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Effect of grass basal diameter on hydraulic properties and sediment yield processes in gully beds in the dry-hot valley region of Southwest China

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ABSTRACT

Vegetation is an important factor impacting the hydrodynamic processes of gully beds and further affecting the headward erosion of gullies. Gully erosion is one of the major contributors to severe land degradation in the Yuanmou dry-hot valley region of Southwest China where soil erosion rates are estimated ranging from 8000 to 20,000 $t \cdot km^{-2} \cdot a^{-1}$, with a mean gully distribution density ranging from 3 to 5 $km \cdot km^{-2}$. However, few studies have been performed in this area which focused on the influence of the aboveground part of grass on soil erosion under natural conditions in gullies. To quantify the temporal variation of hydraulic properties (i.e., shear stress (τ), Darcy–Weisbach friction factor (resistance f) and Sediment Concentration (*SC*) and analyse the change trends of hydraulic properties and *SC* in gully bed along with the downslope direction under different grass basal diameters, a series of in situ scouring experiments were conducted in development areas of gully erosion in the Yuanmou dry-hot valley region. With the grass basal diameter increased from 0 (no grass) to 17 to 43 to 70 to 98 mm in gully beds, the mean shear stress of concentrated flow increased slightly (4.03 to 4.49 Pa) and then decreased obviously (4.49 to 3.45 Pa). On the other hand, increasing trends were observed in temporal variations of shear stress for every grass basal diameter and the increase rate varied from 0.05 to 0.18. Whereas no notable regular changes in shear stress were detected in the downslope direction for grass basal diameters of 0 to 43 mm, obviously increasing trends were observed for the grass basal diameters of 70 mm and 98 mm. The resistance f experienced a notable increase with increasing grass basal diameter in this study. A logarithmic growth of resistance f was observed in the gully bed as the experiment progressed ($f = a\ln(t+b)$, $P < 0.01$), and increasing trends were detected for the resistance f in the downslope direction of the gully bed for all grass basal diameters although regression equation could only be fitted for grass basal diameter of 98 mm ($f_{98} = 2.438\ln(DOH_{98} - 2.643)$, $P < 0.01$). However, the *SC* showed an exponential decline with the scouring time. And the *SC* showed an increasing trend along with the downslope direction of the gully bed in all experiments. In addition, a negative correlation could be detected between *SC* and resistance f in all five grass basal diameter experiments. In this study, only the disposal for grass basal diameter of 98 mm was clearly more effective than other disposals in conserving gully bed, which might because grass basal diameter (≥98 mm) that could cover a relatively large section of gully bed could exert apparent impact on reducing runoff shear stress, increasing resistance coefficient and then further decline the sediment yield. In contrast, when grass basal diameter was <98 mm, the reduction effect for soil erosion was very limited due to overland concentrated flow could detour around the grass base and erode the gully bed.

1. Introduction

Gully erosion is an important form of soil erosion in a variety of environments, causing considerable soil losses and producing large volumes of sediment (Chaplot et al., 2005; Poesen et al., 2003; Valentin et al., 2005a,b), which has attracted increasing attention from international researchers in recent years (Mousazadeh and Salleh, 2014b). The earliest gully erosion research can be traced back to 1928 (Rubey, 1928). In the 1980s, hillslope gullies, which formed by critical flow shear stress excess at the soil surface (Montgomery and Dietrich, 1988), received the most attention (Su et al., 2015). Development stage classification and qualitative description of morphologic

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characteristics as well as studies of factors that influence gully erosion first caught the attention of scholars in the 1930s (Menéndez-Duarte et al., 2007; Mousazadeh and Salleh, 2014a; Muñoz-Robles et al., 2010). Subsequently, studies about the severity and perniciousness of gully erosion at the watershed scale, especially on unpaved roads, cultivated land and infrastructure became of interest for a growing body of researchers around the world (Dotterweich et al., 2013; Dube et al., 2014). The investigations of Poesen et al. (2003) and Valentin et al. (2005b) indicated that gully erosion was triggered by human-induced modification of vegetation cover due to land use change, over-grazing, burning of vegetation and road construction (Muñoz-Robles et al., 2010). In recent years, more and more attention have been paid to the inner mechanisms of the formation and development of gully erosion (Gomez-Gutierrez et al., 2012; Yang et al., 2015a; Zhang et al., 2014) and to kinetic process research on headward erosion of bank gully headcuts (Esteves et al., 2005; Su et al., 2015; Xiao et al., 2014). However, comparatively few studies focused on the abatement of gully erosion, which was due to the complexity of the factors controlling gully erosion as well as the low efficiency of water and soil conservation measures. Despite this, vegetation restoration measures, engineering measures and conservation tillage in arable land were conventional attempts to prevent gully erosion (Hudson, 1995; Poesen et al., 2003; Valentin et al., 2005b). In consideration of the high cost of engineering measures and lack of ecological function for engineering measures (Hudson, 1995), ecological control techniques and measures have become the research focus of most scholars (Molina et al., 2009; Poesen et al., 2003; Rey, 2003).

As a vital component of vegetation restoration measures, herbage could reduce runoff with luxuriant foliage, reduce the kinetic energy of raindrops and prevent soil erosion. This was due to the powerful root system of herbage, which enhanced the resistance of soil to erosion (Zhang and Zhou, 2015). Many studies have proven that herbage played a more positive role in rain closure and sediment reduction than other species when natural conditions were poor and subject to serious erosion (Tian, 2010; Wu et al., 2010; Xiao et al., 2011; Yu et al., 2009). The results of Palacio et al. (2014) indicated that shrub steppes generally experience soil erosion, whereas the grass steppe commonly did not show signs of soil erosion/deposition, which further illustrated that grass steppe was more resistant to land degradation than shrub steppe. A similar conclusion was reported by Zhang et al. (2015), who demonstrated that plots covered with 5-year mixed legume plants (*Medicago sativa*, *Melilotus suaveolens*, *Onobrychis viciaefolia*) and mixed grass-shrub-arbor forest (*Robinia pseudoacacia* × *Chinese pine* × *Astragalus adsurgens*/*Medicago sativa*/*Melilotus suaveolens*) were overall more effective in preventing both runoff and soil erosion than other plant types on reclaimed land in an opencast coal-mine dump. Additionally, the results of Fusun et al. (2013) showed that high coverage of grass surface could cut down runoff and soil erosion more effectively than other vegetation types, including shrub, deciduous tree and evergreen tree. Yang et al. (2014, 2015a,b) concluded that grass in gully beds could effectively reduce sediment yield. Furthermore, Fox et al. (2011), Gan et al. (2010), and Puttock et al. (2014) concluded that grass was an effective tool for soil-erosion control. However, few studies that focused on the influence of the aboveground part of grass on soil erosion in gullies had been performed under natural conditions (Pan and Shangguan, 2006). This was due to limitations of the study methods and techniques and the complexity of microtopography for grass growth. In contrast, many studies have been conducted to explore the effect of branches and leaves on water closure as well as the effect of the vegetation root system on enhancing anti-erodibility and reducing sediment yield (Zhang and Zhou, 2015). It was worth mentioning that enhancing research on the restraining effect of hydraulic properties and sediment yield of the aboveground portion of grass was important to complement theoretical gully erosion studies.

In 1995, Prosser et al. (1995) conducted a flume experiments to investigate flow resistance and sediment yield under natural conditions and with progressive clipping of grass cover and found that plant stems can exert over 90% of flow resistance so as to prevent sediment transport. In addition, a few researchers have involved themselves in exploring relationship between erosion intensity and flow erosivity, among which some scholars held that erosion rate had a positive correlation with shear stress(τ), such as Howard and Howard and Kerby (1983) found that channel incision rate scaled as τ^a with $a \approx 1$ in rapidly eroding badlands, and Whipple and Tucker (1999) and Whipple et al. (2000) obtained similar results and argued that the exponent a was between 1 and 5/2. In contrast, there also some researchers proposed that there was a negative correlation between erosion rate and shear stress (Zhao et al., 2014; Chen, 2012; Foster, 1981; Meyer et al., 1975a,b), for example, Sklar and Dietrich (2004) found that fluvial bedrock erosion rate decreased with increasing shear stress with the exponent on excess shear stress being negative (exponent $a = -0.5$) in the saltation-abrasion model, and in 2010, Johnson and Whipple (2010) then further verified and explained these results. Besides, some study results indicated that no direct dependence relationship could be detected between erosion intensity and shear stress and argued that the exponent of erosion rate on excess shear stress was zero (Parker, 1991; Chatanantavet and Parker, 2009). All these results indicated that there were some controversies about the relationship between erosion intensity and flow erosivity. And In order to explore the effect of grass basal diameter on hydraulic properties and sediment yield process in Yuanmou dry-hot valley region, a series of in situ field scouring experiments were conducted in this study to (1) address differences in temporal variation of runoff shear stress, Darcy-Weisbach friction factor (resistance *f*) and Sediment Concentration (*SC*), (2) analyse the change trends of hydraulic properties and *SC* in gully bed along with the downslope direction, and (3) examine the interactions between *SC* and shear stress and resistance *f* for a variety of grass basal diameters in gully beds in the dry-hot valley region of Southwest China.

2. Material and methods

2.1. Study area

Experiments were carried out from March to May 2013 at the Yuanmou Gully Erosion and Collapse Experimental Station, a field station operated by the Institute of Mountain Hazards and Environment (IMHE) of the Chinese Academy of Sciences (CAS). This station is located in the Jinsha River Basin in Yuanmou County (25°23′ N to 26°06′ N, 101°35′ E to 102°06′ E) (Su et al., 2015), Yunnan Province, China, which is a typical dry-hot valley region where the altitude ranges from 898 to 2836 m and the slope mainly ranges from 5°to 20° (Fig. 1). The study area features dry-hot climate, sunshine, low rainfall and notable dry and wet seasons, with a mean annual precipitation of 634.0 mm, a mean annual temperature of 21.8 °C, and an average annual potential evaporation of 3847.8 mm. Approximately six to seven major high-intensity convective storms occur in this area each year, which typically last one to 2 h (Zhong, 2000). The dominant soil types are Ustic Ferrisols and Vertisols. Soil erosion rates are estimated ranging from 8000 to 20,000 $t \cdot km^{-2} \cdot a^{-1}$, with a mean gully distribution density ranging from 3 to 5 $km \cdot km^{-2}$ and a maximum density of 7.4 $km \cdot km^{-2}$, which accounts for the majority of soil erosion in this area (Zhong, 2000) (Fig. 2). The zonal vegetation type is tropic bushveld with scattered trees, which results in a tropical savanna-like ecosystem. Herbs dominate the vegetation (mainly *Heteropogon genus* and *Bothriochloa pertusa* species). In addition, dispersed trees (*Leucaena leucocephala* and *Bombax malabaricum*/*B. ceiba*) and shrubs (*Dodonaea viscosa* and *Osteomeles schwerinae* C. K. Schneid) can be found in this region (He, 2013).

2.2. Experiment design and data collection

To evaluate the effect of the grass basal diameter on runoff shear stress, resistance *f* and *SC*, a series of simulated in situ scouring tests