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Interaction of soil water storage dynamics and long-term natural vegetation succession on the Loess Plateau, China

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ABSTRACT

Soil water is a key terrestrial water resource, particularly in arid and semi-arid regions of the world such as the Loess Plateau of China. Information on the dynamics of soil moisture following vegetation restoration is essential for managing water resources and can be helpful for adjusting relevant government policies. To evaluate the response of soil water storage (SWS) to long-term natural vegetation succession (~160 a), we examined the soil moisture for different restoration ages in the Ziwuling forest region, which is located in the central part of the Loess Plateau. Our results showed that the SWS decreased with long-term natural vegetation restoration. The bulk density (BD), soil water content (SWC), and clay and silt content presented similar trends to those of the SWS throughout the entire vegetation succession. The SWS was significantly and positively correlated with the SWC and aeration porosity ($P < 0.05$). The SWC was lower in the upper soils (0–50 cm) than in the deeper soils (>50 cm) at every restoration stage, as was the SWS; however, the SWS in the 200–300 cm soil layer was the highest (164.61–212.80 mm) compared to other layers in all restoration stages. These results are expected to help improve the understanding of the response of deep soil water to long-term natural vegetation restoration and to provide insights into the dynamics of deep soil water influenced by vegetation.

1. Introduction

Vegetation succession can lead to the recovery of deteriorated soil properties (Jia et al., 2005; Zhao et al., 2010). To control soil erosion and ecosystem degradation, China's government has initiated several vegetation restoration projects on the Loess Plateau due to its infamous erosion (Deng et al., 2012); thus, a large area of agricultural land in the Loess Plateau has been converted into other uses during the past few decades. For example, farmland has been converted into grasslands, shrublands or forests with natural vegetation (Deng et al., 2014; Feng et al., 2013; Fu et al., 2006; Zhou et al., 2012). The study of recovery processes is of great significance, as it could deepen the understanding of the relationship between the succession of vegetation and the evolution of soil ecological function and provide recommendations for eco-environmental reconstruction or rehabilitation.

Soil water is a significant terrestrial water resource, particularly in arid and semi-arid regions of the world such as the Loess Plateau of China, where groundwater is buried below the thick unsaturated loessial soil (Tsunekawa et al., 2014) and concentrated precipitation is lost in the form of overland flow (Yang, 2001). The quantity of the soil–water resources depends to a large extent on soil depth. Water resources in deep soil profiles are relatively stable for vegetation growth due to the insulating effect of the upper soil (Wang et al., 2012b). Water resources may be used differently by the various vegetation types (forest, grassland, and crops) due to differences in the distribution of root systems, the characteristics of transpiration, and the amount of water taken up by roots (Wang et al., 2012b). Large spatial variation in deep soil water may thus be induced by consumption by vegetation (Yang et al., 2012a, 2012b). Additionally, Yang et al. (2014) reported that soil water decreases drastically after vegetation restoration, with no significant difference in near-surface soil moisture among the vegetation types but significant differences in the sub-surface and deep soil layers. Previous studies have mainly focused on soil water in the shallow layers, whereas soil water in deeper layers has largely been ignored due to the high costs of labor and time required for such investigation (Gao and Shao, 2012; Tombul, 2007; Wang et al., 2013; Zhu et al., 2009; Zhu, 2014. Therefore, water resources in deep soil profiles play an important role in ensuring a well-established vegetation cover in semi-arid regions, and understanding the response of deep soil water to vegetation restoration is essential for estimating the productivity and sustainability of semi-arid ecosystems.

The recovery of vegetation is very important in accelerating the amelioration of soil quality. Soil physical properties are usually recognized as important soil quality indicators (Boix-Fayos et al., 2001). Much research has been done recently on the influence of vegetation

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recovery or different land-use patterns on soil physical properties (Fu and Chen, 2000; Fu et al., 2003; Stolte et al., 2003). However, changes in soil physical properties are still under study during the long-term recovery of vegetation. Research into changes in soil physical properties is considered necessary for understanding the ecological consequences of vegetation recovery. In the semi-arid area of the Plateau, vegetation recovery or reconstruction is always limited by the shortage of water resources. Transformation of precipitation into soil water is also influenced by soil physical properties, such as bulk density, porosity, and hydraulic conductivity. There is little literature concerned with this particular issue, especially the long-term change of soil physical properties under natural restoration in the Plateau. Recently, Chinese scientists have increased the attention paid to the succession of secondary forests on the Loess Plateau (Cheng et al., 2012; Jia et al., 2005; Wang et al., 2010a; Zhao et al., 2010). While many studies have focused on changes in the aboveground vegetation of secondary forests in the central part of the Loess Plateau (Wang et al., 2010a; Zou et al., 2002) and soil carbon and nitrogen dynamics (Jia et al., 2005; Deng et al., 2013, 2014), few studies have focused on changes to soil water following long-term natural vegetation restoration, although studies have been done on soil water in other regions of the Loess Plateau (Chen et al., 2008; Jia and Shao, 2013). In addition, Cao et al. (2009) reported that the consequences of large-scale vegetation restoration have been associated with an increased severity in water shortages; therefore, information on the dynamics of soil water following long-term vegetation restoration is essential for managing water resources and would be helpful for adjusting relevant government policies.

In this study, we hypothesized that the soil water storage varied with long-term natural vegetation restoration ages throughout succession. In the Ziwuling forest region of the Loess Plateau, there is an intact series of naturally recovering vegetation succession. We chose this study area to provide a scientific foundation for constructing the eco-environment and rehabilitating the water storage and regulation capacity of the soil reservoir. Therefore, the specific objectives of the study were to investigate the following: (1) the dynamics of deep soil water storage with the succession of long-term natural vegetation restoration from grassland to forests, (2) the effects of natural vegetation succession on the soil water content, and (3) the soil factors affecting soil water storage.

2. Materials and methods

2.1. Study area

The study was conducted at the Lianjiabian Forest Farm of the Heshui General Forest Farm of Gansu (35°03′–36°37′ N, 108°10′–109°18′E, 1211–1453 m a.s.l.), covering a total area of 23,000 km^2 in the hinterland of the Loess Plateau in the Ziwuling forest region (Fig. 1). The area's annual temperature is 10 °C, annual rainfall is 587 mm, accumulative temperature is 2671 °C, and annual frost-free period is 112–140 days. The region's soils are largely loessial, having developed from primitive or secondary loess parent materials, which are evenly distributed at thicknesses of 50–130 m above red earth consisting of calcareous cinnamon soil (Jia et al., 2005). Soil pH ranges from 7.92 to 8.31. The area is covered in species-rich uniform forests with a forest canopy density ranging between 80% and 95% (Cheng et al., 2012). The natural biomes of the region are deciduous broadleaf forests, of which the climax vegetation is the *Quercus liaotungensis* Koidz. Throughout the region, *Populus davidiana* Dode and *Betula platyphylla* Suk communities dominate the pioneer forests; *Sophora davidii* (Franch.) Skeels, *Hippophae rhamnoides* (Linn.), *Rosa xanthina* Lindl and *Spiraea pubescens* Turcz are the main shrub species; and *Bothriochloa ischaemum* (Linn.) Keng, *Carex lanceolata* Boott, *Potentilla chinensis* (Ser) and *Stipa bungeana* Trin are the main herb species. Based on previous research in the study area, secondary forests naturally regenerated on abandoned land from grassland to shrubland and climax forest (*Q. liaotungensis*) over approximately 150 years (Wang et al., 2010a; Table 1).

2.2. Experiment design and soil sampling

A field survey was undertaken between July 15 and August 15, 2014. The sampling areas were determined according to the size of the communities. There were five 20 m × 20 m plots chosen in each forest community, five 5 m × 5 m plots in the shrub communities, and five 2 m × 2 m plots in the herbaceous communities. The largest relative elevation difference between two plots was less than 120 m. Most of the plots faced north and had a slope gradient of less than 20°. All the soils surveyed developed from the same parent materials and have had

Fig. 1. Location of the study site in the Loess Plateau.