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

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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. 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.

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

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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 (Laflen 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

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

Clay[a] (%)	Silt[a](%)	Sand[a](%)	Gravel[a](%)	Bulk density (g cm^{-3})	Organic matter (g kg^{-1})
1.4	29.9	68.7	20.8	1.2	5.1

[a] The soil texture was classified based on the USDA soil classification system.