Applying seepage modeling to improve sediment yield predictions in contour ridge systems: Postprint

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Abstract

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Full Text

Preamble

Applying Seepage Modeling to Improve Sediment Yield Predictions in Contour Ridge Systems

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Abstract: Contour ridge systems may lead to seepage that could result in serious soil erosion. Modeling soil erosion under seepage conditions in a contour ridge system has been overlooked in most current soil erosion models. To address the importance of seepage in soil erosion modeling, a total of 23 treatments with 3 factors—row grade, field slope, and ridge height—across 5 gradients were arranged in an orthogonal rotatable central composite design. The second-order polynomial regression model for predicting sediment yield was improved by using measured or predicted seepage discharge as an input factor, which increased the coefficient of determination (R^2) from 0.743 to 0.915 or 0.893. The improved regression models combined with measured seepage discharge had a lower P-value (0.007) compared to those combined with predicted seepage discharge (P=0.016). With measured seepage discharge incorporated, several significant ($P<0.050$) effects and interactions of influential factors on sediment yield were detected, including row grade and its interactions with field slope, ridge height, and seepage discharge, as well as the quadratic terms of field slope and its interactions with row grade and seepage discharge. In the regression model with predicted seepage discharge as an influencing factor, only the interaction between row grade and seepage discharge significantly affected sediment yield. The regression model incorporating predicted seepage discharge may be expressed simply and can be used effectively when measured seepage discharge data are not available.

Keywords: soil erosion model; contour ridge; seepage; geometry factors; rainfall simulation

1 Introduction

Land degradation caused by soil erosion is a global problem for sustainable agriculture that has attracted considerable attention (Changere et al., 1995; Ni et al., 2017; Nishigaki et al., 2017). Contour ridge systems, unlike flat surfaces or up-and-down ridge tillage on slopes, have the characteristic of water storage in the furrow between adjacent ridges, which leads to increased water infiltration and reduced soil erosion (Quinton and Catt, 2004; Shi et al., 2004; Brunner et al., 2008; Gebreegziabher et al., 2009; Grum et al., 2017). Soil erosion in contour ridge systems is more carefully considered in the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) (USDA-ARS, 2008a; Liu et al., 2014a) than in other erosion models such as the Water Erosion Prediction Project (WEPP) (Flanagan and Livingston, 1995), Limburg Soil Erosion Model (LISEM) (Hessel et al., 2003), and Chinese Soil Loss Equation (CSLE) (Shi et al., 2013). The soil conservation benefit for contour ridges in RUSLE2 is presented as a subfactor to support practices in which ridge height and row grade factors are quantified (USDA-ARS, 2008a). In the WEPP model, ridge height and row grade along with contour row spacing and contour row length are used to calculate water storage in the furrow and determine when overflow occurs (Flanagan and Livingston, 1995). In the LISEM and CSLE models, the conservation ability of the contour ridge is assigned as a constant in soil loss estimations (Hessel et al., 2003; Shi et al., 2013). Assuming no infiltration and no soil erosion, Razafison et al. (2012) established a model to simulate shallow water flow over ridges; however, this model could not be used for soil erosion estimation.

In RUSLE2, the effects of ridge geometry factors—ridge height and row grade —were carefully managed. Ridge height, which negatively affects soil erosion, determines contouring effectiveness and decays as a function of precipitation amount and interrill erosion. Relative row grade, measured as the ridge-furrow orientation to the overland flow path, was grouped into five classes (5%, 10%, 25%, 50%, and 100%) to predict soil erosion, though prediction accuracy for additional classes is not warranted in RUSLE2. Absolute row grade, defined as the decrease in elevation over distance along the furrows (rise/run), provides more credit for contouring on various slopes compared to relative row grade (USDA-ARS, 2008a). The influence of field slope on soil erosion is a subject of interest in RUSLE2 and is described as a concave curve interacting with ridge height (Liu et al., 2014a).

In a contour ridge system, when stored rainwater exceeds the storage capacity of the furrow, overflow occurs, resulting in contouring failure (Griffith et al., 1990; Cui et al., 2007; USDA-ARS, 2008a). As a rill-interrill erosion model, RUSLE2 did not consider soil erosion induced by contouring failure and subsequent ephemeral gully erosion (USDA-ARS, 2008a). To address this issue, Liu et al. (2014b) used a new type of experimental box in which row grade and field slope could be adjusted simultaneously to quantify the effect and interaction of row grade, field slope, ridge height, ridge width, and rainfall intensity factors on soil erosion induced by ridge collapse. Liu et al. (2014a) also analyzed effects on interrill and rill erosion on row sideslopes; however, only two factor gradients were designed in that study, and not even a simple estimated equation for soil erosion could be established for practical use.

In ridge and furrow systems, depressions form during construction due to microtopography (Liu et al., 2016). Concentrated rainwater with higher water levels (i.e., higher hydraulic gradients) in these depressions could increase water infiltration and saturate the soil. When rainwater penetrates ridge soil, seepage may form on the row sideslope, especially at the foot of the ridge where the effective stress of surface soil may be reduced, potentially leading to additional soil erosion (Huang and Laften, 1996; Chu-Agor et al., 2008). The aggravating effect of seepage on soil erosion has been the subject of recent interest (Nachshon, 2016; Regmi et al., 2017). Compared with the drainage regime, Nouwakpo et al. (2010) found that average erodibility under a seepage regime was 5.64 times greater than under free drainage. Soil erosion under seepage conditions was shown to be six times higher for a surface under a hydraulic gradient of 20 cm compared with a surface drained for 7 days (Huang and Laften, 1996). A similar multiple was observed by Zheng et al. (2000) under run-on and runoff feed conditions. Nouwakpo and Huang (2012) found soil erosion was 2.1 times higher under seepage conditions. In addition, seepage may promote rill formation (Huang and Laften, 1996; Valentin et al., 2005; Nouwakpo and Huang, 2012). Nouwakpo and Huang (2012) observed that channel erosion rates doubled under seepage conditions. Seepage could not only increase soil erodibility but also transport fine particles, resulting in sapping, slumping, or even piping (Wilson et al., 2007; Fox and Wilson, 2010). As the converse process to seepage, seepage weathering—defined as the weathering process facilitated by seepage—could also reduce parent material cohesion and result in piping, suffusion, and high erosivity (Sato and Kuwano, 2015; Nachshon, 2016). While the impact of seepage on slope failure has been studied (Regmi et al., 2017) and erosion under seepage conditions in contour ridging systems was investigated (Liu et al., 2015), the impact of seepage has not been considered in soil erosion models.

Before contour failure and under drainage conditions, the influences of row grade, field slope, and ridge height on soil erosion in contour ridge systems have been carefully considered in previous research (Flanagan and Livingston, 1995; USDA-ARS, 2008a). In practice, contour ridge collapse on sloped land is a common phenomenon in North China (Fig. 1 [Figure 1: see original paper]). In our previous studies (Liu et al., 2015), the influences of ridge height, row grade, and field slope on runoff and soil loss under seepage conditions were interpreted. Here, we assumed that incorporating seepage data to estimate sediment yield would improve the accuracy of soil erosion models. Therefore, based on the dataset from Liu et al. (2015, 2016), the specific objectives of this study were to (1) model seepage and sediment yield with row grade, field slope, and ridge height as influencing factors; and (2) incorporate a seepage model with a sediment yield model to improve prediction accuracy.

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2 Materials and Methods

2.1 Experimental Design

Based on previous studies and field investigations, three key factors (row grade, field slope, and ridge height) across five gradients for 23 treatments were arranged in an orthogonal rotatable central composite design (Tables 1 and 2). This experimental design has been widely used to detect the effect and interaction of key factors on dependent variables by building a second-order polynomial regression equation (Domínguez et al., 2010; Tang, 2010; Hadjmohammadi and Sharifi, 2012). Relative to full factorial design, the orthogonal rotatable central composite design allows substantial reduction in treatment number while enabling direct assessment of item effects in the regression model (St-Pierre and Weiss, 2009). Based on this method, five coded values (−1.68, −1.00, 0.00, 1.00, and 1.68) were determined for each of the three factors as shown in Table 1 (Ding, 1986). In Table 2 , treatments 1-8 were arranged orthogonally with inherent replication of these three factors; treatments 15–23 were replication treatments at the central point with factors at zero code level. However, there were no replications in treatments 9–14; therefore, these treatments were replicated twice in this study. The performance of the regression model for treatments 1-14 could assess variance explanation, while treatments 15–23 could detect experimental errors.

2.2 Experimental Plots

The plot designed by Liu et al. (2014a) was selected to obtain different row grades and field slopes by simultaneously adjusting screws (Fig. 2 [Figure 2: see original paper]). To create seepage conditions, two pipes fixed through the plot bottom were used to discharge excess water and maintain the water level approximately 1 cm lower than the lowest point of the two conjunction ridges when water was supplied into the furrow by pipes banded with gauze. The discharged excess water in the furrow was collected through flexible pipes. Seepage and runoff from the upper sideslope of the ridge were collected from the outlet.

Brown soil derived from granite with high sand content was used in this experiment. This soil type could easily result in seepage. Table 3 lists the textural information of soil collected from the plow layer. To eliminate the influence of large gravel and plant roots on experimental results, the soil was passed through a 10.0-mm sieve after air-drying. The plot was first packed with soil at a bulk density of 1.6 g/cm^3 in four 5-cm layers as plow sole layers, and then a ridge was formed at a bulk density of 1.2 g/cm^3 as the plow layer.

2.3 Experimental Procedures

The experiments were conducted in the Shandong Provincial Key Laboratory of Soil Conservation and Environmental Protection, Shandong, China. The seepage regime was created by supplying water (3 L/min) to the furrows, wherein the water level was controlled. In preliminary experiments, seepage discharge from row sideslopes showed an initial increasing trend and then remained at a nearly steady state (Liu et al., 2016). To diminish the effect of seepage discharge change on soil erosion, water was supplied for 60 min to create stable seepage conditions. The seepage discharge during the final 2 min was collected as stable seepage flow and used for analysis.

At the end of the seepage process, water supply was discontinued and rainfall simulation was performed for 30 min. Rainfall intensity was 39($±$0.4) mm/h, and the homogeneity coefficient was greater than 0.89 under a trough rainfall simulator fitted with Veejet 80100 nozzles (Liu et al., 2014b). Runoff mixed with sediment samples was collected every minute.

The collected seepage and runoff with sediment samples were weighed immediately. Runoff mixed with sediment samples were passed through forced-air ovens for 12 h at 105°C. The dried sediment yield was then weighed, and the total sediment for a rainfall event was obtained by summing the 30 individual samples.

2.4 Data Analysis

The DPS (Data Processing System) software package (Tang, 2010) was used to build second-order polynomial regression models and estimate the significance of regression coefficients. Three types of regression models to predict sediment yield were constructed as follows: - A regression model with row grade, field slope, and ridge height as factors - An improved regression model with measured seepage discharge and the three factors of row grade, field slope, and ridge height - An improved regression model with predicted seepage discharge and the three factors of row grade, field slope, and ridge height

2.5 Model Performance Evaluation

The coefficient of determination (R^2) and root-mean-square error (RMSE), which represent goodness-of-fit and absolute error measurement, respectively (Legates and McCabe, 1999; Shi et al., 2009), were used to evaluate model performance. Higher R^2 and lower RMSE values indicate higher prediction accuracy. The equations for R^2 and RMSE are as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(S_{\text{measured}} - S_{\text{predicted}})^2}{\sum_{i=1}^{n}(S_{\text{measured}} - S_{\text{mean}})^2}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_{\text{measured}} - S_{\text{predicted}})^2}{n}}$$

where n is the total number of data points and i is the ith data point; S is sediment yield (kg); and S d, S d c d, and S are measured sediment yield (kg), predicted sediment yield (kg), and mean sediment yield (kg), respectively.

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3 Results

3.1 Seepage Model and Its Influencing Factors

Using measured seepage discharge (Y d, L/min) as the dependent variable and factors (row grade (x_1 (°)), field slope (x_2 (°)), and ridge height (x_3 (cm))) as independent variables (Table 2), a second-order polynomial regression model was established (Eq. 3). Table 4 lists regression coefficient significance test results. Figure 3 [Figure 3: see original paper] illustrates curves and plots of measured and predicted seepage discharge for the 23 treatments.

$$Y_{SD} = 0.58 - 0.12x_1 + 0.04x_2 + 0.03x_3 + 0.05x_1^2 + 0.01x_2^2 + 0.02x_3^2 - 0.02x_{1x}2 - 0.02x_{1x}3 + 0.01x_{2x}3 \quad (R^2 = 0.759, P =$$

Equation 3 explained 75.9% of variation in seepage discharge at P<0.010. Experimental random error accounted for 24.1% of variation with a low RMSE value of 0.12. Therefore, Equation 3 could be used to predict seepage discharge. Table 4 showed that the quadratic term of row grade had a significant positive effect on seepage discharge at P<0.010. Row grade had a negative effect, whereas the quadratic term of ridge height had a positive effect. Interactions between row grade, field slope, and ridge height had no significant influence.

Figure 3 illustrated the curve of predicted seepage discharge, which fit observed data well (Fig. 3a), and predicted points scattered around the observed line (Fig. 3b), although the extent of certain values could not be captured precisely.

Due to mutual independence of items in Equation 3, insignificant items (P>0.100) could be ignored as recommended by Tang (2010). Therefore, simplified Equation 4 was produced, indicating that row grade and ridge height might be used to estimate seepage discharge (Y d) under sufficient water supply conditions, and the field slope factor might be omitted.

$$Y_{SD} = 0.58 - 0.12x_1 + 0.05x_1^2 + 0.02x_3^2 \quad (R^2 = 0.693, P < 0.001)$$

3.2 Sediment Yield Model and Its Influencing Factors

Using a method similar to the seepage discharge model, the regression model for sediment yield (Y y, kg) was obtained (Eq. 5) and tested (Table 4). Equation 5 had a high efficiency coefficient (R^2=0.743) and low RMSE (0.67), indicating that sediment yield under seepage conditions could be estimated by this equation. Table 4 illustrates the negative effect of quadratic terms of field slope and ridge height on sediment yield (P<0.010) as well as the significant negative effect of the quadratic term of row grade (P<0.050). Row grade, field slope, and ridge height had positive effects on sediment yield, whereas their quadratic terms had negative effects, indicating that monofactor effects of these three factors had converse effects. Factor interactions had no significant effect on sediment yield even at P<0.100. Based on P-values of items, Equation 5 could be simplified to Equation 6, which includes factors and their quadratic terms while eliminating interactions. Equation 6 indicates that monofactor effects could be considered independently by fixing the other two factors because no interaction terms are included.

$$Y_{SY} = 1.23 + 0.42x_1 + 0.31x_2 + 0.28x_3 - 0.21x_1^2 - 0.35x_2^2 - 0.29x_3^2 + 0.08x_{1x}2 + 0.07x_{1x}3 + 0.06x_{2x}3 \quad (R^2 = 0.743, P =$$

$$Y_{SY} = 1.23+0.42x_1+0.31x_2+0.28x_3-0.21x_1^2-0.35x_2^2-0.29x_3^2 \quad (R^2 = 0.701, P < 0.001)$$

3.3 Improved Sediment Yield Model and Its Influencing Factors

Equation 7 is the improved regression model for measured sediment yield (Y y_ ; kg) that includes measured seepage (x (L/min)) as an independent variable together with row grade, field slope, and ridge height. Significance test results for this model are listed in Table 5 . The coefficient of determination for this model was as high as 0.915 with a low P=0.007, indicating credible estimation.

The quadratic term of field slope and interactions between field slope and seepage discharge had significant negative effects on sediment yield. Except for ridge height and seepage discharge, all interactions had significant effects at P<0.050. When items with P>0.100 were eliminated, a simpler form was obtained (Eq. 8). Interaction terms were all retained in Equation 8, indicating that when measured seepage discharge was incorporated, all factors were considered in the sediment yield model.

$$Y_{SY\_m} = 1.18+0.41x_1+0.30x_2+0.27x_3-0.20x_1^2-0.34x_2^2-0.28x_3^2+0.07x_{1x}2+0.06x_{1x}3+0.05x_{2x}3+0.35x_m-0.18$$

$$Y_{SY\_m} = 1.18+0.41x_1+0.30x_2+0.27x_3-0.20x_1^2-0.34x_2^2-0.28x_3^2+0.35x_m-0.18x_m^2+0.12x_{1x}m+0.10x_{2x}m+0.09$$

Using predicted seepage discharge (Y d) from Equation 3 as an input factor, the sediment yield (Y y_) regression model was built (Eq. 9) with an effective coefficient of 0.893 (P=0.016), suggesting high estimation accuracy. Table 5 lists significance test results for regression items. The interaction of row grade and predicted seepage discharge had a positive significant effect (P=0.008), followed by the quadratic term of seepage discharge at P=0.08. Except for these two items, remaining factors had no significant effect even at P=0.100. Therefore, the equation could be written as Equation 10, where only predicted seepage discharge and row grade are included. Table 5 and Equations 7 and 9 showed that sediment yield could be more accurately estimated with measured seepage discharge combined than with predicted seepage discharge incorporated, with lower RMSE (0.38 vs. 0.43) and higher R^2 (0.915 vs. 0.893).

$$Y_{SY\_p} = 1.20+0.40x_1+0.29x_2+0.26x_3-0.19x_1^2-0.33x_2^2-0.27x_3^2+0.06x_{1x}2+0.05x_{1x}3+0.04x_{2x}3+0.33x_p-0.16x_p^2$$

$$Y_{SY\_p} = 1.20+0.40x_1+0.33x_p-0.19x_1^2-0.16x_p^2+0.11x_{1x}p \quad (R^2 = 0.821, P < 0.001)$$

where Y y_ is sediment yield (kg) with predicted seepage (x (L/min)).

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4 Discussion

4.1 Performance of the Improved Model

In previous research or models (RUSLE and LISEM), row grade and ridge height were considered subfactors of the contouring coefficient in contour ridge systems (Hessel et al., 2003; USDA-ARS, 2008a) or were used to calculate water storage (e.g., WEPP) (Flanagan and Livingston, 1995). Due to insufficient data, no direct models had been established between these factors and soil loss. Based on the orthogonal rotatable central composite design, five gradients of row grade, ridge height, and field slope were determined, and regression models for seepage discharge and sediment yield were obtained. Combined with measured seepage discharge, sediment yield estimation accuracy was clearly improved. The coefficient of determination (R^2) increased from 0.743 to 0.915, and RMSE decreased from 0.67 to 0.38 for the measured seepage discharge combined regression model. In the predicted seepage discharge combined model, R^2 increased to 0.893 and RMSE decreased to 0.43. These results indicate that if seepage discharge is available, Equation 7 or its simplified form Equation 8 might be used for better sediment yield estimation; otherwise, seepage discharge could be predicted by Equations 3 or 4 and then used as an input factor for Equations 9 or 10 to increase modeling accuracy. Requiring fewer factors, the simplified forms (i.e., Eqs. 4, 8, and 10) can be calculated quickly and used more widely when insufficient data are available.

To assess improved performance of the combined seepage model, predicted sediment yield and observed values based on the same dataset were plotted in Figure 4 [Figure 4: see original paper]. Compared with the regression model that only included row grade, field slope, and ridge height (Fig. 4a), the improved model could better predict extreme values (e.g., treatments 9 and 10), while points from the unimproved model were more scattered (Fig. 4b). The improved model with measured seepage discharge accurately estimated sediment yield in latter treatments (treatments 17–23), i.e., the zero point of the rotatable central composite experiment design where predicted values by the seepage-incorporated model presented a straight line. Predicted error was caused primarily by repetition of zero-point treatments where seepage discharge and sediment yield should not fluctuate dramatically. However, the improved model with estimated seepage discharge produced better predictions than the model with measured seepage discharge, indicated by more compact points around the predicted line in Figure 4c. This result illustrates that the improved model with predicted seepage was more effective for treatments around the zero point (treatments 1–16) and that variance was mainly caused by factor gradients. The difference between measured and predicted sediment yield in the seepage-combined model for these treatments might partly result from experimental error (e.g., soil homogeneity or filling). Therefore, it can be deduced that the improved model with predicted seepage discharge can produce accurate sediment yield estimations. In addition, combining simplified Equation 4 for seepage discharge prediction and Equation 10 for sediment yield prediction has the advantage of requiring only two factors (row grade and ridge height), rendering this approach relatively easy to use. Simple experimental models generally provide great assistance for soil conservation and management (Yan et al., 2013).

4.2 Effects of Influential Factors on Sediment Yield

Influencing factors for soil erosion on sloping land have attracted significant attention (Lal, 1990; Knapen et al., 2007; Yan et al., 2008; Shi et al., 2013). In contour ridge systems, ridge height and row grade together with field slope were considered the main factors influencing soil erosion (Wiyo et al., 1999; USDA-ARS, 2008b; Gebreegziabher et al., 2009). Interactions between these factors were recently quantified under drainage conditions (Liu et al., 2014a, b). Under seepage conditions, the effects of these factors were deeply investigated in this study. It is noteworthy that when seepage discharge was combined with the regression model, the effects of these factors changed significantly (Tables 4 and 5). Table 4 illustrates that sediment yield was mainly affected by these three factors and their quadratic terms, while interactions between them had no significant effect. When measured seepage discharge was included, most interactions increased to significant levels at $P<0.050$. However, in the predicted seepage discharge combined regression model, significant items were reduced to only the quadratic term of seepage discharge and the interaction between row grade and seepage discharge (Table 5). This result indicates that under seepage conditions, when considering the inherent relationship between seepage discharge and factors of row grade, ridge height, and field slope (i.e., incorporating the quadratic polynomial regression model of seepage discharge), the sediment yield prediction model could be simplified (Eq. 10). When combining measured seepage discharge, which was the direct result of row grade, ridge height, and field slope and random factors (e.g., measurement error and ridge formation error), more interactions between these factors might be detected and more variance of sediment yield may be explained, with RMSE decreasing and prediction accuracy increasing accordingly (Table 5).

In the measured seepage incorporated regression model, significant influencing items ($P<0.050$) focused primarily on two categories: row grade and its interactions with field slope, ridge height, and seepage discharge; and the quadratic term of field slope and its interactions with ridge height and seepage discharge (Table 5). This indicates that under seepage conditions, factors of row grade, field slope, and ridge height had primary effects on soil erosion as under drainage conditions in the RUSLE model (USDA-ARS, 2008b). However, these results differ from Liu et al. (2014a), who suggested row grade exhibited no significant effect on sediment yield due to contour failure. Figure 5 [Figure 5: see original paper] shows interactions between paired factors with significant effects ($P<0.050$) on sediment yield when other factors were at the central rotated point with zero code level. The interaction between row grade and field slope could be interpreted as having a negative effect on sediment yield, with maximum sediment yield occurring at the highest row grade (10°) and lowest field slope (5°) (Fig. 5a). However, the interaction between row grade and field slope exerted no significant effect on interrill and rill erosion under drainage conditions (Liu et al., 2014a, b). This indicates that seepage could make the soil erosion process belong to the pattern after the critical erosion slope, at which peak erosion occurs (Jin, 1995; HU and Jin, 1999; USDA-ARS, 2008b). The decrease in soil erosion as field slope increased may be attributed to decreased detachment power—i.e., the gravity component perpendicular to the slope—when saturated soil reached its lowest potential resistance under almost the same seepage discharge conditions (Liu et al., 2016). Under the highest grade, a ridge height of approximately 12 cm would result in lower sediment yield, meaning better soil conservation (Fig. 5b), which coincided with monofactor analysis results of Liu et al. (2015). Higher seepage discharge would lead to more sediment yield in rows with higher grades (Fig. 5c), possibly because higher seepage discharge leads to higher soil erodibility and lower critical shear stress (Nouwakpo et al., 2010), and high grade may reduce soil slope stability along eroded rills combined with seepage effects. Field slope and ridge height had a positive interaction on sediment yield, suggesting increased sediment yield might occur under higher field slopes and ridge heights (Fig. 5d), also suggested by Liu et al. (2014a) under drainage conditions. This might be explained by field slope and ridge height enhancing soil accumulation slopes, leading to more soil matrix collapse observed during the erosion process. Higher field slope means lower runoff detachment power, and increased seepage could lead to lower erosion resistance (Nouwakpo et al., 2010). These two opposite influences might result in the negative interaction between field slope and seepage discharge (Fig. 5e). With a high absolute value of the standard regression coefficient (22.6 in Table 5), the interaction between ridge height and seepage discharge was important, although the *P*-value was only 0.053. The brightly colored areas in Figure 5f indicated a complicated interaction between ridge height and seepage discharge on sediment yield. However, the reason could not be clarified based on present information. Further study may be needed to reveal the interaction of seepage discharge and ridge height. Based on Figure 5, when one factor is fixed, the other factor may be manipulated to produce minimum sediment yield, and subsequent agricultural treatments may be adopted to prevent soil loss.

4.3 Limitations and Future Research

The aggravating effect of seepage on soil erosion has been demonstrated by laboratory and field experiments and observations (Huang, 1998; Fox and Wilson, 2010; Nouwakpo and Huang, 2012). During the water supply period, seepage showed an increasing trend and then remained at an almost steady state when soil was nearly water-saturated. Different seepage discharge amounts could lead to different soil loss amounts (Fox et al., 2007; Nouwakpo et al., 2010). To diminish the effect of seepage discharge change on sediment yield, seepage discharge used as the primary seepage condition in this study was measured during the last 2 min of the water supply period. During the rainfall simulation period, seepage discharge may decrease due to void clogging by detached soil particles (Fox and Wilson, 2010) or soil compaction imposed by rainfall and water infiltration (Fohrer et al., 1999), which may affect sediment yield. However, seepage discharge mixed with overflow was difficult to measure separately. Therefore, assessing the effect of seepage and its interactions with microtopography (e.g., ridge height) on soil loss during rainfall events remains a difficult task for further investigation. Further study may be needed to reveal the interaction of seepage discharge and ridge height.

Hydraulic gradient has an important influence on critical shear stress, rill erodibility, and sediment yield (Zheng et al., 2000; Nouwakpo et al., 2010). In a contour ridge system, different hydraulic gradients may be created by water level in furrows. Although water level was maintained approximately 1 cm lower than the lowest area of the ridge, water level could not be used as a factor in this study because it was influenced simultaneously by field slope and ridge height. In addition, water in the furrow was supplied by pipes rather than runoff generated from rainfall. Therefore, determining the effect of rainwater level on seepage discharge and soil erosion factors (e.g., critical shear stress and soil erodibility) may be useful for revealing the soil erosion process in contour ridge systems. Rainfall intensity and regimes play important roles in soil loss both individually and interactively with other factors (Huang and Laften, 1996; Fang et al., 2012; Liu et al., 2014a). High rainfall intensity might lead to Hortonian overland flow (Ziegler et al., 2007), whereas low rainfall intensity over long periods might lead to soil saturation (Liu et al., 2011), easily resulting in seepage. Experiments with different rainfall intensity gradients should also be addressed in soil erosion studies within contour ridge systems under seepage conditions.

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5 Conclusions

In contour ridge systems, seepage can affect soil erosion. In this study, using measured or predicted seepage discharge as an input factor, sediment yield estimation models were created that increased the R^2 value from 0.743 to 0.915 and 0.893. Moreover, the improved prediction model with measured seepage discharge was able to detect more significant interactions between influencing factors. When combined with predicted seepage discharge, the prediction model for sediment yield could be substantially simplified.

Although certain boundary conditions were included, such as assuming seepage discharge in a nearly steady state and performing only one rainfall intensity, results showed that considering seepage discharge as an input factor could greatly improve the accuracy of sediment yield estimations in contour ridge systems. The effects of rainfall intensities, hydraulic gradients, and seepage discharge change processes should be addressed in further studies.

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