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Runoff and soil loss characteristics on loess slopes covered with aeolian sand layers of different thicknesses under simulated rainfall

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ABSTRACT

In the Wind-Water Erosion Crisscross Region of the northern Loess Plateau, parts of loess slopes have been covered by layers of aeolian sand of different thicknesses. Knowledge of soil erosion processes and magnitudes on these slopes is essential to understanding the coupled water-wind erosion processes and to address the resulting downstream coarse sediment problems in the Yellow River. Simulated rainfall (intensity 90 mm h^{-1}) was performed to explore the effects of sand layer thickness on runoff and soil loss from loess slopes covered with different sand layer thicknesses (0, 0.5, 2, 5, 10, 15, 20, and 25 cm). Initial runoff time increased with increasing sand layer thickness, with greater changes occurring for the increases in the thinner (0–5 cm) than for the thicker layers (5–25 cm). Total runoff yield from the sand-covered loess slopes was 18%–55% lower than from the uncovered loess slope and decreased with increasing sand layer thickness. In contrast, total sediment yield was up to 14 times greater from the sand-covered loess slopes than from the uncovered loess slope and rapidly increased with increasing sand layer thickness. During the rainstorm, runoff and soil loss rates exhibited unimodal distributions, and they were related by a positive linear function, both before and after the maximum soil loss rate, that had a high determination coefficient ($R^2 > 0.8$, $p < 0.05$) on loess slopes with sand layer thicknesses greater than 5 cm. The maximum runoff and soil loss rates tended to occur simultaneously and increased abruptly with increasing sand layer thickness. During the rainstorms, some runoff rates on the loess slopes with thicker sand layers were higher than the rainfall intensity due to rainwater combining with water emerging from the saturated sand, which could never occur on the uncovered loess slope. The critical sand layer thickness, which produced a qualitative change in runoff and sediment production modes, appeared to be in the range of 5–10 cm. These results indicated that the thickness of the sand layer on the loess slope significantly influenced runoff and sediment production processes and mechanisms. These effects should be considered when assessing and predicting soil losses in this region and from similar slopes elsewhere.

1. Introduction

The Wind-Water Erosion Crisscross Region of the northern Loess Plateau undergoes the combined actions of water erosion in summer and autumn with wind erosion in winter and spring. It is an area of severe erosion with soil loss rates exceeding 10,000 t km^{-2} a^{-1} (Li et al., 2005). Previous studies in this region have indicated that the strong winds during the winter and spring transport large quantities of aeolian sand to the loess slopes, gullies and river channels. This results in a special geomorphologic landscape with layered soil profiles, i.e., the loess soil covered by layers of aeolian sand (Zhang et al., 1999; Xu et al., 2000), which are similar to texture-contrast or duplex soils (Rab et al., 1987; Tennant et al., 1992; Hardie et al., 2012a). Xu et al. (2000) estimated that the areas covered by this layered soil landscape total approximately 13,099 km^2 and are widely distributed in the Wind-Water Erosion Crisscross Region. The sand covering the loess can be easily eroded during subsequent rainy seasons and the eroded material then becomes a major source of the coarse sediment (>0.05 mm) that is transported by the Yellow River and deposited on the riverbeds of the Yellow River downstream (Xu, 2000, 2005b; Xu et al.,

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2000, 2006). Therefore, the problem of the great soil losses in this region is detrimental not only for the local agriculture and environment but also for the ecological sustainability of the lower reaches of the Yellow River (Xu et al., 2000; Wang et al., 2012; Zhou and Zhang, 2012).

In contrast to uniform soils, the layered soil profiles in the area of loess covered by aeolian sand have a clear boundary between the two layers (sand and loess) with very different chemical and physical properties, especially that of hydraulic conductivity (Wu et al., 2014). The low permeability of the subsoil is the factor that has the greatest influence on the behavior of these texture-contrast soils (Gregory et al., 1992; Tennant et al., 1992) and changes the responses to the infiltration and runoff modes on the slope (Gregory et al., 1992; Cox and McFarlane, 1995; Cox et al., 2002; Hardie et al., 2012a, 2013). A few studies have indicated that runoff and erosion processes on the sand-covered loess slopes are very different from those occurring on the uncovered loess slopes (Zhang et al., 1999; Xu et al., 2000, 2015). Zhang et al. (1999) performed two simulated rainfall experiments in the field and found that unique patterns of runoff and sediment production, i.e., infiltration-interflow-collapse processes, occurred on a sand-covered loess slope. Although runoff and sediment production were delayed, once runoff was initiated, the sediment yield rapidly increased with the runoff amount and was markedly higher on the sand-covered loess slopes than on the uncovered loess slopes. Zhang et al. (1999) also suggested that further studies were needed to explore the various effects of other factors that would affect the runoff and erosion processes and dynamic features on the sand-covered loess slopes under different conditions of rainfall, sand layer thickness, slope degree and slope length. Xu et al. (2015) conducted simulated rainfall experiments on sand-covered loess slopes in the laboratory and found that the thickness of the sand layer could affect runoff and sediment yield. However, the thickness of the covering sand layer considered in their study was too thin (less than 2 cm) to fully represent the runoff and erosion processes on the typical sand-covered loess slopes in the field. Even so, at the large scale, an analysis of data from the hydrometric stations led to the hypothesis that the hyperconcentrated flow occurring in the Wind-Water Erosion Crisscross Region and deposition of the coarser sediment particles on the riverbeds of the Yellow River downstream resulted because of the landscape of sand layers over loess (Xu, 2000, 2005a), and this hypothesis was supported by the findings of the limited laboratory studies.

Compared to the scarce studies of the sand-covered loess soils, more studies have been reported for the texture-contrast or duplex soils in other regions. The texture-contrast soils classified as "duplex" soils were definitively defined as having a subsoil (B horizon) with a texture that is at least one and a half texture groups finer than the surface soil (A Horizon), and the boundary between the surface soil and the subsoil has to be clear to sharp (Northcote, 1971). Physical and chemical characteristics of duplex soils, and the areas over which they were distributed across the Australian landmass have been determined (Rab et al., 1987; Chittleborough, 1992; Tennant et al., 1992). The large differences in the permeability of the subsoil and surface soil layers greatly affected the hydrological behavior of the duplex soils, and resulted in the formation of seasonal perched water tables, subsurface lateral flow, and numerous other management problems that were summarized by Hardie et al. (2013). Eastham et al. (2000) investigated water movement associated with a perched water-table in a duplex soil on a gentle (1.6%) slope and found that lateral water movement occurred in response to topographical gradients in the soil surface and the depth of the clay layer. The effects of antecedent soil water contents on hydraulic conductivity and preferential flow in duplex soils, and comparisons of subsurface lateral flow occurring in duplex soils with that in catchments with shallow bedrock have been studied in order to understand the mechanisms responsible for the development of perched water-tables and subsurface lateral flow in duplex soils (Hardie et al., 2011, 2012a,b, 2013). In addition, other studies considered seepage erosion and shallow landslides occurring on slopes with other kinds of texture-contrast soils worldwide to examine river bank failure (Fox et al., 2007; Karmaker and Dutta, 2013), embankment failure (Zeng et al., 2012; Raj and Sengupta, 2014), erosion of soil over bedrock (Hardie et al., 2012a; Lanni et al., 2013; Kim et al., 2015), and shallow landslides induced by rainfall (Okura et al., 2002; Wang and Sassa, 2003; Lourenço et al., 2006; Bogaard and Greco, 2016). However, while the sand covered loess soils can be described as texture-contrast or duplex soils, their characteristics differ from other kinds of texture-contrast soil due to their formation processes, the variations of layer thickness and the physicochemical properties in their profiles. Although similar theories might possibly have been used to reveal infiltration, runoff and erosion/failure modes on other texture-contrast soil slopes, the characteristics of runoff and sediment production processes during rainstorms are expected to differ between them and the sand-covered loess slopes. Moreover, most studies of texture-contrast soil slopes mainly focused on variations in groundwater, water-table, pore pressure, seepage gradient forces, water content and other hydrological parameters in order to explain slope failure modes, mechanisms and processes. There are few studies that focused on variations in runoff and sediment production and their characteristics on texture-contrast soil slopes during rainstorms. Therefore, compared to the great progress made in understanding the processes of soil erosion on uniform soil slopes due to surface runoff and incorporating these in prediction technologies, the characteristics of the runoff and sediment production processes and mechanisms on the aeolian sand-covered loess slopes have not been completely identified and warrant further study.

The thickness of a coarser texture layer on a texture-contrast soil slope has been found to affect the infiltration mode, water-holding capacity and gravitational driving force (Kirkby and Chorley, 1967; Eastham et al., 2000; Okura et al., 2002; Chu and Mariño, 2005; Pornprommin et al., 2010) and subsequent runoff and sediment production patterns and processes (Xu et al., 2015). Variations in the depth of the sand layer covering the loess slopes in the Wind-Water Erosion Crisscross Region range from thin, in the order of millimeters, to thick, in the order of meters, due to the differences in the coupled interaction between wind and water erosion (Xu et al., 2000; Wu et al., 2014). However, no study of the effects of a wide range of sand layer thicknesses on runoff and erosion processes has been conducted for the sand-covered loess slopes. The objective of this paper is to analyze the influences of the thickness of an aeolian sand layer overlying a loess slope on hydrological and erosive processes during simulated rainfall. Our results are expected to provide insight into the runoff and sediment production from texture-contrast soil slopes and to enhance our understanding, prediction and control of soil losses in the Wind-Water Erosion Crisscross Region of the Loess Plateau.

2. Materials and methods

2.1. Experimental design

To achieve the objectives of this study, seven different thicknesses of an aeolian sand layer overlying a loess slope were established, i.e., 0.5, 2, 5, 10, 15, 20, and 25 cm thick, with uncovered soils (i.e., 0 cm thick) used as the control. The range of sand layer thicknesses investigated were based on field observations and on previous studies that simulated shallow landslides in the laboratory (Okura et al., 2002; Wang and Sassa, 2003; Lourenço et al.,