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Influence of microtopography, ridge geometry and rainfall intensity on soil erosion induced by contouring failure

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ABSTRACT

Contour ridging is an effective soil conservation practice used throughout the world. Because of microtopographic relief on sloping land, rainwater concentrates in low areas along furrows where contouring failure can occur. To quantify the effects and interactions of factors that influence runoff and sediment yield induced by contouring failure, a total of 32 rainfall simulation experiments were conducted, with two microtopography indices (row grade, RG, and field slope, FS), two ridge geometry indices (ridge height, *H*, and ridge width, *W*), and two levels of rainfall intensity (RI) arranged in an $L_{16}(2^5)$ orthogonal array with two replications. The results showed that all of the factors considered except for row grade exerted significant influences on runoff and sediment yield ($p = 0.01$). Rainfall intensity was the most important factor for runoff, with a contribution of 68.1%, followed by ridge height, field slope, and ridge width. Field slope and rainfall interacted negatively, with a contribution of 5.4%, resulting in increased runoff with increasing field slope at lower rainfall intensities, while the opposite effect was observed at higher rainfall intensities. The negative interaction of ridge height and width and the positive interaction of field slope and ridge height also had significant effects on runoff. For sediment yield, the most important factor (21.4%) was ridge height, which had a negative effect. Rainfall intensity had less effect on sediment yield than on runoff, while the row grade and its interaction with ridge width had greater influences. The optimal combinations of factors for control of runoff were determined to be RG_1, FS_1, H_2, and W_2 for lower rainfall intensity and RG_1, FS_2, H_2, and W_2 for higher rainfall intensity, and the optimal combinations of factors for sediment yield conservation were determined to be RG_1, FS_1, H_1, and W_2, where in all cases, the subscripts 1 and 2 denote lower and higher factor levels.

1. Introduction

Ridge tillage is an agricultural practice widely used throughout the world (Lal, 1990; Müller et al., 2009). Ridge tillage, which raises the seedbed above the natural terrain, has distinctive advantages, such as increasing soil temperature, saving labor, enhancing soil depth, controlling pests and weeds, and reducing soil and water loss (Gupta et al., 1990; Hatfield et al., 1998; Lal, 1990; Shi et al., 2012a; Wang et al., 2008). Ridge tillage practices evolved from manual operations with simple tools used in ancient agriculture to the use of tractor-driven implements in modern cultivation (Lal, 1990; Materechera and Mloza-Banda, 1997) and from alternating the positions of ridges and furrows from year to year to keeping the ridge permanent for many years (Karlen et al., 2013; Lal, 1990). Some modifications were also applied in ridge tillage systems to form certain spatial characteristics, e.g., furrow diking (or some form thereof: tied ridges, basin tillage, basin listing, micro-basin tillage) (Jones and Stewart, 1990; Truman and Nuti, 2010), double furrows with raised beds (Gammoh, 2011), and broadbed furrows (Omer and Elamin, 1997). The main intention of these modifications was rainwater collection and soil conservation. Ridge tillage is widely used in arid and semiarid areas to maintain soil moisture and in humid zones to control soil erosion (Hatfield et al., 1998; Jin et al., 2010; Lal, 1990; Griffith et al., 1990).

The soil conservation function of ridge tillage has attracted great attention. Studies show that when ridges run parallel to the overland flow path, they can increase soil loss because of the steepness of ridge sideslopes, which increases interill erosion (USDA-ARS, 2008b). Consequently, ridge tillage is always conducted approximately perpendicular to the overland flow path on sloping land, and the ridges formed are referred to contour ridges.

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Contour ridges can pond water in the furrows between the ridges, which increases rainwater infiltration, which in turn decreases soil detachment, runoff and soil erosion (Hatfield et al., 1998; Lal, 1990; Ma et al., 2010; Stevens et al., 2009). This capacity for soil conservation can be diminished on steep slopes or under high-intensity rainfall, and it is recommended that ridges follow the contour of the ground (Flanagan and Livingston, 1995; USDA-ARS, 2008b; Hatfield et al., 1998).

In practice, it may be impossible to make the ridges follow the contour of the ground precisely on slopes with irregular microtopographic relief (Griffith et al., 1990). Some low areas will occur along the furrow, and rainwater collects in these low areas (Cui et al., 2007). If the rainwater volume produced by a rainfall event exceeds the storage within a contour row, it will overflow from the ridge. When the overflow is sufficient to exceed the critical shear stress for ridge stability, rills will form on the ridge sideslope, and the runoff will then flow downslope with increasing erosive power, which can lead to ridge collapse. If such breakovers occur, the contour ridge will have lost its anti-erosion capacity and may even enhance soil erosion. In northern China, contour ridge systems are widely used on sloping land (Liu et al., 2011b, 2006), and contouring failure is a common phenomenon (Fig. 1).

Among previous studies, contouring failure is considered to the greatest extent in the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) (USDA-ARS, 2008b; Hessel et al., 2003). The effect of contour ridges on soil loss is regarded as a subfactor to the support practice factor (*P*) in the RUSLE2 model, and ridge height is modeled daily to compute the effect of contouring on erosion. RUSLE2 only addresses rill–interrill erosion and cannot compute soil erosion caused by contouring failure influenced by soil properties, ridge height or grade along the ridge furrows (USDA-ARS, 2008b). In the Water Erosion Prediction Project (WEPP) model, row grade, contour row spacing, contour row length and contour ridge height are used as input factors in the computation of the amount of water storage within a contour row (Flanagan and Livingston, 1995). The influence of microtopographic relief and ridge geometry on soil erosion caused by ridge collapse is not, however, considered in the model. A better understanding of the soil erosion associated with contouring failure would improve our knowledge of erosion processes, which would improve the management of this practice in terms of soil and water conservation. Therefore, this study was undertaken to examine the issue of soil erosion induced by contouring failure. The specific objectives were the following: (i) to quantify the effects of microtopography, ridge geometry and rainfall intensity on soil erosion; (ii) to assess the effects of the interactions of these factors on runoff and sediment yield and (iii) to determine the optimal combinations of factors for soil conservation.

Fig. 1. Contouring failure on sloped land.

2. Methods and materials

2.1. Experiment design

Based on the results of field investigations and previous studies, two microtopography indices—row grade (RG) and field slope (FS), two ridge geometry indices—contour ridge height (*H*) and contour ridge width (*W*), and two levels of rainfall intensity (RI) were used in the design of our experiments (Table 1). An $L_{16}(2^5)$ orthogonal array with all first-order interactions of the factors considered was chosen to arrange these treatments. To reduce experimental error, all of the treatments were replicated.

2.2. Experiment plots

The artificially simulated rainfall experiments were conducted at the Shandong Provincial Key Laboratory of Soil Conservation and Environmental Protection. To obtain row slope and field slope simultaneously, a new type of experimental plot was designed (Fig. 2). Two cassettes, 80 cm wide and 160 cm long and made of stainless steel, were hinged together along one side boundary. The row grade could be adjusted continuously from 0° to 15° by rotating a screw (a) with one end fixed on the cassette boundary and the other on the chassis. The crevice in the conjunction of the two cassettes was sealed with adhesive tape to prevent water from leaking. The field slope along the plot was obtained by adjusting a screw (b) fixed under the two stabilizer blades.

Textural information for the sandy brown soil used in this experiment is provided in Table 2. The soil was collected from the plough layer and then passed through a 10.0-mm sieve after being air dried. The sieved soil was packed 20 cm deep (in four 5-cm layers) at a bulk density of 1.6 g m^{-3} in each plot. The ridges were formed at a bulk density of 1.2 g m^{-3}. In the treatments with the same row grade, the soil mass packed into the plot was kept the same by adjusting the furrow bottom. The outlet level was varied with the furrow bottom using adhesive tape on the inside wall of the plot.

To reduce the disturbance of the sheet flow generated from the upper area (c) on soil erosion in the lower area (d) of the furrow, two plastic plates (e) were inserted into the soil surface and fixed to the adjacent plot wall, thus directing the runoff flow out from the outlet (f). At the middle outlet (g), the runoff and sediment were collected.

2.3. Rainfall simulation experiments

A trough rainfall simulator with a Veejet 80100 nozzle (Xie et al., 2008; Zhang et al., 2007) was used to produce the desired rainfall intensities (39 ± 0.3 mm and 61 ± 0.6 mm) with a homogeneity coefficient greater than 0.89. A pre-rain treatment with an intensity of 20 mm h^{-1} and a duration of 60 min was applied 12 h before the experiment to settle the soil surface and reduce its variability. Because of ridge height decay caused by the pre-rain treatment, the initial height of the ridge was formed 2 cm higher than the design height. Based on the erosion process observed in

Table 1
Factors and their levels.

Factor level	RG (°)	FS (°)	*H* (cm)	*W* (cm)	RI (mm h^{-1})
1	5	5	10	53	40
2	10	10	15	80	60