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

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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.

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,

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1994; Lal, 2001) 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 nonselective (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.