



Soil water depletion patterns of artificial forest species and ages on the Loess Plateau (China)



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ABSTRACT

Afforestation as an effective measure to control soil erosion has achieved remarkable effects in northern China. However, large scale of artificial afforestation can increase soil water consumption and induce soil desiccation in arid and semi-arid areas. This study analyzed the variations of soil water storage following the conversion of croplands into forests with different species and stand ages on the Loess Plateau. Three most common artificial forests dominated by *Salix matsudana*, *Populus cathayana*, and *Sophora japonica* with stand ages of 5, 10, and 15 years were investigated to determine the variations in soil water storage. The results showed that soil water storage decreased with increasing afforestation ages and soil depth. *Salix matsudana* mainly consumed shallow soil water (0–100 cm), *P. cathayana* mainly consumed deep soil water (100–150 cm), while *S. japonica* had relatively lower water consumption than the other two species. Converting cropland into forest resulted in a significant water deficit. Soil water deficit in the 0–100 cm soil profiles was significantly higher under *S. matsudana* than under the other two artificial forests. Severe soil water depletion and obvious soil desiccation occurred after 12 years of afforestation. Therefore, artificial forests with less water consumption, e.g. *S. japonica*, should be given priority in future afforestation practice. To maintain the sustainability of vegetation, changes in land-use patterns should be considered after 12 years of afforestation.

1. Introduction

Afforestation has been implemented worldwide (IPCC, 2014) and received increasing attention because of its numerous benefits to ecosystems, such as carbon sequestration (Richter et al., 1999; Fang et al., 2001), desertification prevention (Wang et al., 2010), soil erosion and water loss control (Chirino et al., 2006; Fu et al., 2011), and biodiversity conservation (Elbakidze et al., 2011). However, large scale of artificial afforestation can increase soil water consumption, thus inducing soil desiccation in arid and semi-arid areas (Deng et al., 2016; Jia et al., 2017a).

Soil water is a crucial component of the hydrological process (Jia et al., 2017b). Biosphere-atmosphere interrelationships are mediated by soil water conditions in each ecosystem (Vivoni et al., 2008). To determine the distribution of soil water across global storage is one of the most essential tasks of hydrological sciences (McColl et al., 2017). Soil water plays an essential role in processes such as soil microbial

respiration (Yuste et al., 2007), streamflow (Koster et al., 2010), and biogeochemical cycles (Falloon et al., 2011). Characterizing the magnitude and dynamics of soil water across a range of spatial and temporal scales has important applications in both theory and practice, and can provide a fundamental guideline for optimal allocation of space for restoring lost vegetation (Deng et al., 2016). The temporal and spatial variations of soil water are influenced by many factors such as soil properties (Gwak and Kim, 2017), topography (Qiu et al., 2001), climate (D'Odorico and Porporato, 2004), and vegetation types (Zheng et al., 2015; Deng et al., 2016). Vegetation has an important influence on soil water content in arid and semi-arid regions (Chen et al., 2007). Vegetation can intercept precipitation and change its spatial distribution, thus mediating soil water (Vivoni et al., 2008). Such influence also varies with plant species and results in temporal variations in soil water. Therefore, quantifying the soil water content under different species across the temporal scale is important as it serves as a driver for many ecohydrological processes in arid and semi-arid regions.

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The Loess Plateau has experienced the most severe soil and water loss in the world, where serious soil erosion has aggravated the fragility of the ecosystem. In 1999, the 0665 Chinese government started to implement the “Grain-for-Green” program, which is a crucial countermeasure to reduce soil and water loss and increase vegetation coverage by converting croplands into forests or grasslands. The program has increased the vegetation cover from 31.6% in 1999 to 59.6% in 2013 on the Loess Plateau (Chen et al., 2015). Precipitation is the only water source to supplement soil water on the Loess Plateau. However, previous studies have shown that forests consume more water by evapotranspiration than other vegetation types, and the replenishment from precipitation is insufficient and soil water deficits frequently occur in the forests on the Loess Plateau (Jian et al., 2015; Deng et al., 2016; Jia et al., 2017a,b), indicating that converting croplands into forests can influence soil water content by increasing soil water consumption.

Forests can influence the water balances in ecosystems by their capacity to access, transport and transpire soil water, and the most direct way is by increasing leaf interception and root water uptake (Jian et al., 2015). It has been well demonstrated that soils become extremely dry in both the deep and shallow soil layers after afforestation in arid and semi-arid regions (Jia and Shao, 2014). Therefore, soil water availability is a key factor determining the success of large-scale afforestation in arid and semi-arid regions (Jiménez et al., 2017). Deng et al. (2016) found that afforestation resulted in severe depletion in soil water levels (as low as 9%) in the 0–100 cm soil profile, and the degree of depletion was mainly influenced by plant species. Jia et al. (2017a) analyzed the changes in soil water content after converting croplands into forests on the Loess Plateau, the results showed that soil water content in the 0–400 cm soil layer declined at a rate of 0.008 to $0.016 \text{ cm}^3 \text{ cm}^{-3} \text{ yr}^{-1}$ under *Caragana korshinskii* plantation. Chen et al. (2008) reported that severe depletion of deep soil water by afforestation and long-term shortage of precipitation triggered soil desiccation and ecological degradation in semi-arid regions. Although recent researches have reported that extensive afforestation has deteriorated water scarcity (Jia and Shao, 2014; Jian et al., 2015; Jia et al., 2017a), the characteristics of water consumption by several common species on the temporal scale remain poorly understood.

Historically, species such as willow (*Salix matsudana*), poplars (*Populus cathayana*) and locust (*Sophora japonica*), which grows fast, propagates and establishes easily, were used as the major plant species for afforestation and have been planted in large-scale afforestation on the Loess Plateau (Chen et al., 2015). Leaf area characteristics have significant effects on rainfall interception, and root characteristics determine the uptake of water by roots. The effects of these variations are mainly determined by plant species, and selection of suitable artificial forest species may reduce water consumption to acceptable levels. Thus, the specific objectives of this study were: (1) to quantify the soil water content under different species in arid and semi-arid regions, (2) to determine the post-planting temporal variations in soil water storage with stand age, and (3) to select optimal plant species for local soil water conditions in arid and semi-arid regions.

2. Materials and methods

2.1. Study site

The experiment was conducted in the Xiaqu town of Wenshui Country ($37^{\circ}15'N$ – $37^{\circ}35'N$, $111^{\circ}29'47''E$ – $112^{\circ}19'15''E$) in Shanxi Province, China. The study region is a typical area with loess geomorphology located in the eastern part of the Loess Plateau. It has a semi-arid temperate continental climate, and the altitude ranges from 739 m to 2169 m asl. The mean annual temperature is 10.1°C and the mean annual precipitation is approximately 457 mm, of which more than 60% occurs in July and August (Chang et al., 2016). The climate is characterized by a cold and dry winter and spring, and a rainy and hot summer. The soils in the study area are Loessial and Castanozems. The

annual maize or sorghum monoculture is the main cropping pattern (Pan et al., 2016). Dominant artificial forest species in this area include *Salix matsudana*, *Populus cathayana*, and *Sophora japonica*.

2.2. Experimental design and sampling

Three artificial forest species, i.e. *S. matsudana*, *P. cathayana*, and *S. japonica*, were planted on 2002, 2007, and 2012, respectively. Therefore, all forest sites were divided into nine treatments according to the differences in species and ages (5yr, 10 yr, and 15 yr) of the artificial forests. Three plots ($50 \text{ m} \times 20 \text{ m}$) were established in each site selected, and three quadrats ($10 \text{ m} \times 10 \text{ m}$) were chosen in each plot. In each quadrat, stand density (number of plants ha^{-1}) and breast-height diameter (cm) were measured. The cropland near the woodland was selected for study. The plots set for the cropland were $10 \text{ m} \times 5 \text{ m}$, and five quadrats ($1 \text{ m} \times 1 \text{ m}$) were randomly placed in each plot.

Soil water contents of the 0–400 cm soil profiles in each quadrat were measured at 10-cm intervals in September during the growing season in 2017. Gravimetric soil water content (SWC, %) was measured by taking soil samples with an auger of 40-mm internal diameter, with three sites randomly chosen for sampling at each quadrat. All samples were weighed in aluminum boxes and then oven-dried at 105°C to constant weight. Soil water content was calculated as the proportion of mass loss during oven-drying to the constant weight after drying. Soil bulk density of the 0–100 cm profiles was measured at 10-cm intervals using a cutting-ring of 5-cm diameter and 5-cm height. Three replicate samples were taken to estimate the average values. Field capacity (F_c , %) of the 0–100 cm soil profiles was measured by the cutting-ring method and calculated according to the following formula for soil water storage (SWS) for converting the unit from percentage to mm. Soil bulk density and field capacity of the 100–400 cm soil profiles were represented by the average values of the 50–100 cm soil profiles.

Soil water storage (SWS) was calculated as follows (Gao et al., 2014):

$$SWS = \sum_{i=10}^n D_i \times B_i \times SWC_i \times 10^{-1} \quad i = 10, 20, 30, \dots, 400$$

where SWS is the soil water storage of the 0–i cm soil profile (mm), D_i is the soil depth (cm), B_i is the soil bulk density (g cm^{-3}), and SWC_i is the gravimetric soil water content (%). Changes in soil water storage were expressed in terms of the differences between the cropland and woodland.

Soil water storage deficit degree (SWSD) was calculated as follows (Wang et al., 2004):

$$SWSD = \sum_{i=1}^n \frac{SWS_i - F_{c_i}}{F_{c_i}} \times 100\% \quad i = 10, 20, \dots, 400$$

where SWS_i is the soil water storage of the 0–i cm soil profile (mm), F_{c_i} is the field capacity (mm), and SWS for the depth of 0–400 cm were used in this study. The average SWS of each plot at time t and depth h , i.e. $\overline{SWS}_{t,h}$, was calculated as follows (Jia and Shao, 2014):

$$\overline{SWS}_{t,h} = \frac{1}{N_i} \sum_{i=1}^{N_i} SES_{i,t,h}$$

where $SWS_{i,t,h}$ is the soil water storage at plot i , depth h , and time t , and N_i is the number of measurements at each plot.

2.3. Statistical analyses

Two-way ANOVA followed by the Tukey's HSD test was used to analyze the differences in the changes of water storage and SWSD among different species. Linear regression analysis was performed to determine the relationships between soil water storage and stand age. Significant differences were evaluated at the 0.05 probability level. All data are presented as means \pm standard errors of means. All statistical

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