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Soil moisture decline due to afforestation across the Loess Plateau, China

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ABSTRACT

The Loess Plateau of China is a region with one of the most severe cases of soil erosion in the world. Since the 1950s, there has been afforestation measure to control soil erosion and improve ecosystem services on the plateau. However, the introduction of exotic tree species (e.g., *R. pseudoacacia*, *P. tabulaeformis* and *C. korshinskii*) and high-density planting has had a negative effect on soil moisture content (SMC) in the region. Any decrease in SMC could worsen soil water shortage in both the top and deep soil layers, further endangering the sustainability of the fragile ecosystem. This study analyzed the variations in SMC following the conversion of croplands into forests in the Loess Plateau. SMC data within the 5-m soil profile were collected at 50 sites in the plateau region via field survey, long-term *in-situ* observations and documented literature. The study showed that for the 50 sites, the depth-averaged SMC was much lower under forest than under cropland. Based on *in-situ* measurements of SMC in agricultural plots and *C. korshinskii* plots in 2004–2014, SMC in the 0–4 m soil profile in both plots declined significantly ($p < 0.01$) during the growing season. The rate of decline in SMC in various soil layers under *C. korshinskii* plots (-0.008 to $-0.016\ cm^3\ cm^{-3}\ yr^{-1}$) was much higher than those under agricultural plots (-0.004 to $-0.005\ cm^3\ cm^{-3}\ yr^{-1}$). This suggested that planting *C. korshinskii* intensified soil moisture decline in China's Loess Plateau. In the first 20–25 yr of growth, the depth-averaged SMC gradually decreased with stand age in *R. pseudoacacia* plantation, but SMC somehow recovered with increasing tree age over the 25-year period. Irrespectively, artificial forests consumed more deep soil moisture than cultivated crops in the study area, inducing soil desiccation and dry soil layer formation. Thus future afforestation should consider those species that use less water and require less thinning for sustainable soil conservation without compromising future water resources demands in the Loess Plateau.

1. Introduction

North China is facing an increasing water shortage (Wang et al., 2011a; Liu et al., 2015) that has translated into declining soil moisture content (SMC). As a vital component of the hydrologic cycle, soil moisture dynamics can be altered by various factors, including climate (e.g., precipitation, temperature, wind, etc.), soil (e.g., soil texture, organic matter, porosity, aggregation, bulk density, etc.), topography and land use/land cover characteristics. Afforestation is worldwide encouraged due to its various benefits (Malagnoux, 2007) including carbon sequestration (Feng et al., 2013; Deng et al., 2014), soil erosion control (Deng et al., 2012), sediment reduction (Moran et al., 2009; Wang et al., 2015a) and hydrological regime regulation (Yaseef et al., 2009). The conversion of agricultural lands into forest lands can affect SMC by increasing the time of plant cover and leaf area index (LAI), which in turn increases soil water consumption (Jian et al., 2015).

Planting of trees could reduce surface runoff (Huang et al., 2003; Huang and Zhang, 2004; Yi and Wang, 2013; Duan et al., 2016), enhance soil porosity and hydraulic conductivity, and thereby increase infiltration rate (Li and Shao, 2006; Ilstedt et al., 2007). For example, Farley et al. (2005) reported 44% reduction in mean annual runoff in humid regions in comparing forest and grassland plots using datasets for 26 catchments. Sun et al. (2006) showed that runoff reduction can exceed 50% after forestation in semi-humid and semi-arid regions of China. In addition, woody species could consume more soil water via evapotranspiration than natural grass and crops (Cao et al., 2009). The planting of forests could decrease SMC due to increased leaf interception and

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root water uptake (Wang et al., 2009, 2010, 2012a,b; Jian et al., 2015). If plant transpiration and soil evaporation exceed precipitation, the resulting loss in SMC could worsen soil water shortage (He et al., 2003; Yaseef et al., 2009).

It is reported that soils become extremely dry in both deep and shallow layers after planting trees (Yaseef et al., 2009; Wang et al., 2010; Jia and Shao, 2014). Chen et al. (2008) noted that excessive depletion of deep soil water by artificial forests and long-term shortage of rainwater cause drying up of soils and ecological degradation in semi-arid and semi-humid regions. Thus the balance between soil water supply and root water uptake is critical for the sustainability of ecosystem health (Issa et al., 2011), especially in water scarce arid regions. This implies that understanding the hydrologic effects of afforestation on soil moisture is important not only for water flux in the soil-plant-atmosphere continuum, but also for water cycle and eco-hydrological processes of the terrestrial ecosystem (Derak and Cortina, 2014).

The Loess Plateau is in the upper and middle reaches of the Yellow River, over an area of 64×10^4 km^2. It is considered the most severely eroded area in the world, where severe water loss and soil erosion have increased the fragility of the ecology (Shi and Shao, 2000). To mitigate soil erosion and improve ecosystem services in the region, trees and shrubs have been planted on the slope lands since the 1950s. A series of large afforestation campaigns, including the Grain-for-Green Program (GFGP) were initiated by the Chinese government at the end of the 1990s to reconvert croplands to forests, shrubs and grass (Cao et al., 2009), dramatically changing the landscape. Based on remote sensing images, vegetation cover in China's Loess Plateau has increased from 31.6% in 1999 to 59.6% in 2013 (Chen et al., 2015).

Large-scale afforestation operations such as the planting of black locust (*Robinia pseudoacacia* Linn.), Chinese pine (*Pinus tabulaeformis* Carr.) and korshinsk peashrub (*Caragana korshinskii* Kom.) are expected to change the water use and soil moisture dynamics by changing the dynamics of evapotranspiration, infiltration and surface runoff in the region. For instance, extensive afforestation has aggravated water scarcity, gradually causing the formation of dry soil layers in some areas in the Loess Plateau region (Wang et al., 2010, 2011b; Jia and Shao, 2014). Jin et al. (2011) showed under decreasing mean annual precipitation, afforestation can sequentially exert positive, negative and negligible effects on SMC. Despite recent research reports on variations in SMC under different forests or shrubs in the Loess Plateau (Jin et al., 2011; Wang et al., 2009, 2010; Yang et al., 2012; Jian et al., 2015), deep soil moisture assessments based on ground-truth observations remain essentially lacking. Furthermore, regional impact of afforestation on SMC is still poorly understood.

Recent studies show that agronomic use of fertilizers and rapid proliferation of water-consuming crops, particularly in the Yellow River Basin have intensified soil moisture decline in North China (Liu et al., 2015). With wide implementation of GFGP, however, it was hypothesized that the intensification of soil moisture decline due to afforestation was much higher than that due to agricultural production. Thus the specific objectives of this study were: (1) to investigate the spatial distribution of profile SMC in different watersheds in China's Loess Plateau region, and (2) to determine post-planting variations in SMC with stand age and different watersheds. The study determined the use of the interactive relationships between soil moisture and forest to support effective afforestation measures in China's Loess Plateau region.

To achieve the above objectives, SMC data were collected within the 5-m soil profile at 50 sites across the Loess Plateau through field survey, long-term *in-situ* observations and documented literature. First, SMC data from field survey and documented literature were used to determine the hydrological effects of afforestation on soil, including SMC variations with stand age. Next, unique long-term *in-situ* soil moisture profile observations in both agricultural and *C. korshinskii* plots in the northern zone of the plateau study area were used to evaluate observed soil drying and the role of intensified afforestation in soil moisture decline.

2. Materials and methods

2.1. Study area description

The study was conducted in the Loess Plateau of China which lies between latitude 33.72°N–41.27°N and longitude 100.90°E–114.55°E and at an elevation of 200–3000 m above mean sea level (Fig. 1). The plateau region has a continental monsoon climate with a mean annual precipitation ranging from 150 mm in the northwest to 800 mm in the southeast. About 55–78% of the precipitation falls in June through September, mostly as high intensity rainstorm. The mean annual temperature is 3.6 °C in the northwest and it increases to 14.3 °C in the southeast (1953–2013 data from 64 weather stations). Soil texture on the plateau is relatively uniform in space and time (Li and Shao, 2006), with loess soil as the most dominant (Guo et al., 1992).

From southeast to northwest, the vegetation changes from forest through forest steppe to typical steppe and then to desert steppe type. The native vegetation has mostly been cleared for crop production, causing severe soil erosion, land degradation and soil fertility loss. Since the 1950s, various government strategies have been used to remediate soil erosion and land desertification on the plateau. The most recent and most successful strategy (in terms of soil erosion control) is the GFGP, which involves reconverting croplands into forestland, shrub-land and grassland. The most common tree species in the restoration drive are *R. pseudoacacia*, *P. tabulaeformis* and *C. korshinskii*. Both *R. pseudoacacia* and *C. korshinskii* are exotic nitrogen-fixing tree species. These tree species are used because of their strong drought resistance, high survival rate, soil-nutrient improvement and fast growth rate (Li et al., 1996; Shan et al., 2003; Zheng and Shangguan, 2007; Jin et al., 2011).

2.2. Data collection

To determine the impact of afforestation on SMC change and to isolate the long-term effects of precipitation and/or temperature on soil moisture, SMC under croplands was analyzed in relation to that under artificial forests. Cropland fields in the study area not only have low evapotranspiration, but also marginal interannual SMC variability in deep soil layers (Wang et al., 2009). To optimize data representativeness, SMC data used in this study were collected from various sources (Fig. S1). The data were collected from a total of 50 sites across the Loess Plateau study area via field survey, long-term *in-situ* observations and documented literature (Fig. 1 and Table S1).

2.2.1. Field survey

To determine the interactions between afforestation and SMC, optimal research methods should be based on long-term monitoring of SMC. However, this type of monitoring is adieus and labor- and time-consuming. Thus a regional, short-term field experiment was conducted in 2014 growing season as an alternative. Also the use of spatial data for inferring temporal dynamics is a long tradition in ecological studies (Buyantuyev et al., 2012). This approach is commonly known as the space-for-time (SFT) substitution, where selected spatially separated sites based on either ecological or environmental gradients serve as proxies for predicting ecological time series such as vegetation succession (Fukami and Wardle,