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Relationship between soil water content and soil particle size on typical slopes of the Loess Plateau during a drought year

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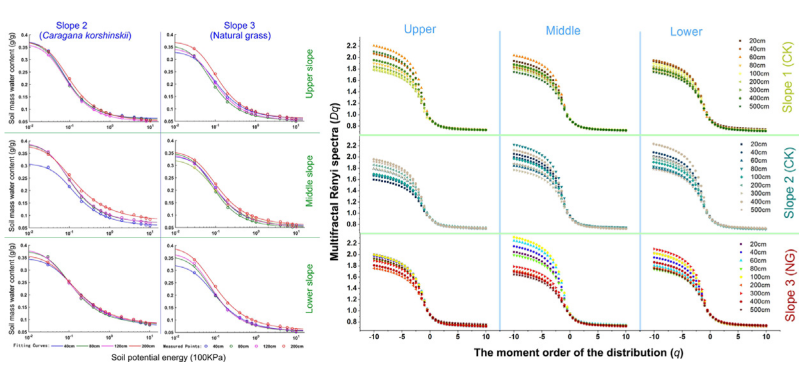
HIGHLIGHTS

- Fractal dimension analysis is a useful tool for understanding hydropedology.
- Shrub and grass used soil water below 2 m and 1.2 m respectively in a drought year.
- Shrub reduces erosion of fine particles but consumes water stored in deep layers.

GRAPHICAL ABSTRACT



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ABSTRACT

In the context of global climate change as well as local climate warming and drying on the Loess Plateau of China, understanding the relationship between soil particle size and soil water distribution during years of atypical precipitation is important. In this study, fractal geometry theory is used to describe the mechanical composition and texture of soils to improve our understanding of hydropedology and ecohydrology in the critical zone on the Loess Plateau. One grassland slope and two shrubland slopes were selected in the hilly and gully region of the Loess Plateau, and soils were sampled along hillslope transects at depths of 0–500 cm. Fractal theory and redundancy analysis (RDA) were used to identify relationships between the fractal dimension of soil particle-size distributions and the corresponding van Genuchten parameters for the soil-water-characteristic curves. The oven-drying method was used to measure soil water content, and the high-speed centrifugation method was used to generate soil-water-characteristic curves. The results show that (1) the soil water that can be used by *Caragana korshinskii* during a drought year is distributed below 2 m from the surface, whereas the soil water that can be used by grass is below 1.2 m; (2) *Caragana korshinskii* promotes the conservation of fine soil particles more than does natural restored grass, and the soil particle-size distribution fractal dimension changes with depth and position; and (3) soil hydraulic properties correlate strongly with soil pedological properties such as bulk density and the soil particle-size distribution fractal dimension. These results provide a case study of the relationships among soil distributions, hydrologic and geomorphic processes for vegetation restoration in drylands with

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a thick vadose zone. More studies on soil property changes are needed to provide case studies and empirical support for ecological restoration in the Loess Plateau of China.

1. Introduction

The Loess Plateau of China is a critical area because it occupies a large areas of arid and semiarid areas and feeds a large amount of the country's population; however, the ecosystem is fragile, and the loose soil is easily eroded (Fu et al., 2002; Lü et al., 2012). With global climate change, extreme weather events have increased, and the climate of the Loess Plateau has become drier and warmer. These changes threaten local ecological restoration (Qin et al., 2002, 2014; Stocker et al., 2013). To conserve soil and water and to control desertification of the Loess Plateau, the Chinese government conducted the *Grain to Green* program in 1999. As the area and age of the shrub- and grass-planting areas have increased, the conflict between water consumption by different types of vegetation planted and soil desiccation has become more evident (Lü et al., 2012; Wang et al., 2004, 2010, 2011). The loess hilly and gully region is the key area of soil and water conservation in the Loess Plateau and is home to millions of people (Fu et al., 2002; Wang and Shao, 2000). The soil in this area is loose with strong erodibility, and the landscape is the most fragmented and rugged of all of the areas in the Loess Plateau. The average amount of soil erosion in this region is >2000 t/(km^2 yr) and is even over 20,000 t/(km^2 yr) in the worst areas (Fu, 1989; Shi and Shao, 2000). The precipitation is concentrated in the summer and most of the intensity of the rainfall is strong and erosive. In this region, grasses and shrubs are the most common vegetation types, occupying more than half of the total area (Zhao and Running, 2010). Most commonly, the dominant species of natural restored grassland (from abandoned slope farmland) are forage grasses, and artificial shrubland restoration uses *Caragana korshinskii* (Wang et al., 2009b; Yao et al., 2012). Precipitation is the only source of soil water that can be used by plants in this area (Jiao et al., 2006; Ning et al., 2013; Yan et al., 2015; Yu et al., 2015b). Due to the close relationship between plant growth and soil water content (Wang et al. 2012), studies of soil water under typical vegetation types in this region have changed from focusing on water content to water movement and hydraulic characteristics (Lü et al., 2014a, b; Shao et al., 2006). Soil available water is the water that can be directly used by plants and is therefore a more useful indicator than volumetric water content, particularly in the context of vegetation growth (Fang et al., 2016; Gao et al., 2015; Wang et al., 2013). Soil available water greatly depends on soil texture and structure (Shao et al., 2006). Soil water content is unable to reach field capacity in the semi-arid Loess Plateau because the amount of evapotranspiration is larger than that of precipitation and the loose soil and deep ground water causes soil moisture infiltration into the deep layer. Texture is an important aspect of soil morphology that can impact the ability of the soil to conserve water as well as support root growth, and strongly influences soil hydraulic characteristics and erosion (Gui et al., 2010; Li et al., 2016; Meskini-Vishkaee et al., 2014; Nguyen et al., 2012). Research on the changes in soil water content and soil texture under different land-use types may reveal the relationships between these factors and long-term vegetation restoration in this erodible area.

The soil-water characteristic curve is important for estimating soil hydraulic parameters that are difficult to measure in the field, such as the wilting point. New techniques require specialized equipment, and the acquisition of undisturbed soil samples from deeper soil layers remains difficult on the Loess Plateau (Arya and Paris, 1981; Daly et al., 2015; Nimmo et al., 1987; Nimmo and Mello, 1991). To solve these issues, the estimation of soil hydraulic properties through inverse modeling has become popular, but it is also time- and resource-consuming (Hopmans and Simunek, 1999; Mirus et al., 2009; Vrugt et al., 2008). Many studies have focused on predicting parameters that are difficult to measure directly based on more easily quantifiable parameters (Carsel and Parrish, 1988; Meskini-Vishkaee et al., 2014; Schaap et al., 2001; Vereecken et al., 2010). The models used to generate soil-water characteristic curves can be divided into direct-fitting (Brooks and Corey, 1964; Campbell, 1974; van Genuchten, 1980) and indirect-calculation methods (Arya and Paris, 1981; Liu and Xu, 2003; Peng et al., 2014). Among the direct-fitting models, the van Genuchten model has been shown to provide good results for most soils in the loess hilly and gully regions of Loess Plateau (Lai and Wang, 2003; Wang et al., 2009a). Since the concept of fractal dimensions has been introduced to soil science with the development of the laser diffraction technique, soil fractal dimensions have received increasing attention (Kong and Song, 2015; Li et al., 2016; Peng et al., 2015). The volume-based fractal model has been proven to be ideal for evaluating and describing soil hydraulic properties as well as soil physical properties and potential (Jin et al., 2013; Montero, 2005; Posadas et al., 2001; Wang et al., 2011; Yang et al., 2008; Yu et al., 2015a).

Most of the research on the relationship between grass- and shrubland ecosystems at the plot and slope scales has been undertaken during normal years, whereas fewer studies have been conducted during drought years (Liu et al., 2007; Liu et al., 2016b; Wang et al., 2014; Yang et al., 2014a; Zhang et al., 2016a). Due to the stronger evapotranspiration on south-facing slopes, the soil water contents on such slopes are markedly lower than those on north-facing slopes; thus, south-facing slopes are more prone to water deficiency under the same precipitation conditions. In this context, studies of the soil water conditions and soil properties of south-facing slopes under different vegetation types during drought years can provide reference baselines for restoration under future climate change scenarios (Lü et al., 2015; Qiu et al., 2001). In this study, two shrubland slopes dominated by *Caragana korshinskii* and one grassland slope dominated by forage grasses, all of which are south-facing slopes, were chosen as study locations. The soil water content, soil-water characteristic curve, soil available water, soil particle-size distribution, and singular and multiple fractal dimensions of soil particle size were measured or calculated at different positions and depths along the slopes. This study aimed to (1) analyze the distribution of soil water content, soil particle size and relevant parameters along typical slopes of the Loess Plateau in a drought year and (2) analyze the relationship between soil particle dimension and the soil available water content to provide a case study of a semi-arid loess area for vegetation restoration management. The hypotheses of this study were as follows: (1) There are significant differences in the depth of water use between grassland and shrubland in a drought year and (2) the relationship between soil particle fractal dimension and the soil-water characteristic curve varies between types of vegetation restoration and among slope positions and soil layer depths.

2. Materials and methods

2.1. Site description

This study was conducted in Liuping Gully in the Ansai Catchment, Shaanxi, China, which is located along the upper reaches of the Yanhe River and belongs to the typical loess hilly gully region of the Loess Plateau. The longitude and latitude are 108°5′-109°26′E, 36°19′-36°32′N, and the area of the Liuping watershed is 24.26 km^2. The landscape is fragmented, and the gully density is high. The study site is located in a temperate semi-arid continental climate zone, and the spatial and