Agriculture, Ecosystems and Environment 266 (2018) 68–75

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Response of soil detachment capacity to plant root and soil properties in typical grasslands on the Loess Plateau

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ARTICLE INFO

Keywords:
Soil detachment capacity
Root mass density
Grassland
Overland flow
The Loess Plateau

ABSTRACT

It is likely that grassland has a significant effect on the process of soil detachment by overland flow. This study tests how soil detachment capacity responds to variation in plant root and soil properties between ten typical grasslands found on the Loess Plateau. 300 soil samples were collected from five grasslands with tap root system and five grasslands with fibrous root systems representing the typical community compositions of different succession stages, then subjected to flow scouring in a hydraulic flume under six shear stresses (ranged from 4.98 to 16.37 Pa). The results showed that the mean soil detachment capacity of each grassland fell between 0.030 kg $m^{-2} s^{-1}$ (*Poa sphondylodes* Trin.) and 3.297 kg $m^{-2} s^{-1}$ (*Astragalus melilotoides* Pall.). The mean soil detachment capacity across all grasslands with tap root systems was 14.7 times greater than that of grasslands with fibrous root systems, indicating that fibrous root systems are significantly more effective at reducing soil erosion. Soil detachment capacity was effectively simulated by power functions of flow velocity, shear stress, or stream power (with mean R^2 values ranging from 0.87 to 0.90) and less effectively simulated by a power function of unit stream power (mean R^2 = 0.74). Soil detachment capacity decreased exponentially with soil bulk density, aggregate, and cohesion (with R^2 values ranging from 0.87 to 0.99) as well as with root mass density (R^2 = 0.31, n = 150 for tap root systems and R^2 = 0.17, n = 150 for fibrous root systems). Soil detachment was significantly worse in grasslands with tap root systems where the root mass density was less than 4 kg m^{-3}. A model was developed to estimate soil detachment capacity based on hydraulic parameters, plant root, and soil properties on the Loess Plateau, and its performance was satisfactory (R^2 = 0.86; NSE = 0.73). Root mass density, soil aggregate, and soil cohesion were indicated as the primary features of grasslands which influencing the process of soil detachment.

1. Introduction

Vegetation generally has a mitigating effect on soil erosion since plants can protect the soil surface from rain or runoff detachment and reduce runoff velocity and sediment transport by intercepting raindrops, increasing soil permeability, increasing the roughness of the soil surface, and reinforcing soil mass stability (Bakker et al., 2005; Gyssels et al., 2005; Li et al., 1992b; Vannoppen et al., 2015). In most soil erosion models, vegetation is considered as an important factor influencing soil erosion rate (Morgan et al., 1998), and vegetation coverage is the parameter most commonly used to represent vegetation in models since it is easy to measure. (Duran Zuazo and Rodriguez Pleguezuelo, 2008; Labriere et al., 2015). Many studies have been conducted to look at the relationship between soil erosion rate and coverage under diverse environmental conditions, and these studies universally indicate that soil erosion rate decreases linearly or exponentially with coverage (Gyssels et al., 2005; Nearing et al., 2005). However, Gyssels et al. (2005) believed that the measured soil loss reduction resulted not only from coverage, or above-ground biomass, but also from the plant roots and soil properties. In many previous studies and soil erosion models, the effects of plant roots and soil properties on reducing soil detachment are attributed to the vegetation coverage due to the difficulty in excavating plant root in the field conditions (De Baets et al., 2006; Gyssels and Poesen, 2003; Wang and Zhang, 2017). In reality, vegetation coverage is only the most important factor in splash and inter-rill erosion, whereas in the process of rill erosion (mainly caused by

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https://doi.org/10.1016/j.agee.2018.07.016
Received 8 May 2018; Received in revised form 18 July 2018; Accepted 21 July 2018

overland flow), plant roots play a much more important role in reducing soil detachment (Gyssels et al., 2005). Therefore, to better understand the mechanisms by which vegetation effects soil erosion, it is important to distinguish the role of plant roots and soil properties from that of vegetation coverage, and to quantify their distinct effects on reducing soil detachment.

The primary mechanisms by which plant roots reduce soil detachment are by reinforcing soil mass and improving soil shear strength (De Baets et al., 2006; Knapen et al., 2007; Herbrich et al., 2018). Soil generally has high compression strength but low tensile strength, whereas plant roots are the opposite (Simon and Collison, 2001, 2002). During the process of plant growth, the root interweaves into the soil mass (producing the soil-root matrix) and intensifies the soil's resistance to flowing water. (Gyssels et al., 2005; Reubens et al., 2007). This process is called the root binding effect as reported by Wang and Zhang (2017). Besides, the root bonding effect, which refers to how mucilage secretion of plant roots cause them to adhere to soil particles (via intermolecular bonding and Van der Waals forces), must also be considered, since it accounts for more than one quarter of the soil loss reduction caused by total plant root system (Wang et al., 2015). As mentioned by Li et al. (1991, 1992a), the soil's resistance to scouring is enhanced by plant roots, and this reduction of soil loss increases as "Effective Root Density" (the numbers of plant root with diameter less than 1 mm in a soil cross-sectional area of 100 cm^2) increases. The effects of plant roots on soil erosion also differs between various root types and root type architectures. Fibrous root systems generally have many fine roots, rather than one large roots and fewer fine roots, and this gives them an erosion-reducing potential that is much more significant than that of tap root systems. (Mamo and Bubenzer, 2001a,b). Wang and Zhang (2017) concluded that soil detachment capacity in grasslands with tap root systems was as much as 14.7 times higher than that of grasslands with fibrous root systems. Moreover, many studies have shown that soil loss rates decrease exponentially as root mass density, root length density, or root area ratio increase. This functional relationship has been applied in some soil erosion models, e.g. USLE and WEPP (Morgan et al., 1992; Nearing et al., 1991).

The growth or development of plant roots can affect the physical properties and nutrient levels of soil, which consequently affect soil erodibility (Islam and Weil, 2000; Schwarz et al., 2015; Xin et al., 2016). The effects of plant roots on soil properties can be summarized in terms of the following aspects: clumping fine soil particles together into firm macroaggregates and improving soil aggregate stability, interweaving with the soil and strengthening soil cohesion, extruding soil mass and changing soil bulk density, improving water movement and infiltration capacity, decomposing organic residues, and increasing soil organic matter (Gyssels et al., 2005; Li et al., 1991; McDonald et al., 2002; Zhang et al., 2017). Many previous studies have confirmed that soil bulk density, soil cohesion, soil aggregate stability (or water stable aggregate), and soil organic matter content are inversely proportional to soil detachment rate (Ghebreiyessus et al., 1994; Li et al., 2015; Morgan et al., 1998; Nearing et al., 1988; Wang et al., 2013). However, the effect of soil properties on soil erosion can also differ between different vegetation types. For example, large-diameter roots (those larger than the soil pores) can push soil particles aside and increase soil bulk density (Simon and Collison, 2001), while fine roots (those with diameter less than 1 mm) would decrease soil bulk density (Li et al., 1992b). Soils from the same area with similar soil textures can still have significantly different soil properties due to differences in community composition (Wang et al., 2018).

Mean annual soil erosion rates on the Loess Plateau range from 5000 to 10 000 tons km^{-2} yr^{-1} (Zhang and Liu, 2005), making it one of the most severely eroded regions in the world, and a series of ecological restoration projects have been implemented in this area to control soil erosion. For example: extensive tree planting on slope farmland in the 1970s, integrated soil erosion control at watershed scales in the 1980s and 1990s, and the "Grain for Green" project in 1999. As a result of these efforts, 41.7% (2.6×10^5 km^2) of the Loess plateau was grassland at the end of 2010, making grassland the primary land-use type in the region (Li et al., 2016). The communities, or dominant species of grasslands, differ between different areas of the plateau due to the differences in seed banks, succession pathways, and growth conditions during the process of vegetation succession (Jiao et al., 2012; Wang et al., 2018). Since they have significantly different root characteristics, these different plants have varying effects on the process of soil erosion, and though the influence of soil and root system properties on soil detachment have been quantified separately, the response of soil detachment to the various combinations of soil and root system properties have not been fully quantified and are in need of further study. Hence, ten typical grasslands with different root types and varied soil properties, reflecting different stages of vegetation succession on the Loess Plateau, were selected to: 1) study how the soil detachment process responds to various combinations of plant root and soil properties, 2) quantify the relationship between soil detachment capacity and root characteristics or soil properties, and 3) develop a model to estimate soil detachment capacity in grasslands based on flow hydraulic parameters, root characteristics, and soil properties.

2. Materials and methods

2.1. Study area and site selection

This study was carried out in the Zhifanggou watershed, which is located in the middle of the Loess Plateau (8.27 km^2; Ansai county; N36°46′28″to N36°46′42″, E109°13′03″to E109°16′46″; Fig. 1). The study area is a typical loess hilly-gully region. The area has a warm climate, and is in the transition region between semi-humid and semi-arid. The mean annual temperature and mean annual precipitation are 8.8 °C and 505 mm, respectively. The soil has a typical silt loam texture,

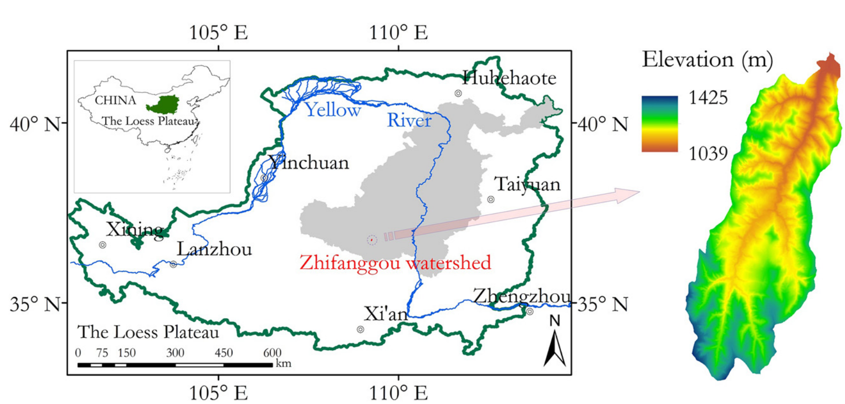

Fig. 1. Location of Zhifanggou watershed.