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Soil moisture decline following the plantation of *Robinia pseudoacacia* forests: Evidence from the Loess Plateau

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ABSTRACT

Soil moisture is the foundation of ecosystem sustainability in arid and semi-arid regions, and the spatial–temporal details of soil moisture dynamics of afforested areas can benefit for land use management in water-shortage regions such as the Loess Plateau of China. In this study, spatial–temporal variations in soil moisture under *Robinia pseudoacacia* plantations on the Loess Plateau were analyzed. A total of 147 observations of soil moisture content (SMC) data to a depth of 500 cm soil profile were collected in 23 counties via field transect surveys and analyses of published literature. The results suggested that (1) the depth-averaged SMC was generally lower under forest sites than under cropland, both in the shallow layers and in the deep profiles. This finding implied that, compared with the native vegetation, the introduced *R. pseudoacacia* plantations caused intense reductions in soil moisture. (2) SMC was positively correlated with climatic factors (mean annual precipitation (MAP), mean annual temperature (MAT), and the Palmer drought severity index (PDSI)), indicating that the SMC under *R. pseudoacacia* plantations was highly consistent with the hydrothermal conditions at the regional scale. (3) The decreasing amplitude of SMC was linearly related to the increasing number of restoration years, especially in the areas below the 500–550 mm precipitation threshold. This finding showed that the restoration ageing sequence was an influential factor that affected the regional SMC variation in *R. pseudoacacia* plantations on the Loess Plateau. Our results suggest that afforestation activities should be avoided if the local total precipitation is insufficient for replenishing the soil moisture and that local tree species with a lower demand for water resources should be considered a top priority for further afforestation of the Loess Plateau.

1. Introduction

Soil moisture is an essential component in terrestrial ecosystems and plays a critical role in hydrological and ecological processes (Choi and Jacobs, 2007; Gao and Shao, 2012), including surface runoff generation, rainfall infiltration and migration, deep percolation, and soil and water conservation (Porporato et al., 2002; Ludwig et al., 2005; Collins and Bras, 2008). Because of its strong impact on the growth of vegetation, soil moisture shortage is one of the main constraints for vegetation restoration in arid and semi-arid ecosystems (Gao et al., 2013; Zhao et al., 2014), and by interacting with hydrological process, vegetation also strongly influences soil moisture balance (Porporato et al., 2002; Wang et al., 2010b; Gao et al., 2014). Thus, a comprehensive understanding of spatial–temporal variation in soil moisture on a regional scale is crucial for proper vegetation restoration and eco-hydrological management in water-limited regions.

The Loess Plateau is both an ecological transitional zone and an ecologically vulnerable area in northern China and is characterized as having an arid and semi-arid climate (Chen et al., 2008; Feng et al., 2016). The Loess Plateau is widely acknowledged as a region of intense soil erosion (Zhou et al., 2012) due to the specific natural environment of the plateau and long-term deforestation, the latter of which resulted from historical agricultural activities and recent improper exploitation (Liang et al., 2013; Zhao et al., 2013; Gao et al., 2016). The Chinese government launched large-scale afforestation campaigns on the Loess Plateau beginning in the 1950s in order to control soil erosion and

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restore vegetation in the region (Feng et al., 2012, 2016). Consequently, almost all of the sloping croplands on the Loess Plateau have been converted into forestlands and grasslands (Wang et al., 2013), and the vegetation of the region has experienced a significant recovery (Chen et al., 2015). Afforestation on the Loess Plateau has resulted in various ecological benefits, including carbon sequestration, soil erosion control, hydrological regime regulation, and increased ecosystem productivity (Deng et al., 2016; Feng et al., 2017; Jia et al., 2017). However, massive afforestation involving introduced species in water-shortage regions can result in the consumption of excessive water resources (Cao, 2008), which can subsequently lead to soil desiccation and forest growth decline (Cao, 2008, Feng et al., 2012).

Robinia pseudoacacia, an exotic species originating from North America (Sheng et al., 2017), has become the most important introduced tree species for afforestation on the Loess Plateau; the importance of this species is due to its high growth rate and strong ability to improve soil nutrient conditions via its N-fixing ability (Shangguan, 2007; Li et al., 2015; Qin et al., 2016). *R. pseudoacacia* covers > 70,000 ha (Qiu et al., 2010; Cao et al., 2017), accounting for > 90% of the revegetation areas on the Loess Plateau (Wei et al., 2009; Zhang et al., 2014b). *Robinia pseudoacacia* has a deep root system and high water consumption; as such, large-scale *R. pseudoacacia* plantations can exacerbate soil moisture reduction and ultimately cause soil desiccation and the formation of a permanently dry soil layer (Chen et al., 2007; Wu et al., 2015; Zhao et al., 2016). Because of their excessive consumption of soil moisture, *R. pseudoacacia* plantations usually present degraded growth signals, including low biomass accumulation and small tree diameters, during later restoration stages, and the trees of those plantations become “small old trees” that generate low ecologic and economic benefits (Wang et al., 2004; Chen et al., 2008; Deng et al., 2016). However, the current knowledge concerning the variation in soil moisture content (SMC) in *R. pseudoacacia* plantations on the Loess Plateau is mainly limited to plot and catchment scales; this knowledge is based on several sample sites (Jin et al., 2011). Related studies both at the regional scale and with enough sample sites are scarce but are necessary for the accurate assessment of spatial–temporal SMC variation in *R. pseudoacacia* plantations on the Loess Plateau.

In this study, we constructed a SMC database for *R. pseudoacacia* plantations on the Loess Plateau to analyze the spatial–temporal SMC variation at the regional scale. This database is based on 17 sample sites and data from 27 publicished sources; in total, 147 records of soil moisture for *R. pseudoacacia* plantations in the region were used. We proposed two hypotheses: (1) *R. pseudoacacia* plantations on the Loess Plateau caused severe shortages in SMC, and the degree of soil moisture deficit increased as the precipitation gradient increased; (2) As the number of restoration years increased, the soil moisture deficit in the *R. pseudoacacia* plantations increased, and this phenomenon worsened in dry areas with low precipitation.

2. Materials and methods

2.1. Study site description

This study was conducted across the Loess Plateau of China, which lies roughly between 100°54′-114°33′ E and 33°43′-41°16′ N and has a general elevation of 200–3000 m above sea level (Fig. 1). The Chinese Loess Plateau (CLP) is located in the upper and middle reaches of the Yellow River and covers an area of approximately 6.4×10^5 km^2; this area extends easterly to the Taihang Mountains, westerly to the Wuqiaoling-Riyue Mountains, southerly to the Qingling Mountains, and northerly to the Yinshan-Helan Mountains (Sun et al., 2014; Gao et al., 2017). The meteorological data from 68 metrological stations across the whole Loess Plateau indicates that the majority of the study area has either a sub-humid or semi-arid temperate continental monsoon climate; the mean annual temperature (MAT) gradient ranges from 14.3 °C in the southeastern region to 4.3 °C in the northwestern region (Yu et al., 2015). Across the same gradient, the mean annual precipitation (MAP) ranges from 750 mm to nearly less than 200 mm. The precipitation is seasonally and inter-annually uneven, and the majority of precipitation occurs during the rainy season (July to September) in the form of intense but short-duration storms (Lin and Liu, 2016).

The Loess Plateau is covered with highly erodible loess layers developed from wind-deposited loess parent material; the total depth of the layers generally ranges from 80 to 120 m (Liu, 1964; Tsunekawa et al., 2014). The surface soil types vary from clayey loess, typical loess, sandy loess, and eolian sand from the southeastern to the northwestern region (Liu, 1964). Across the same gradient, the vegetation types range from broad-leaf deciduous forest to forest steppe, typical steppe, desert steppe and ultimately desert (Feng et al., 2012; Jia et al., 2017).

2.2. Data preparation

To analyze the impact of afforestation on SMC variation and to study the SMC characteristics at different depths along the precipitation gradient, the SMC profiles of 0–500-cm deep soil layers under *R. pseudoacacia* plantations across the whole Loess Plateau were analyzed. The SMC profile data in our study were obtained using various methods. The data were acquired from a total of 147 sampling sites across the Loess Plateau via field transect surveys and analyses of published sources (Appendix dataset Table S1).

2.2.1. Transect observations

In our study, the space-for-time substitution method (Buyantuyev et al., 2012) was used to measure SMC variation within stand age (Jin et al., 2011; Wang et al., 2015). A transect consisting of 27 sampling points across the whole Loess Plateau was established; this transect extended in the northwest-southeast direction along the precipitation gradient.

In June 2015, 17 sampling sites were chosen for measuring the SMC under *R. pseudoacacia* plantations. Correspondingly, croplands near the sampling sites were chosen as control plots; those croplands were purely rain-fed and received no extra irrigation. Fortunately, no rainfall events occurred during the sampling periods, which eliminated the effects of individual precipitation events on SMC measurements (Jin et al., 2011; Wang et al., 2017). Soil samples to a depth of 500 cm were obtained in triplicate by a soil auger (5-cm diameter) at 20-cm intervals. The gravimetric SMC of the samples was subsequently measured using the oven-drying method (105 °C for 24 h). At the same time, undisturbed soil cores were excavated with metal cylinders (5-cm diameter, 5-cm length, and 100-cm^3 volume) near each sampling site to determine soil bulk density, field capacity, and other physical characteristics. The volumetric SMC was then transformed by multiplying the gravimetric SMC by the soil bulk density.

For our transect survey, *R. pseudoacacia* stand age was determined by using the tree-ring method and a Pressler increment borer as well as by interviewing local residents. Geographic elements such as longitude, latitude, and altitude were measured with a Garmin GPS device, and the slope gradient and aspect were determined with a compass.

2.2.2. Documented literature

The SMC profile data within the 0–500 cm soil layers under *R. pseudoacacia* plantations on the Loess Plateau were collected from published literature sources (1989–2017) available from the China National Knowledge Infrastructure (CNKI, available online: http://www.cnki.net) and the Web of Science (Thomson Reuters, New York, NY, USA) via keywords “soil moisture content”, “soil water content”, “Black locust”, “*Robinia pseudoacacia*”, and “Loess Plateau”. Since precipitation events can affect SMC profiles, especially for shallow layers, the SMC data retrieved from published sources were all measured before the rainy season or when rainfall did not occur during the sampling period on the upper slope. The raw data were either acquired from original tables or were extracted by digitizing graphs using Get Data