Agricultural and Forest Meteorology 232 (2017) 1–11

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Straw mulch can induce greater soil losses from loess slopes than no mulch under extreme rainfall conditions

Abbas E. Rahma a, b, Wei Wang d, Zejun Tang a, Tingwu Lei a, c, *, David N. Warrington c, Jun Zhao c

a College of Water Resources and Civil Engineering, China Agricultural University, Beijing, 100083, PR China
b College of Agricultural Studies, Department of Agricultural Engineering, Sudan University of Science and Technology, Khartoum, Shambat, Sudan
c State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resources, Yangling, Shaanxi Province, 712100, PR China
d College of Engineering, China Agricultural University, Beijing, 100083, PR China

ARTICLE INFO

Article history:
Received 3 March 2016
Received in revised form 1 July 2016
Accepted 17 July 2016

Keywords:
Straw mulch
Mulch rate
Simulated rain
Rill
Erosion
Runoff
Loess soil

ABSTRACT

Mulching a soil has long been considered an effective way of reducing soil and water losses as compared to an un-mulched soil. However, under certain conditions of extreme rainfalls, a soil may be more susceptible to rill erosion under a straw mulch cover, where the mulch can concentrate overland flow, than without such a cover if the soil developed a resistant surface seal. This study used two typical soils of the Loess Plateau of China (a silt loam and a clay loam) to study mulch induced erosion under intense simulated rainstorms of 100, 140 and 180 mm h⁻¹ amounting to a rainfall depth of 60 mm on 5-m slopes set at different gradients. Under three mulch rates tested (0, 0.2, and 0.8 kg m⁻²), application of mulch always reduced runoff from the soils. No rills were formed in the silt loam soil without a mulch cover under any of the experimental rainfall conditions due to the formation of a seal that resisted rill formation. However, under the 0.8 kg m⁻² mulch treatment, rills were initiated under all but the least severe experimental conditions combinations and soil losses exceeded those from the soil without mulch. In one case, the soil loss under the mulch was almost three times that from the soil without mulch. In the clay loam soil, which developed a more erodible seal than the silt loam soil, rills were formed under all mulch treatments and rainfall intensity and slope conditions, with the exception of the mulch covered soil under one set of conditions. At the end of the 60-mm rainstorm and under the most intense conditions, the total soil loss from the clay loam soil under mulch (0.8 kg m⁻²) was less than 50% of that from the soil without mulch and in all cases total soil loss was reduced by mulch; however, towards the end of the storm, the soil loss rates, which had been increasing, exceeded those of the un-mulched soil. These phenomena were attributed to the relatively high resistance to rill formation of the surface seal developed on the silt loam soil as compared to the soil without a seal under the high mulch rate, which protected the soil from raindrop impact. Rill initiation was more likely to occur under the mulch due to the increased surface roughness of a soil without a seal and the presence of the mulch, and to individual straws of the mulch laying directly on the soil surface diverting and concentrating soil surface runoff. The results suggest that, with a greater amount of runoff, the same phenomenon may occur on the clay loam soil, which was more susceptible to rill formation under all mulch treatments and developed a less resistant seal. Reducing the mulch rate when severe runoff events are likely from soils similar to the silt loam should avoid such large soil losses. However, for soils more susceptible to rill formation under mulch, such as the clay loam in this study, this may not be effective. Future studies, and especially field studies, should address this issue.

© 2016 Published by Elsevier B.V.

1. Introduction

Soil erosion by water is a serious problem worldwide, resulting in the loss of a non-renewal resource together with its nutrients and organic matter that leads to soil degradation (Fu and Gulinck, 2009).
while sediments and pollutants can cause problems downstream (Rose, 1985). Consequently, measures to control soil erosion are an important part of land management. The application of mulch or other cover (litter, stones, vegetation) has long been considered as an effective measure.

Soil erosion initiates from interrill areas but the rates of soil loss increase greatly with the development of rills and the associated concentrated flow (Cerdan et al., 2002; Poesen, 1987). Detachment in interrill erosion is almost entirely caused and enhanced by raindrop impact (Beuselinck et al., 2002). It depends on the intrinsic properties of the soil (Le Bissonnais et al., 2005) but the other main factor is the rainfall intensity (Bryan, 2000). It tends to be limited by its transport capacity, is sediment particle size selective and increases with slope length until reaching a constant rate (Meyer et al., 1975). In contrast, detachment in rill erosion is caused by concentrated overland flow (Bryan, 2000) although when the flow depth is relatively shallow, it is enhanced by raindrop impact (Ferreira and Singer, 1985). As the amount of flow increases with the slope length, rill erosion continues to rise and tends to be detachment limited and becomes sediment particle size non-selective (Meyer et al., 1975). Rill erosion is initiated when the effect of flowing water exceeds some threshold of soil resistance (Horton, 1945; Knapen et al., 2007) and the value of the threshold depends on the soil conditions (Slattery and Bryan, 1992). Intrinsic soil properties such as soil texture and aggregate stability may make the soil more susceptible to rill erosion (Bryan, 2000). Hydraulic parameters affecting the shear stress of the flow include the flow velocity, depth and turbulence. Surface roughness can contribute to the turbulence of overland flow.

Under raindrop impact, surface seals are often formed on a soil surface. Surface sealing occurs as a result of aggregate breakdown followed by compaction due to raindrop impact and the partial blocking of pores in the surface layer of soil by “washed-in” smaller soil particles that reduces its hydraulic conductivity (McIntyre, 1958). Aggregate breakdown of a dry soil under intense rainfall results initially from both slaking and raindrop impact (Le Bissonnais et al., 2005; Panabokke and Quirk, 1957). Slaking results from the explosive force of air entrapped within the aggregate under pressure when wetting is rapid. After the soil surface is wet, aggregate breakdown continues to occur due to the impact of raindrops but slaking becomes minimal. Aggregate breakdown is enhanced by clay dispersion that occurs due to the absence of electrolytes in rainwater, and dispersion is increased with increasing exchangeable sodium percentage (Agassi et al., 1981). Dispersed clay particles and other small soil particles can either enter the pore system of the soil, where they may become trapped and partially block the pores, or are among the most readily eroded material to be transported by runoff. Compacted, consolidated surface seals can resist the shear forces generated by overland flow more than the soil surface without a seal. In contrast, seals in which, for example, there is a high content of dispersed clay or of micro-aggregates containing dispersible clay, are less resistant to soil erosion. This is because the micro-aggregates continue to disperse under the impact of the raindrops leading to a less stable seal that is subject to greater seal destruction forces (Poesen, 1987).

Protecting the soil surface from raindrop impacts by covering it with a layer of mulch or other form of cover is considered to be an effective way to reduce soil and water losses since this will reduce surface sealing and runoff, as well as the detachment of soil particles. The common view is that the greater the cover, the more soil losses are reduced. However, although soil under mulch is protected from surface seal formation, some detrimental effects of a rainstorm still occur. Aggregate breakdown can still initially occur due to slaking and subsequently due to hydraulic shear forces (Shi et al., 2013), and is still enhanced by clay dispersion. The resulting smaller particles are washed into the pores in the soil surface reducing soil infiltrability albeit not to the same extent as in the case of a soil without mulch cover. Infiltrability also decreases as the soil wets up and suction forces are reduced. When the infiltrability is less than the rainfall intensity, runoff is produced and this overland flow can detach and transport soil particles. A further advantage of using straw mulch is that the flow velocity of the runoff is reduced due to the increased roughness and tortuosity of the flow paths (Foster and Meyer, 1972). However, it is still possible for rills to develop under mulch when the shear force of the overland flow exceeds the critical threshold value.

We hypothesize that given these processes, under certain conditions straw mulch could adversely affect erosion. This is because straws laying directly on the soil surface could divert and concentrate overland flow along the lengths of the straws, which might induce rill development earlier than in the case of a soil without mulch cover. The absence of a surface seal under total mulch cover could also promote rill initiation since seals resist rill initiation. In contrast, the presence of seals and the absence of such an overland flow mechanism potentially results in less erosion from bare soil. In which case, soil losses could be greater under the mulch than those from the soil without mulch cover.

The objectives of this study were to: (1) identify the critical conditions of slope gradient and rainfall intensity, under which the soil losses generated from two typical soils under mulch cover could exceed those of the soils without mulch; and (2) to determine the effects of slope gradient and rainfall intensity on rill initiation under the various mulch rates.

2. Materials and methods

There exists an extreme rainfall region in the middle reach of the Yellow River at north-western corner of the plateau. The region is affected by the Mu Us Desert, with different thermal capacity from the Loess Plateau, to cause different atmospheric circulation. These unique conditions cause frequent extreme rainfall events of greater than 300 mm/d (The Editorial Committee of flood and drought disasters in Yellow River Basin and the northwest part of China, pp110) in these regions, where is featured with loamy silt loess soil, with high erodibility. Another center featured with extreme rain fall events is located in the south-eastern cover of the Loess Plateau, around Sanmenxia Reservoir and the capital city of Henan Province, Zhengzhou city. The region is located in the transient part of lower northern China plain, where the altitude is about 100 m a.s.l. and the Loess Plateau which is typically at 1000–1500 m a.s.l. Typhoons with high moisture content from south-eastern when encounter with the cool air from the plateau, can cause extreme rainfall events of 350–500 mm/d (The Editorial Committee of flood and drought disasters in Yellow River Basin and the northwest part of China, pp112). These events also can cause heavy erosion of clay loam soil in the region, where has very much the similar soil to that in Yangling. Therefore, two soils from Shaanxi Province on the Loess Plateau of China were used in this study; a silt loam soil from Ansai and a clay loam soil from Yangling. The soils were collected from the upper 20 cm layer of cultivated fields, air-dried and passed through a 2-mm mesh. Table 1 presents the basic properties of the soils. For the mulch treatment, wheat straw was collected from harvested fields, air-dried, and the longer straws were cut to 30-cm lengths.

A rainfall simulator in the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau was used for the experiments. The equipment was capable of generating simulated rainfall with deionized water over large areas. Simulated rainfall was projected sideways from eight nozzles situated 16 m above the ground, and then fall vertically towards the ground. Rainfall intensity was determined by valves linked to pressure gauges, controlled automatically by a computer monitoring an electronic rain gauge.
Three adjacent flumes, 5 m long by 0.3 m wide and 0.25 m deep, separated by plastic dividers were used to contain the soils under investigation. The flumes were on a mobile hydraulic jack that could be positioned under the rainfall simulator and raised to attain a designed slope gradient. Drainage holes were made at the bottom of the flume to facilitate the escape of soil-air. A funnel was attached to the end of each flume to direct sediment-laden runoff water into collection buckets.

With the flumes in a horizontal position, the air-dried soil was uniformly packed into the flumes to a depth of 0.2 m, section by section and layer by layer, to achieve bulk densities of about 1200 kg m\(^{-3}\) for the silt loam and clay loam soils, respectively, by pouring a known mass of soil into a known volume of the flume and gently tamping down the soil with a flat wooden paddle. To ensure continuity between soil layers, the surface of a soil layer was first scored before filling in the overlying layer. Following packing, the soil surface was uniformly covered by an assigned mulch, at the rates of 0, 0.2 or 0.8 kg m\(^{-2}\), equivalent to 0, 2, and 8 t ha\(^{-1}\). Immediately prior to the simulated rainstorm, the flume was moved into position underneath the rain simulator and raised to the designed slope angle.

Three slope gradients and three intensities of rainfall simulated with deionized water were investigated in a non-factorial design. The design was intended to potentially identify threshold values of factors that would induce rill formation to occur. The slope gradients were gentle (5°, 8.7%), moderate (10°, 18.3%) and steep (15°, 26.8%). The rainfall intensities were 100, 140 and 180 mm h\(^{-1}\). For the 180 mm h\(^{-1}\) storm, all the slopes were investigated. For the 100 mm h\(^{-1}\), only the moderate and steep slopes were used, while for the 140 mm h\(^{-1}\) only the steep slope was used.

Each rainstorm had a rainfall depth of 60 mm. This ensured that the lower soil layers remained dry, that there were no artifacts due to water movement transitions to a drainage medium, and that no pot effect occurred. Furthermore, comparisons between storms were made on a total rainstorm energy level basis, which differentiated between the means of the total runoff

\[ \text{Total runoff (mm)} = \text{Total infiltration} + \text{Total soil loss} \]

One-way Analysis of Variance was used to test the significance of mulch rate, water quality, soil type, slope and rainfall intensity on total runoff, total infiltration and total soil loss. A Tukey HSD post-hoc test or t-tests were used to separate means at a level of 5%.

### 3. Results and discussion

#### 3.1. Total runoff

Table 2 presents the results of the ANOVA of the runoff data for the 60 mm simulated rainfall events. Mulch rate significantly affected the amount of runoff generated from the soils, as did the rainfall intensity, slope gradient and soil type. Interactions between mulch rate and soil type or slope gradient were significant, but the interaction of mulch rate with rainfall intensity was just outside the cutoff significance level used in this study (p < 0.05). Furthermore, the interaction of mulch with both soil type and slope also significantly affected runoff amount, as did the interaction between soil type, rainfall intensity and slope.

Table 3 presents the results of the post-hoc Tukey HSD test, which differentiated between the means of the total runoff.

### Table 1

Some basic properties of the studied soils.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Cation exchange capacity (m mol kg(^{-1}))</th>
<th>Sodium exchangeable percentage (%)</th>
<th>Organic matter content (%)</th>
<th>Particle size distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt loam</td>
<td>62.2</td>
<td>3.9</td>
<td>0.5</td>
<td>17.5</td>
</tr>
<tr>
<td>Clay loam</td>
<td>110.6</td>
<td>4.2</td>
<td>0.8</td>
<td>24.8</td>
</tr>
</tbody>
</table>

### Table 2

Analysis of variance results for total runoff.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS(^{a})</th>
<th>DF</th>
<th>F-value</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch</td>
<td>3080.336</td>
<td>2</td>
<td>188.509</td>
<td>0.000</td>
</tr>
<tr>
<td>Soil</td>
<td>680.013</td>
<td>1</td>
<td>832.532</td>
<td>0.000</td>
</tr>
<tr>
<td>Rainfall intensity</td>
<td>294.008</td>
<td>2</td>
<td>17.993</td>
<td>0.000</td>
</tr>
<tr>
<td>Slope</td>
<td>967.318</td>
<td>2</td>
<td>59.197</td>
<td>0.000</td>
</tr>
<tr>
<td>Mulch × Soil</td>
<td>322.733</td>
<td>2</td>
<td>19.750</td>
<td>0.000</td>
</tr>
<tr>
<td>Mulch × Rainfall intensity</td>
<td>80.840</td>
<td>4</td>
<td>2.474</td>
<td>0.052</td>
</tr>
<tr>
<td>Mulch × Slope</td>
<td>38.597</td>
<td>4</td>
<td>1.181</td>
<td>0.327</td>
</tr>
<tr>
<td>Soil × Rainfall intensity</td>
<td>50.117</td>
<td>2</td>
<td>3.067</td>
<td>0.053</td>
</tr>
<tr>
<td>Soil × Slope</td>
<td>34.966</td>
<td>2</td>
<td>2.140</td>
<td>0.125</td>
</tr>
<tr>
<td>Rainfall intensity × Slope</td>
<td>1.621</td>
<td>1</td>
<td>0.198</td>
<td>0.657</td>
</tr>
<tr>
<td>Mulch × Soil × Rainfall intensity</td>
<td>35.333</td>
<td>4</td>
<td>1.081</td>
<td>0.372</td>
</tr>
<tr>
<td>Mulch × Soil × Slope</td>
<td>161.161</td>
<td>4</td>
<td>4.931</td>
<td>0.001</td>
</tr>
<tr>
<td>Mulch × Rainfall intensity × Slope</td>
<td>34.634</td>
<td>2</td>
<td>2.119</td>
<td>0.128</td>
</tr>
<tr>
<td>Soil × Rainfall intensity × Slope</td>
<td>99.750</td>
<td>1</td>
<td>12.209</td>
<td>0.001</td>
</tr>
<tr>
<td>Mulch × Soil × Rainfall intensity × Slope</td>
<td>28.504</td>
<td>2</td>
<td>1.744</td>
<td>0.182</td>
</tr>
</tbody>
</table>

\(SS^a\) = Sum of squares, DF = degrees of freedom and Sig = significance.

### Table 3

Total runoff (mm) from the two soils under different mulch rates and rainfall intensities.

<table>
<thead>
<tr>
<th>Rainfall intensity (mm h(^{-1}))</th>
<th>Slope</th>
<th>Silt loam</th>
<th>Clay loam</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Moderate (10°)</td>
<td>28.0a</td>
<td>19.7b</td>
</tr>
<tr>
<td>Steep (15°)</td>
<td>29.8a</td>
<td>22.3b</td>
<td>17.6b</td>
</tr>
<tr>
<td>140</td>
<td>Steep (15°)</td>
<td>33.4a</td>
<td>25.0b</td>
</tr>
<tr>
<td>Gentle (5°)</td>
<td>17.6a</td>
<td>15.8a</td>
<td>13.5a</td>
</tr>
<tr>
<td>180</td>
<td>Moderate (10°)</td>
<td>26.1a</td>
<td>16.0b</td>
</tr>
<tr>
<td>Steep (15°)</td>
<td>38.6a</td>
<td>25.0b</td>
<td>24.1b</td>
</tr>
</tbody>
</table>

Different lowercase letters following the mean values denote significant differences between mulch treatments for a given soil (p < 0.05) (Tukey HSD post-hoc test)
amounts, while Fig. 1 displays this data in a form where trends are more readily seen.

In general, for both soils, applying mulch significantly reduced runoff as compared to the no mulch treatment (p < 0.05) but the levels where significant differences depended on the mulch rate, soil type and the slope and rainfall intensity conditions (Table 2). The only conditions under which the addition of mulch did not significantly reduce the runoff amount occurred under the rainfall intensity of 180 mm h\(^{-1}\) on the gentle slope for the silt loam soil. It is worth noting that under no given set of rainfall intensity and slope conditions, did an application of mulch increase the runoff amount as compared to the no mulch treatments.

In the case of the silt loam soil, under the 100 and 140 mm h\(^{-1}\) rainfall, as well as under the 180 mm h\(^{-1}\) rainfall on the steep slope, runoff was significantly reduced by applying mulch at the rate of 0.2 kg m\(^{-2}\) (Table 2). However, further increasing the mulch rate to 0.8 kg m\(^{-2}\) did not result in further significant reductions in runoff (p < 0.05). Under the rainfall intensity of 180 mm h\(^{-1}\), adding mulch at the rate of 0.2 kg m\(^{-2}\) or 0.8 kg m\(^{-2}\) significantly reduced runoff.

In contrast, for the clay loam soil, a mulch rate of more than 0.2 kg m\(^{-2}\) was generally required to achieve a significant reduction in runoff amount. However, 0.2 kg m\(^{-2}\) did significantly reduce the runoff amount under the 180 mm h\(^{-1}\) rainfall on the gentle and steep, but not the moderate, slopes.

Higher slope gradient tended to generate more runoff under all treatments and rainfall intensities for both soils (Fig. 1a and b). However, there were only significant differences in runoff amount under the 180 mm h\(^{-1}\) storm (Table 2). These significant differences occurred under all mulch rates for the silt loam soil but only under the 0.2 kg m\(^{-2}\) mulch rate for the clay loam soil. Higher rainfall intensity generally increased the runoff amount under most of the treatments (Fig. 1c and d). However, under the 140 mm h\(^{-1}\) rainfall intensity, runoff was notably less under the 0.2 kg m\(^{-2}\) treatment for the silt loam soil as well as under the 0.8 kg m\(^{-2}\) treatment for the clay loam soil.

### 3.2. Total infiltration

Table 4 presents the results of the ANOVA of the infiltration data for the 60 mm simulated rainfall events. Clearly, since runoff amount was inversely related to the total infiltration, the significance of the relationships found for runoff would be the same for infiltration, although the effects act in an opposite way. Therefore, the ANOVA detected that mulch rate significantly affected the infiltration rates.
amount of water infiltrating the soils, as did the rainfall intensity, slope gradient and soil type.

Interactions between mulch rate and soil type or slope gradient were significant, but the interaction of mulch rate with rainfall intensity was just outside the cutoff significance level used in this study (p < 0.05). Furthermore, the interaction of mulch with both soil type and slope also significantly affected the infiltration amount, as did the interaction between soil type, rainfall intensity and slope.

Table 5 presents the results of the post-hoc Tukey HSD test, which differentiated between the means of the total infiltration amounts, while Fig. 2 displays this data in a form where trends are more readily seen.

For both soils under any given set of rainfall intensity and slope conditions, applying mulch generally increased the amount of infiltrated water as compared to the no mulch case (Table 5; Fig. 2). For both soils, infiltration amounts tended to decrease with increases in slope and rainfall intensity (Fig. 2). The infiltration was generally higher for the silty loam than for the clay loam soil.

3.3. Total soil loss

Table 6 presents the results of the ANOVA of the total soil loss data for the 60 mm simulated rainfall events. Mulch rate significantly affected the total soil loss, as did the soil type, rainfall intensity, and slope gradient. Furthermore, the interactions between mulch rate and each of the other three factors had highly significant effects on soil loss (p < 0.05).

Table 7 presents the results of the post-hoc Tukey HSD test, which differentiated between the means of the total soil loss, while Fig. 3 displays this data in a form where trends are more readily seen.

Table 5 presents the results of the post-hoc Tukey HSD test, which differentiated between the means of the total infiltration amounts, while Fig. 2 displays this data in a form where trends are more readily seen.

Table 6 Analysis of variance results for total soil loss.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS*</th>
<th>DF</th>
<th>F-value</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch</td>
<td>50.862</td>
<td>2</td>
<td>143.391</td>
<td>0.000</td>
</tr>
<tr>
<td>Soil</td>
<td>37.401</td>
<td>1</td>
<td>210.887</td>
<td>0.000</td>
</tr>
<tr>
<td>Rainfall intensity</td>
<td>4.652</td>
<td>2</td>
<td>13.115</td>
<td>0.000</td>
</tr>
<tr>
<td>Slope</td>
<td>11.287</td>
<td>1</td>
<td>156.901</td>
<td>0.000</td>
</tr>
<tr>
<td>Mulch × Rainfall intensity</td>
<td>10.716</td>
<td>4</td>
<td>15.105</td>
<td>0.000</td>
</tr>
<tr>
<td>Mulch × Slope</td>
<td>7.940</td>
<td>1</td>
<td>11.192</td>
<td>0.000</td>
</tr>
<tr>
<td>Soil × Rainfall intensity</td>
<td>9.834</td>
<td>2</td>
<td>27.725</td>
<td>0.000</td>
</tr>
<tr>
<td>Soil × Slope</td>
<td>11.287</td>
<td>1</td>
<td>156.901</td>
<td>0.000</td>
</tr>
<tr>
<td>Rainfall intensity × Slope</td>
<td>0.351</td>
<td>1</td>
<td>1.976</td>
<td>0.164</td>
</tr>
<tr>
<td>Mulch × Soil × Rainfall intensity</td>
<td>2.075</td>
<td>4</td>
<td>2.925</td>
<td>0.027</td>
</tr>
<tr>
<td>Mulch × Soil × Slope</td>
<td>5.606</td>
<td>2</td>
<td>4.702</td>
<td>0.000</td>
</tr>
<tr>
<td>Soil × Rainfall intensity × Slope</td>
<td>2.366</td>
<td>2</td>
<td>3.851</td>
<td>0.127</td>
</tr>
<tr>
<td>Mulch × Soil × Rainfall intensity × Slope</td>
<td>0.422</td>
<td>2</td>
<td>2.381</td>
<td>0.127</td>
</tr>
<tr>
<td>Mulch × Soil × Rainfall intensity × Slope</td>
<td>1.579</td>
<td>2</td>
<td>4.451</td>
<td>0.015</td>
</tr>
</tbody>
</table>

SS* = Sum of squares, DF = degrees of freedom and Sig = significance.
Fig. 2. Total infiltration amounts of the two soils at different slope gradients under 180 mm h\(^{-1}\) rainfall intensity (a and b) or at different rainfall intensity on a steep slope (15\(^{\circ}\)) (c and d).

0.8 kg m\(^{-2}\) mulch treatments, while under the 0.2 kg m\(^{-2}\) treatment there was no significant difference between the soil losses under the 100 and 180 mm h\(^{-1}\) rainstorms, but under the 140 mm h\(^{-1}\) they were reduced (Fig. 3d).

### 3.4. Occurrence of rills

No rills were apparent in the silt loam soil without mulch or under mulch applied at the rate of 0.2 kg m\(^{-2}\) under any of the experimental conditions. However, rills were formed under the 0.8 kg m\(^{-2}\) mulch treatment under all the sets of slope and rainfall intensity conditions except when the slope was gentle under the 180 mm h\(^{-1}\) rainfall, which accounts for the lower soil losses under this treatment as compared to the other mulch treatments in this particular case. With changes in slope gradient from moderate to steep, the slope length at which rills were initiated was the same (3 m) under the 100 mm h\(^{-1}\) rainfall but decreased to 1–1.5 m under the 180 mm h\(^{-1}\) rainfall. On the steep slopes, increasing the rainfall intensity resulted in rill initiation occurring higher up the slope, at 3, 2 and 1 m from the up end of the flume for the 100, 140, and 180 mm h\(^{-1}\) respectively. Rills occurred in the clay loam soil under all mulch rates with the exception of the gentle slope under the 180 mm h\(^{-1}\) rainfall intensity. Increasing the slope gradient under the 180 mm h\(^{-1}\) resulted in rill initiation occurring higher up the slope under all mulch rates, but under the 100 mm h\(^{-1}\) rainfall rill initiation occurred lower down the slope under the mulched soil and higher up the slope for the soil without mulch.

On the steep slope, rill initiation occurred further down the slope as rainfall intensity decreased for all mulch treatments. The mulch rate of 0.2 kg m\(^{-2}\) was the most effective mulch treatment for impeding rill initiation. Rills were also the least developed under the 0.2 kg m\(^{-2}\) mulch, as indicated by the smaller rill widths. However, while the rills under the 0.8 kg m\(^{-2}\) mulch treatment were usually less developed than those in the soil without mulch, on the steep slopes under 100 and 140 mm h\(^{-1}\) rain they were more developed. Rills under mulch tended to have steeper sides than those without mulch.

### 3.5. Rill formation processes

In the absence of mulch, surface sealing occurred on the soil surface. The composition of the seal was different for the two soils and affected their erodibility. Surface sealing occurred as a result of aggregate breakdown followed by compaction due to raindrop impact and reductions in hydraulic conductivity due to the partial blocking of pores in the surface layer of soil by “washed-in” of
Fig. 3. Total soil loss from the two soils at different slope gradients under 180 mm h$^{-1}$ rainfall intensity (a) and (b) or at different rainfall intensity on a steep slope (15°) (c and d).

smaller soil particles (McIntyre, 1958). Aggregate breakdown of a dry soil under intense rainfall, as used in this study, resulted initially from both slaking and raindrop impact (Le Bissonnais et al., 2005; Panabokke and Quirk, 1957). Slaking resulted from the explosive force of air entrapped within the aggregate under pressure when wetting is rapid. After the soil surface was wet, aggregate breakdown continued to occur due to the impact of raindrops but slaking became minimal. Aggregate breakdown was enhanced by clay dispersion that occurred due to the absence of electrolytes in rainwater, and this process would be increased with increasing exchangeable sodium percentage (Agassi and Ben-Hur, 1991). Dispersed clay particles and other small soil particles could either enter the pore system of the soil, where they may become trapped and partially block the pores, or were among the most readily eroded material to be transported by runoff. The silt loam soil maintained higher infiltration rates than the clay loam soil since it had significantly less clay that could enter and block the soil pores. In addition, since the compacted surface was composed of coarser particles than the clay loam soil, it was more porous. These coarser particles were both primary soil particles, mainly silt-sized, and micro-aggregates. Compacted, the consolidated surface layer could resist the shear forces generated by overland flow more than the soil without a seal. In contrast, the seal of the clay loam was less able to resist the shear forces because the micro-aggregates continued to disperse under the impact of the raindrops leading to a less stable seal that was subject to greater seal destruction forces (Poesen, 1987). Hence, soil losses were lower from the silt loam soil than from the clay loam soil for the same runoff amount (Fig. 4a and c).

Fig. 4 Under the 0.8 kg m$^{-2}$ mulch treatment, raindrop impact was minimal so that a compacted seal did not develop. However, aggregate breakdown initially occurred due to slaking and subsequently due to hydraulic shear forces (Shi et al., 2013), and was enhanced by clay dispersion. Even so, the degree of aggregate breakdown was less under mulch than in the absence of mulch. Consequently, blockage of pores in the soil by the smaller particles generated by aggregate breakdown occurred to a lesser extent and infiltration rates were thus higher under mulch than in the absence of mulch (Fig. 2).

Rill initiation occurs when the shear force of the overland flow, or runoff, exceeds a critical threshold value (Slattery and Bryan, 1992). Among other factors affecting the critical threshold value is the roughness at the soil surface, which generates turbulence leading to greater rates of soil detachment by overland flow. Surface sealing often reduces the roughness of the soil surface due to the breakdown of aggregates into a more heterogeneous particle size.
range and compaction. Thus, in the case of the un-mulched soil surface, a greater shear force might be required to detach soil particles from the seal to the degree needed to create rills than from an unsealed soil surface. Furthermore, as noted above, the seal of the silt loam soil is more cohesive than that of the clay loam soil and so resists rill initiation to a greater extent. Once rill initiation commenced in the clay loam soil, raindrop splash impact would likely enhance the development of the rill, also increasing the width of the rills by breaking down the sides of the rill. This latter action would lead to broader flow paths than if the sides were not broken down, which reduces the shear force of the water in the rill.

Under the 0.8 kg m\(^{-2}\) mulch rate, the factors affecting rill initiation and development included the following. The surface of the soil was rougher and roughness was also imparted to it by the mulch. Water flowing along individual straws lying on the soil surface and converging, or being diverted by straws, creates turbulence and at these points rill initiation was more likely to occur. Although the total runoff amount was less under the mulch than that from the un-mulched soil surface, the straws of the mulch laying on the soil surface directed the water flow to become more concentrated in places where the shear force would be greater than the mean runoff rate would suggest. Once initiated, the rills could back-cut along the straw blades creating a relatively straight channel along which water may accelerate, further increasing the shear force. Some evidence of this was observed at the end of the storms where individual straws projected over, and in the same direction as, a rill (Fig. 5).

In the absence of raindrop impact, the sides of the rill tended to be cut vertically and the rill width only increased when the sides are undercut. This maintained a more concentrated flow than the rills developed in the bare soil where the sides were destroyed by raindrop impact and were wider. Furthermore, because the individual straws laying directly on the soil surface diverted the flow, the rills were typically sinuous (Fig. 5 inset) rather than straight as seen in the bare soil (the clay loam) (Fig. 6).

Fig. 4 illustrates the shear strength of the soil surfaces under the 180 mm h\(^{-1}\) storms for the three slope gradients for the 0 and 0.8 kg m\(^{-2}\) mulch rates. It should be noted that soil losses from the clay loam soil included interrill as well as rill eroded material, and it appears that the interrill erosion but dominant under the experi-
mental conditions since the linear relationship indicates a transport limited situation, which is characteristic of interrill erosion (Fig. 4c).

In contrast, the soil losses from the soil under mulch were primarily from the rills as indicated by the exponential relationships that suggest a detachment limited situation, which is characteristic of rill erosion (Fig. 4b and d).

The phenomenon whereby greater soil losses occurred for soil under the 0.8 kg m$^{-2}$ mulch than when no mulch was applied was only observed for the silt loam soil in this study. In the case of the clay loam soil, under all of the experimental conditions, soil losses were always observed to be reduced by the application of mulch. However, extrapolating the curves shown in Fig. 4 suggests that the same phenomenon might occur in the clay loam soil if the rainstorm was of greater duration as the soil loss rate under mulch continued to increase. It might also occur if the slope was of longer length, thereby increasing the runoff amount. Furthermore, increases in runoff amount would possibly also reduce the rate of soil loss from the bare soil relative to the mulched soil since the overland flow depth would increase and shield the soil surface from raindrop splash detachment in the former case. However, this requires further study in the laboratory as well as in the field. The soil loss processes under the 0.2 kg m$^{-2}$ mulch treatment were likely a combination of those occurring under no mulch and 0.8 kg m$^{-2}$ mulch treatments. Sealing would have occurred where the soil was exposed to raindrop impact, which afforded some resistance to detachment. Thus, for the silt loam soil, no rills were observed under the 0.2 kg m$^{-2}$ mulch treatment in this study. Rills initiated under the mulch in the clay loam soil tended to be discontinuous as they intersected with soil patches where seals were present, and the resulting drop in flow velocity resulted in areas of deposition. Hence, soil losses were not observed to be higher than those from the soil without mulch. Therefore, under intense rainfall conditions and/or on steeper slopes, high rates of mulch cover should be avoided especially when the soil is similar to the silt loam soil. However, greater amounts of runoff may induce this phenomenon under lower rates of mulch in soils that are weakly sealed and this should be a subject for future study.

The experimental design was intended to identify the threshold slope and/or rainfall intensity conditions under which rill formation would occur under mulch. For the 0.8 kg m$^{-2}$ mulch treatment covering both of the soils, rill formation did not occur under the most intense rainfall on the gentle slope, and so it could be deduced that it would not occur under the lower rainfall intensities. Likewise, when it was proven that rill formation occurred under the lowest and highest rainfall intensities on the moderate slope, it could be deduced that it would also occur on the moderate slope. This suggested that rainfall intensity, and hence runoff rate, was of less importance in rill formation under mulch than the slope, which induced higher flow velocities with increasing gradient. Furthermore, the slope threshold must be between 5° and 10°. Such slopes represent a considerable area of cultivated land, not only in China but in the rest of the world, and so these findings should be of importance when considering the use of mulch on agricultural land.

As a supplement to this study, a wider flume (1 m) was used for the 0.8 kg m$^{-2}$ mulch treatment for both soils. Fig. 7 shows the patterns of rill formation under the mulch, after the mulch was removed following 60-mm of rainfall at an intensity of 180 mm h$^{-1}$. The rill system was more developed than those in the narrower flume (0.3 m) used in the main study and soil losses were much higher. This can be ascribed to the greater amounts of water intercepted by rills when they traversed the flume in a horizontal direction as well as the water diverted by the straws into the rills, and the greater catchment area. The greater amounts of water had more erosive power leading to the higher soil losses.

Conditions in the laboratory study, where the had been passed through a 2-mm sieve and was relatively homogeneous, are different from those in the field. For example, clods can occur in field soils that are less erodible although they may increase overland flow detachment of other soil particles by diverting and concentrating the overland flow. Clods may affect the surface sealing process, for example, by acting more like stones shielding the underlying soil from raindrop impacts and increasing infiltration in the surrounding area. Consequently, the presence of clods may enhance or inhibit the processes that occurred in this laboratory study. In the field, slopes longer than 5 m usually occur. As noted above, longer slopes would likely result in greater runoff amounts downslope, which could affect infiltration by shielding the surface soil from raindrop impact resulting in higher infiltration rates lower rates of detachment by raindrop impact. However, detachment by overland flow would also increase. Therefore, while more laboratory studies could be conducted to study processes, future field studies are essential to aid in the translation of our results to the real world.

4. Conclusions

The effect of mulch rate on rill formation in two typical soil types of the Loess Plateau was investigated under simulated rainfall. Comparisons of the results were made for 60 mm rainstorms under various rainfall intensity and slope gradient conditions on a 5-m long slope. Covering the soil with mulch tended to reduce runoff amounts as compared to those from the soils with no mulch.
Fig. 7. The patterns of rill formation under the mulch (0.8 kg ha\textsuperscript{-1}) for two soils (1-m wide flume).

cover. However, under a mulch rate of 0.8 kg m\textsuperscript{-2} soil losses from the silt loam soil greatly exceeded those from the soil without mulch. At the end of the 60-mm rainstorm and under the most intense conditions, the total soil loss from the clay loam soil under mulch (0.8 kg m\textsuperscript{-2}) was less than 50% of that from the soil without mulch and was always lower than under mulch; but soil loss rates, which had been increasing, exceeded those of the un-mulched soil.

This phenomenon was linked to the relatively high resistance to rill formation of the surface seal developed on the silt loam soil as compared to the soil without a seal under the high mulch rate, which was almost totally protected from raindrop impact. Furthermore, rill initiation was more likely to occur under the mulch due to the increased surface roughness of a soil without a seal and the presence of the mulch, and to the concentration of flow by the individual straws of the mulch laying directly on the soil surface, which diverted the flow. The results suggest that, with a greater amount of runoff, the same phenomenon may occur in the clay loam soil, which was more susceptible to rill formation under all mulch treatments and developed a less resistant seal. Reducing the mulch rate when severe runoff events are likely from soils similar to the silt loam should avoid large soil losses. However, for soils more susceptible to rill formation under mulch, such as the clay loam in this
study, this may not work. Future studies should address this issue and field studies are essential to translate our findings to the real world.

**Acknowledgements**

This work was financially supported by the projects of the Knowledge Innovation Program of the Chinese Academy of Sciences (KZCX2-YW-442), and the National Natural Science Foundation of China under Project No. 41230746 and No. 51321001.

**References**


