at a slope of less than 20° (Horton, 1945) was confirmed and modified in some models (e.g., USLE and RUSLE) and studies (Liu et al., 1994). More soil loss studies have been performed with the rows oriented parallel to the contour or flow directions (Hatfield et al., 1998; Maetens et al., 2012). Fewer studies have examined variation in row grade. Our results show convex curves representing the influence of row grade on soil loss (Fig. 3c). From this, we infer that previously predicted soil loss at higher row grade may have been overestimated because lower values may occur below the monotonically increasing curve used in RUSLE2 (USDA-ARS, 2008b). In addition, a row grade of about 10%, at which the higher soil loss occurs, should be avoided in contour tillage.

Sediment concentration and soil loss show a similar trend as row grade increases, and approach their maximum values at similar row grades (Figs. 2a, 3b, and c), while runoff shows no obvious trend. This result indicates that row grade affects soil loss mainly through influencing sediment concentration. The soil loss amount and modulus did not show a steady trend with an increase in sediment concentration (Figs. 2b, 3c, and e), as reported in previous studies where higher sediment concentration resulted in less soil detachment (Nearing et al., 1989; Lei et al., 2002). Thus, the soil erosion process in this study is limited by soil detachment. It is also possible that, after row grade increases to a point greater than the critical value where maximum soil loss occurs, soil detachment would decrease.

4.2. Interpretation of row length effect

In the RUSLE2 model, row length was not considered, whereas in the WEPP model, row length was used with row grade, contour row spacing, and ridge height to calculate the time at which the contour failure occurs (Flanagan and Livingston, 1995). Because of the plastic film covering the ridge, the bare furrows could be regarded as a well-defined (uniform slope with no variation in width) rill channel, as used by Huang et al. (1996) and Lei et al. (2001, 2008): rill width was limited to 0.2 m and 0.1 m, respectively. Polyakov and Nearing (2003) used a 0.61-m wide and 8-m long flume where rills could widen in unlimited fashion and found that Eq. (2) was able to describe the relationship of sediment concentration and rill length. In contrast to the saturated hydraulic conditions used by Huang et al. (1996), Lei et al. (2001), and Polyakov and Nearing (2003), this study was performed in unsaturated and drainage conditions in a field with limited rill width of 25 cm (the width of furrow). The relationships of rill length and sediment concentration in this study can also be described by Eq. (2), which suggests that sediment concentration would reach the potential transport capacity as row length increases. These results indicate that the Box Lucas model has a wide application when describing the change in sediment concentration as rill length varies.

As row length increases, runoff shows an exponentially decreasing trend because a longer row length leads to more water infiltration. However, the runoff modulus decreases as an exponential function, indicating that the reduction in runoff modulus occurs at a faster rate at first and then slows down. This trend may be caused by the infiltrated water from the upper rows accumulating under the lower side of the row areas, which results in less infiltration per area per time.

In a field where a plowpan or a hardpan exists, general concentrated flow with moderate discharge caused by most rainfall events will denude the loose surface of soil. This mass wasting process, also called the “bulldozer-effect” (Seeger et al., 2004), results in high soil loss, after which soil loss is reduced (Franti et al., 1999). As row length increases, looser soil with higher erodibility is available for detachment and transport and, in turn, average sediment concentration from different row grades increases, as shown in Fig. 3b. However, sediment concentration at the 3% row grade was an exception. The reason may be that this row grade could not generate runoff with enough power to detach the soil matrix and carry the sediment out of the furrows as row length increases.

For the decrease in runoff and increase in sediment concentration along row length, soil loss presents a convex curve and has the maximum value at the length of 5.0 m (Fig. 3c). Under the flume rate of this study (8 L min⁻¹), the soil loss towards zero because the runoff power to detach soil matrix or carry out sediment decreases with increasing row length. From Fig. 3c and 4e, it can be concluded that the increasing soil loss up to 5.0 m is mainly controlled by the increase in erosion sources, corresponding to the increase in row length. When row length is greater than 5.0 m, the increase in erosion sources does not offset the effect of runoff reduction.

When row length increases, less runoff is generated, and soil loss increases to a maximum value and then decreases (Fig. 3a and c). On the contrary, when the row length approaches zero, the maximum soil loss modulus is obtained, as suggested by (Lei et al., 2001). However, the maximum soil loss modulus here is not equal
to the soil detachment rate because runoff duration is long enough that little soil is eroded during the last several minutes, leading to an underestimate of the soil detachment rate. Under this kind of “bulldozer-effect,” only the data measured before nonerodible layer exposed was used by Franti et al. (1999) to calculate soil detachment rates, because measurements could not represent a homogeneous hill after the nonerodible layer was exposed. Although sediment concentration increases with increasing row length in the current study, the soil loss modulus presents an exponential decrease (Fig. 3b and c), which indicates that short furrows suffered more serious soil erosion. Lower sediment concentration and greater runoff in short furrows leads to more soil detachment and transportation (Huang et al., 1996; Lei et al., 2008).

4.3. Coupling effect of row grade and length on soil erosion

Fig. 4 presents contour maps detailing changes in the soil erosion indices under different row grades and row lengths. Under concentrated flow discharge (8 L min⁻¹ in this study), runoff and runoff modulus both show a decreasing trend with an increasing row length at each row grade (Fig. 4a and 4d), which means that row grade does not influence the changing trend of runoff and its modulus when row length changes. However, the row length has an effect on the changing trend of runoff and its modulus when row grade changes. This indicates that using fixed-length plots to study the effect of row grade on runoff or its modulus would provide different results. For example, when row length is 1 m, the trend of runoff and its modulus show a single peak curve as row grade increases. A more complex trend is expected when row length is 3 m. Sediment concentration and soil loss have a similar changing trend (Fig. 4b and c): when the row grade is less than 5% or row length is less than 2 m, they show no dramatic changes. The soil loss modulus has a similar changing trend at different row grades and row lengths, respectively. Therefore, more attention needs to be paid to the experimental conditions when describing the change in patterns of runoff and runoff modulus in furrows. In addition, when studying the effect of row grade on soil loss, using different row length would not influence the result and could give a reliable result, but when studying the runoff and runoff modulus, row length would influence the results.

4.4. Practical meaning

A row grade around 10% should be avoided in ridge and furrow cultivation where ridges are mulched with plastic films and irrigation is the method of supplying water to cultivations. Using long rows (e.g., 6 m under 8 L min⁻¹ of water irrigation) could reduce the soil loss modulus and allow more water to infiltrate soils, and then increase the irrigation efficiency, but longer row. In a general rainfall event, the concentrated flow is not high enough to produce hydraulic rill erosion and the mass wasting process is the main influence on soil erosion in furrows.

5. Conclusions

Row grade and length exerted a significant effect on sediment concentration, runoff, soil loss, and modulus of runoff and soil loss, while their interaction had no significant effect on runoff and its modulus. The relationship between row grade and sediment concentration, soil loss and its modulus could be modeled by second-order polynomial exponent functions with maximum values occurring at the row grade of 10%. The Box Lucas model could be used to fit the relationships between row length and sediment concentration. Soil loss modulus decreased gradually when row length increased, while soil loss showed a convex curve trend with the maximum value occurring in 5-m row length. Therefore, in the contouring ridges where plastic film covers the ridges and irrigation is the main method of supplying water to cultivations, a row grade of 10% and row length < 5 m should be avoided.

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