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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 inter-annual 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,

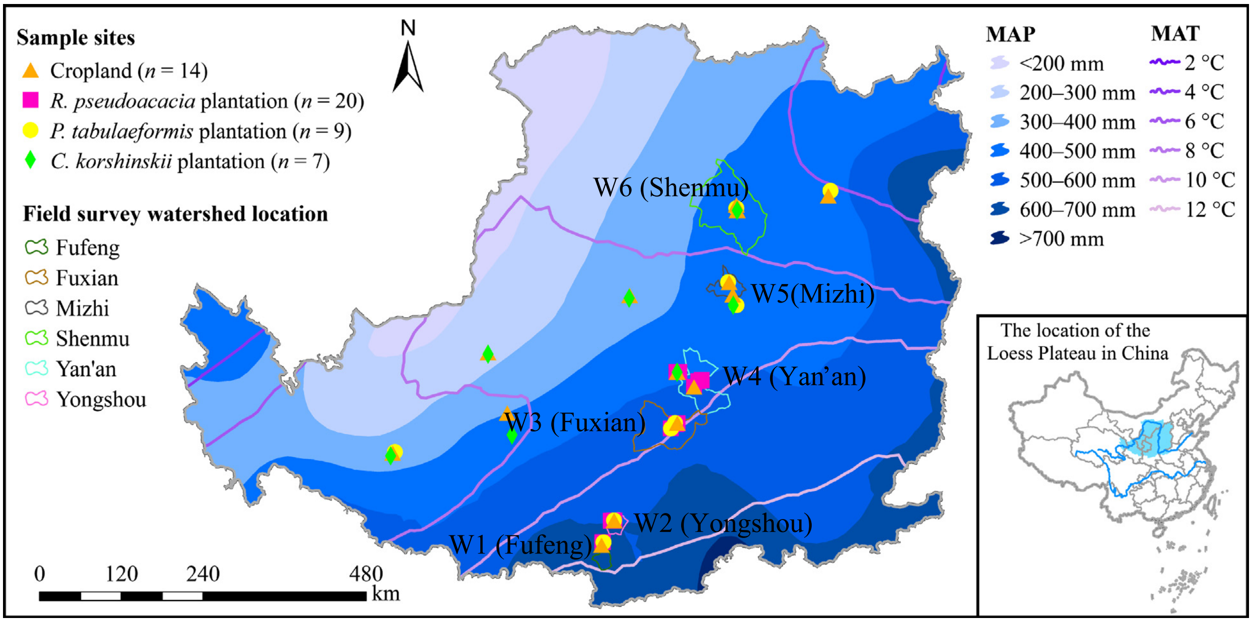

Fig. 1. Map of the study area in the Loess Plateau in Northern China depicting spatial distributions of mean annual precipitation (MAP) and mean annual temperature (MAT). A total of 50 sites were selected. The labels W1-W6 are the six field-surveyed watersheds in the southern (W1 and W2), central (W3 and W4) and northern (W5 and W6) regions of the study area, respectively.

2005), carbon and nitrogen dynamics (Jia et al., 2012) and SMC variations with stand age (Jin et al., 2011; Wang et al., 2015b). The SFT approach was therefore used to select different sampling sites with various stand ages to fill gaps in scarce regional SMC time series. In this study, the selected sampling sites in small watersheds were relatively homogeneous fields with similar slope gradients, elevations and parent materials, making them comparable in terms of topographical conditions. Although individual rainfall events can significantly influence SMC measurements in the short-term, there was no rainfall throughout the sampling period. Thus SMC measurements at the different sites were good for comparative analyses.

At regional scale, 27 sites were selected in six watersheds, spanning a distance of *ca.* 800 km from south to north of the Loess Plateau (Fig. 1). The range of annual precipitation at the sampling sites was 400–612 mm (1953–2013 data from 64 weather stations). As only one or two *P. tabulaeformis* plantation sites were in the selected watersheds, it was impossible to conduct time-series analysis of SMC for this vegetation type. A total of 20 sites in four watersheds (W1 in Fufeng, W2 in Yongshou, W3 in Fuxian and W4 in Yan'an) were used in time-series analysis of SMC variations in watersheds under *R. pseudoacacia* plantation. As in Fig. 1, sites W1 and W2 were in the southern zone of the Loess Plateau, which was the wettest and warmest region of the study area. The landscape at W1 and W2 was a typical plateau topography that was relatively flat compared with the northern Loess Plateau region. The sites W3 and W4 were in a typical loess hilly-gully region of the Loess Plateau. Further details on the selected watersheds and sampling sites are given in Tables S1 and S2.

R. pseudoacacia and *P. tabulaeformis* stand ages were determined via the tree-ring method using Pressler increment borer. An RTK-GPS receiver (5 m location precision) was used to determine the latitude, longitude and elevation of each site, while site slopes and aspects were determined using a compass. In the field measurements, three 10 m × 10 m quadrants were established at each site and one 2 m × 2 m sub-quadrant was chosen within each 10 m × 10 m quadrant. In each of the three 10 m × 10 m quadrants, stand density (plants/ha), canopy density (percent area under tree canopy), average tree height and breast-height diameter (DBH) were recorded. For each of the 2 m × 2 m sub-quadrants, understory cover (percent grass/shrub cover) was recorded and volumetric SMC measured with a calibrated neutron probe (Jia et al., 2015) to the depth of 500 cm at 20 cm intervals.

2.2.2. Long-term observations

To monitor the temporal patterns of SMC under *C. korshinskii* plantation in the northern Loess Plateau, permanent plots were established for continuous profile SMC measurements in Liudaogou watershed in Shenmu County, Shaanxi Province. The Liudaogou watershed is characterized by deep gullies and undulating slopes. This area is also peculiar for its unique landforms shaped by severe soil erosion. It belongs to the mild-temperate and semi-arid zone with mean annual temperature of 8.4 °C and mean annual precipitation of 430 mm (1970–2014 data from local weather station) (Table S1).

A plot (61 m × 5 m) was established in 2003 in each of the four land use zones (cropland, shrub-land, artificial grassland and fallow-land for natural vegetation recovery) on a uniform slope (12°) facing the northwest. The agricultural plot consisted of two typical crops (soybean or millet) cultivated in rotation. Fertilizer was applied to the soybean or millet at a rate of 120 kg ha^{-1} N and 60 kg ha^{-1} P_2O_5 per annum as recommended by the local agricultural service. A total of 11 aluminum neutron-probe access tubes (each 420 cm in length) were installed at 5 m intervals along the midline of each plot. Volumetric SMC was measured to the depth of 400 cm at 20 cm intervals using calibrated neutron probe (Liu and Shao, 2016). The main focus of the study was on the hydrological effect of afforestation on the soil, including profile SMC under *C. korshinskii* and cropland fields. There were a total of 81 sampling events in 2004–2014, which data were used to analyze the temporal variations in SMC after planting of the forest trees. Further details on the experimental plots and SMC measurements are documented by Liu and Shao (2014).

2.2.3. Documented literature

The profile SMC data were also extracted from published works (Li et al., 2008; Wang et al., 2008, 2009, 2012b; Zou et al., 2011; Yang et al., 2012; Zhang et al., 2014a,b) on the 0–5 m soil layer under croplands and artificial forests in the Loess Plateau. In all the cases, SMC was measured using the oven-drying method. For the data to be fit for comparison with SMC data collected by other methods, the gravimetric SMC was converted into volumetric SMC as follows:

$$\theta_v = \theta_m \times (\rho_b/\rho_w) \tag{1}$$

where θ_v is volumetric SMC; θ_m is gravimetric SMC; ρ_b is soil bulk density; and ρ_w is water density. Based on this method, 8 data sites were used to analyze the hydrological effect of afforestation on soil in the study area. Further details on the selected sites are available in Table S1.

2.3. Statistical analyses

Statistical analyses were performed using the SPSS statistical package version 17.0 (SPSS 17.0; SPSS Inc., Chicago, IL, USA). The profile SMC data were analyzed for mean and standard deviations for various soil depths at each site ($n = 3$). The one-way analysis of variance (ANOVA) was used to compare mean SMC with different stand ages in a watershed. This was followed by post hoc multiple comparisons using the least significant difference (LSD) at $p < 0.05$.

3. Results

3.1. Distribution of watershed profile SMC

SMC data collected in afforested and cropland fields, long-term *in-situ* observations and documented literature were used to determine variations in soil moisture after afforestation in the Loess Plateau. Figs. 2 and 3 plot the vertical distributions of volumetric SMC in the 5-m soil profile at 28 surveyed sites in six watersheds (W1-W6, see Fig. 1) in the Loess Plateau study area. Generally, cropland fields had higher SMC than afforested fields under *R. pseudoacacia* or *P. tabulaeformis* on the plateau. Large differences also existed

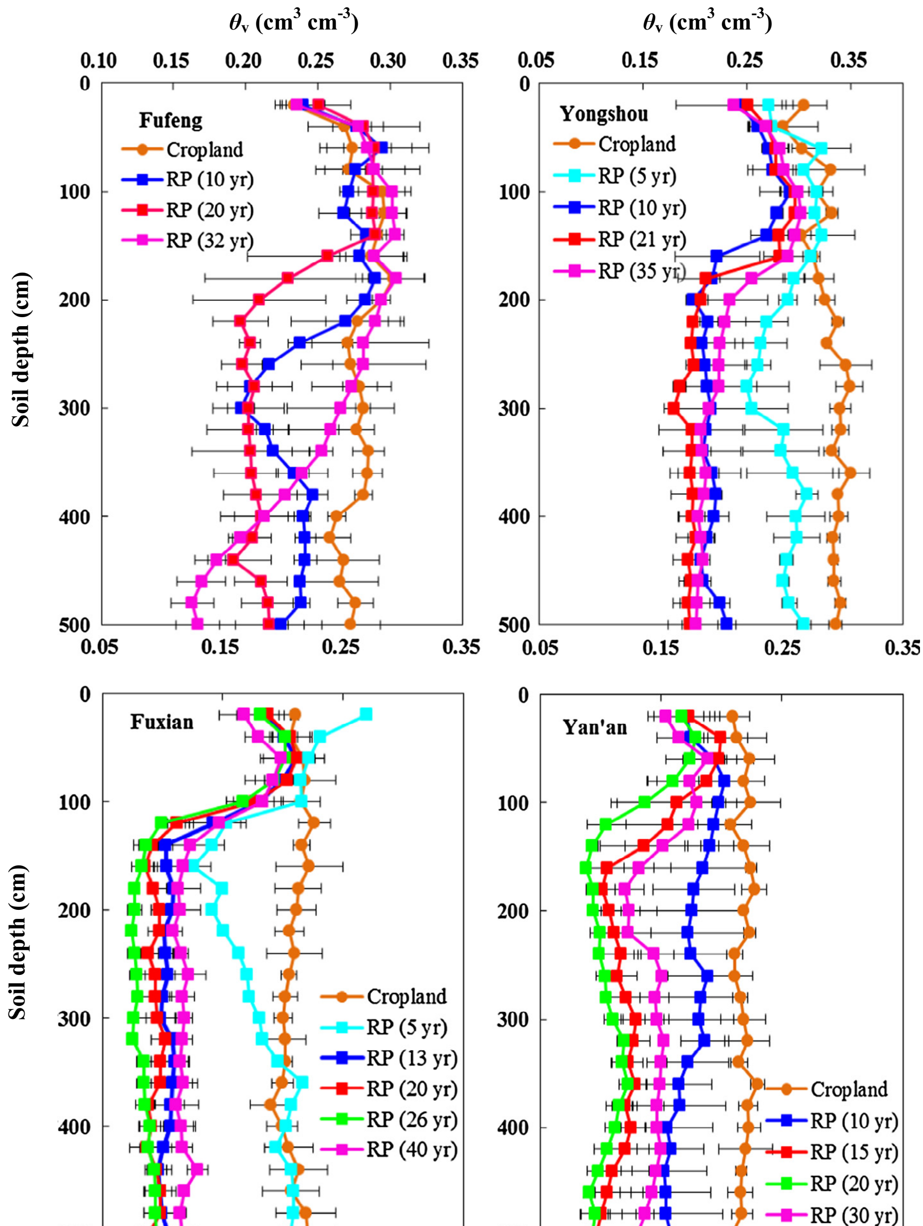

Fig. 2. Volumetric soil moisture (θ_v) profiles for cropland and *R. pseudoacacia* (RP) plantations in Fufeng, Yongshou, Fuxian and Yan'an in the study area. The bars denote the standard deviation of the mean ($n = 3$). In the legends, the numbers in the parentheses below cropland in Fufeng, Yongshou, Fuxian and Yan'an denote stand age.

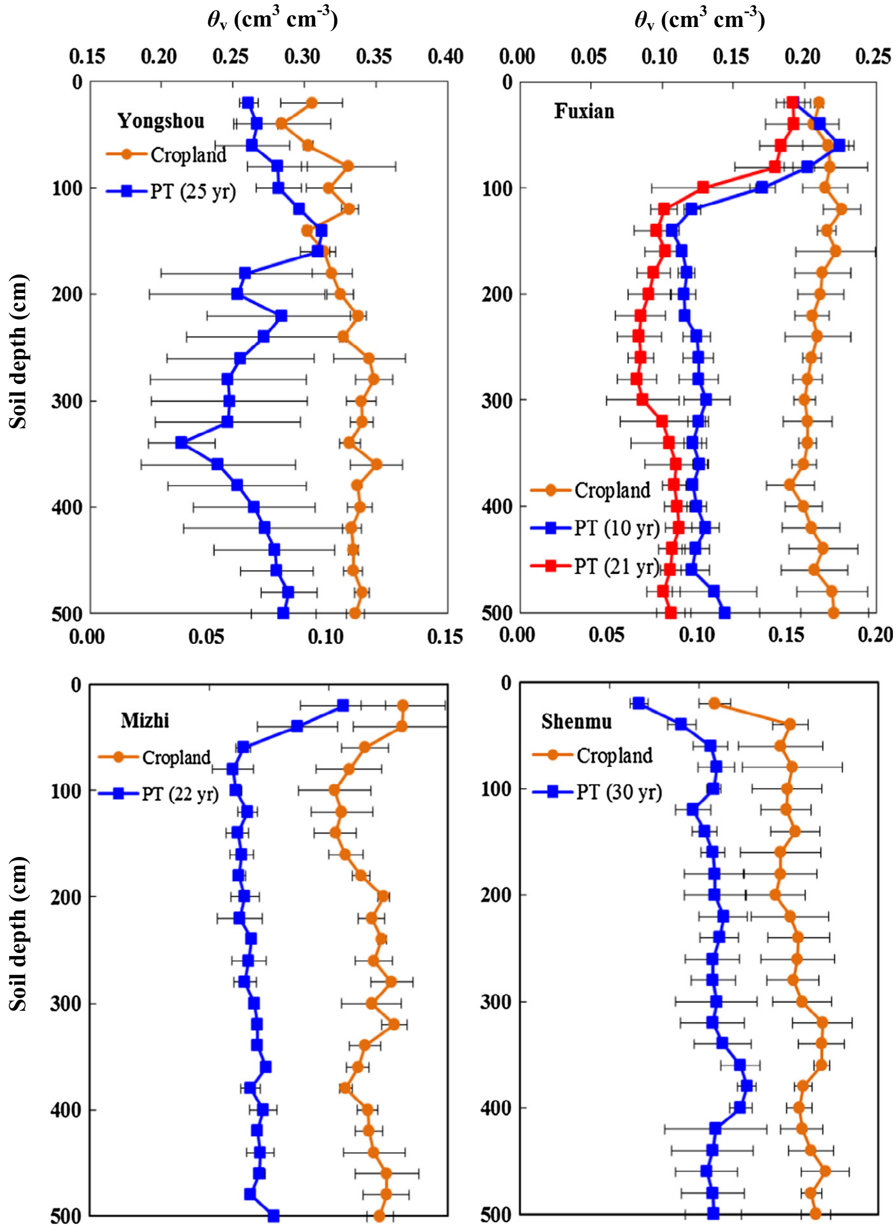

Fig. 3. Volumetric soil moisture (θ_v) profiles for cropland and *P. tabulaeformis* (PT) plantations in Yongshou, Fuxian, Mizhi and Shenmu of the study area. The bars denote the standard deviation of the mean ($n = 3$). In the legends, the numbers in the parentheses below cropland in Yongshou, Fuxian, Mizhi and Shenmu denote stand age.

between the six watersheds in terms of profile SMC. Average SMC was highest for W1 (Fufeng, with MAP of 612 mm) and W2 (Yongshou, with MAP of 601 mm) due to the high precipitation (Table S1). Furthermore, the relatively high soil clay content and soil field capacity in W1 and W2 suggested that soil water-holding capacity and SMC were high (Jia et al., 2015).

For afforested fields with *R. pseudoacacia* in W1-W4, SMC was relatively constant with increasing soil depth in the 140–500 cm soil layer. The only exceptions were the W1 site with 30-year-old trees and in W2 and W3 sites with 5-year-old trees (Fig. 2). For W2 and W3 sites with the youngest trees (5-year-old trees), SMC increased with increasing depth in the 140–500 cm soil profile due to low root concentration in this layer. For W1 site with 30-year-old trees, however, SMC in the 140–500 cm soil profile decreased with increasing soil depth. For W2, W3, W5 and W6 sites with afforested *P. tabulaeformis* fields, SMC was lower than in cropland fields and varied marginally across the entire soil profile, except for the shallow layer.

Compared with croplands, SMC data from documented literature suggested a large decline in soil moisture after planting *P. tabulaeformis* or *C. korshinskii* (Fig. 4). The depth-averaged SMC generally decreased by 18.2–45.6% and 33.6–59.9% after planting *P. tabulaeformis* and *C. korshinskii*, respectively. The differences in magnitude for the same tree species was attributed to differences in stand age, plant density, microclimatic conditions, soil properties and/or topography across the various locations (Shaxson and Barber, 2003). This was another evidence that SMC declined after the conversion of agricultural lands into forests in the Loess Plateau of China.

3.2. Soil moisture variation with afforestation age under R. pseudoacacia

As in Fig. 5, SMC in the study area varied with stand age. Across the six watersheds, the depth-averaged SMC was high for cropland fields (counted as 1-year-old stand in this study). For W1, W2, W3,

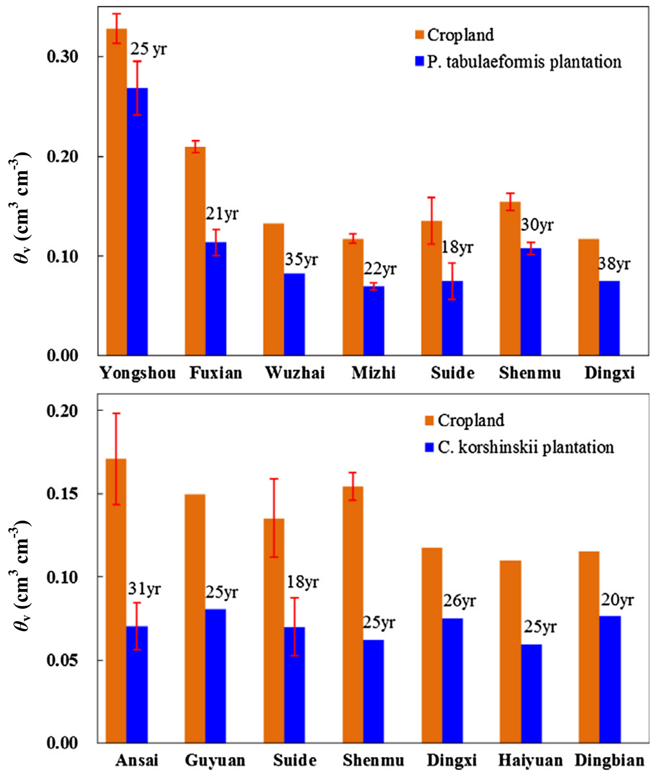

Fig. 4. Average depth of volumetric soil moisture (θ_v) under cropland, artificial *P. tabulaeformis* and *C. korshinskii* plantations in the Loess Plateau in Northern China. The bars denote the standard deviation of the mean ($n = 3$) and the numbers above the columns are the stand ages.

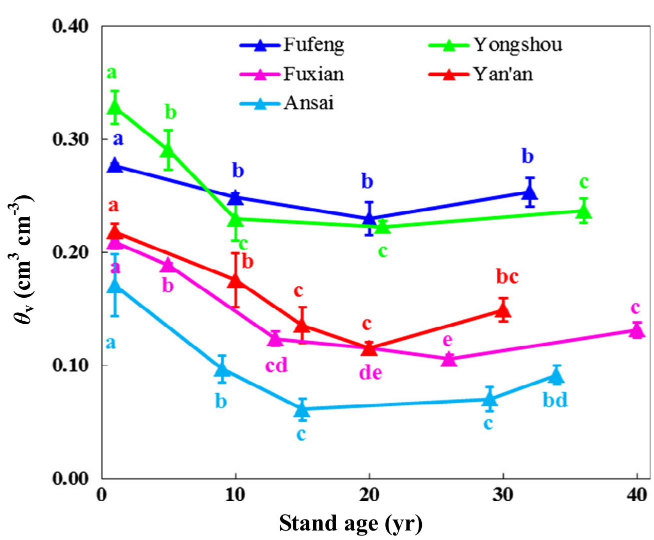

Fig. 5. Volumetric soil moisture (θ_v) versus stand age under *R. pseudoacacia* plantations for the different sampling sites in the Loess Plateau in Northern China. The bars denote the standard deviation of the mean ($n = 3$). Significant differences in depth-averaged θ_v between stand age at each measurement site is labelled with different lowercase letters ($p < 0.05$).

W4 and W7 (regions in Ansai County and data from literature), the depth-averaged SMC variations were similar in trend; initially decreasing and then slightly increasing with increasing stand age. For example, SMC decreased significantly from 0.277 to 0.249 and then to 0.229 $cm^3\ cm^{-3}$ in W1 for corresponding increase in stand age from 1 to 10 and then to 20 yr. As stand age increased from 20 to 32 yr, SMC increased marginally from 0.229 to 0.253 $cm^3\ cm^{-3}$ that was statistically not significant (Fig. 5). Although SMC in W7 was considerably low (0.061–0.171 $cm^3\ cm^{-3}$), it also changed with stand age. The average SMC for forestlands was 0.079 $cm^3\ cm^{-3}$, close to permanent wilting point (Wang et al., 2012b). The SMC decreased significantly (from 0.171 to 0.097 and then to 0.061$cm^3\ cm^{-3}$) for corresponding increase in stand age (from 1 to 9 and then to 15 yr). However, it significantly increased from 0.061 to 0.092 $cm^3\ cm^{-3}$ as stand age increased from 15 to 34 yr (Fig. 5).

3.3. Long-term variations in SMC under C. korshinskii

Long-term *in-situ* SMC measurements under *C. korshinskii* in Shenmu County showed a significant decline in soil moisture (Fig. 6). In Liudaogou watershed (W6) in Shenmu County, soil moisture under *C. korshinskii* and cropland was monitored 1–2 times per month using neutron probe (generally in April to October 2004–2014). Throughout the period, the depth-averaged SMC under both cropland and *C. korshinskii* decreased significantly during the growing season. There was significant ($p < 0.01$) trend in θ_v ($-0.008\ cm^3\ cm^{-3}\ yr^{-1}$) for the 0–1 m soil depth under *C. korshinskii*. The fitted θ_v curve for the 0–1 m soil layer decreased by ~50.8% from 0.183 $cm^3\ cm^{-3}$ in 2004 to 0.090 $cm^3\ cm^{-3}$ in 2014. SMC for the 1–2 m soil depth under *C. korshinskii* also significantly decreased (at the rate of $-0.016\ cm^3\ cm^{-3}\ yr^{-1}$) in 2004–2011. Although SMC slightly increased in 2011–2014 due to precipitation recharge, it was still lower than that for croplands. Consistent with the changes in SMC in the 0–2 m soil layer, the trend in θ_v of -0.014 and $-0.013\ cm^3\ cm^{-3}\ yr^{-1}$ were respectively significant ($p < 0.01$) for the 2–3 and 3–4 m soil layers under *C. korshinskii* plantation in 2004–2012. However, the depth-averaged SMC was constant (0.086 $cm^3\ cm^{-3}$) for the period 2012–2014. This suggested that soil moisture below 0.086 $cm^3\ cm^{-3}$ was not available for uptake by *C. korshinskii*.

There were also significant ($p < 0.01$) trends in θ_v (-0.004, -0.005, -0.005 and $-0.004\ cm^3\ cm^{-3}\ yr^{-1}$ for the 0–1, 1–2, 2–3 and 3–4 m soil depths, respectively) under cropland. This suggested that the fitted θ_v curve for each of the soil layers decreased in the range of -20.7 and -27.4% (Fig. 6). The rate of SMC decline under cropland was much lower than that under *C. korshinskii*. This suggested further intensification of soil moisture decline in afforested fields, compared with agricultural fields on the northern Loess Plateau. Since no significant differences existed between cropland and *C. korshinskii* fields in terms of soil texture, topography and microclimatic conditions, the differences in volumetric profile SMC were attributed to afforestation activities in the region.

4. Discussions

4.1. Negative effects of afforestation on SMC

Soil conservation, measured as the decline in soil erosion, has been achieved after nearly 60 years of sustained afforestation efforts in China's Loess Plateau. Since the early 1950s, afforestation of slope lands has been used to control soil erosion and other forms of environmental degradation in the Loess Plateau. With the implementation of various restoration programs, annual runoff in the Yellow River has dropped over the century. This was particularly the case since the late 1960s (Chen et al., 2015; Wang et al., 2015a), largely attributed to human activities such as GFGP and construction of dams, reservoirs, terraces and other conservation structures. Lü et al. (2012) noted a decreasing runoff of 10.3 mm yr^{-1} in the period 2002–2008 in the Loess Plateau. After analysis of the variations in vegetation cover, water yield and sediment concentration in 12 main sub-catchments in the region of

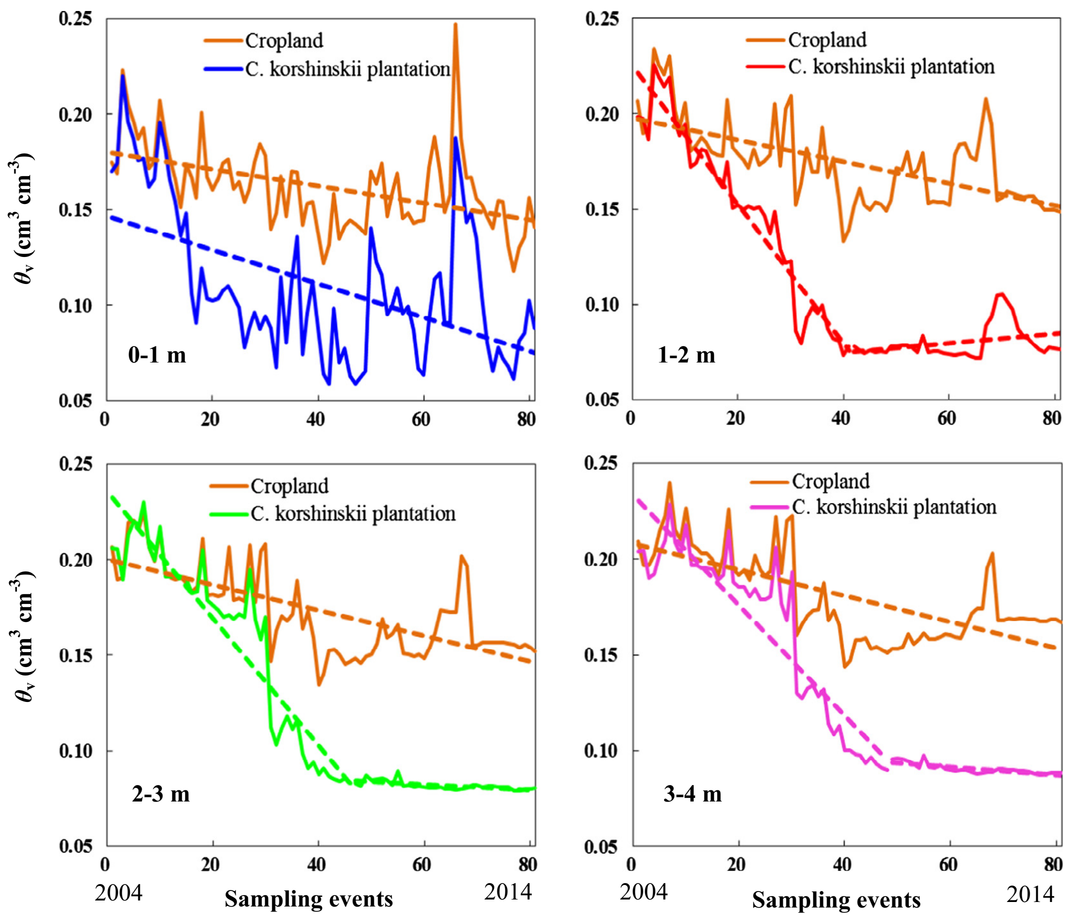

Fig. 6. Average volumetric soil moisture (θ_v) curve for the 0–1, 1–2, 2–3 and 3–4 m soil depths under cropland and *C. korshinskii* plantations in 2004–2014 in Shenmu County in the northern region of the Loess Plateau.

the Loess Plateau in the Yellow River Basin using remote sensing data for 1998–2010, Wang et al. (2015a) observed 26% decline in water yield and 21% decline in sediment concentration; attributed to the massive afforestation in the region.

Although the effects of vegetation restoration on soil erosion and water yield in the Loess Plateau have been investigated in recent years (Feng et al., 2012; Lü et al., 2012; Wang et al., 2015a), only few studies have actually analyzed hydrological effect of afforestation on soils, particularly that on deep soil layer in the Loess Plateau (Jin et al., 2011; Yang et al., 2012; Wang et al., 2013; Jian et al., 2015). This study showed that the conversion of agricultural land into forests caused soil moisture decline in deep soil layer across the plateau. This finding supports the results of previous studies (Wang et al., 2010; Jia and Shao, 2014; Jian et al., 2015) where dry soil layers were noted under *R. pseudoacacia*, *P. tabulaeformis* and *C. korshinskii* plantations in the Loess Plateau. For example, Yang et al. (2012) observed 35% decrease in deep SMC due to the conversion of cropland into shrub-land and forestland, causing an apparent soil moisture deficit. Jian et al. (2015) showed that the amount of soil water storage consistently decreased within a 1-m depth in *R. pseudoacacia*, *P. tabulaeformis* and *C. korshinskii* fields during growing season. This was because the planted shrubs and forests in the region had higher evapotranspiration than precipitation recharge (Cheng et al., 2005; Zhao and Li, 2007; Jian et al., 2015).

The three tree species (*R. pseudoacacia*, *P. tabulaeformis* and *C. korshinskii*) investigated in this study deep-rooted and therefore had high evapotranspiration due to the consumption of large amounts of water from deep soil layers (Wang et al., 2010; Jia et al., 2013; Zhang et al., 2014a,b; Jian et al., 2015). By analysis of spatial distributions of main and lateral roots of *R. pseudoacacia* in Yan'an, Ma et al. (1990) observed deep penetration of lateral roots (>7 m). Based on the dynamics of profile SMC and vertical distribution of roots, it was concluded that the depth of extraction of soil moisture by *R. pseudoacacia* was >7 m. As reported by Wang et al. (2009), the depth of depleted soil moisture under *C. korshinskii* and *R. pseudoacacia* in the Loess Plateau could reach 22.4 and 21.5 m, respectively.

In-situ SMC measurements in north Loess Plateau region showed a significant decline in soil moisture under cropland (Fig. 6). This was consistent with the work of Liu et al. (2015) where volumetric water content of the 0–50 cm topsoil layer in north China under dryland crop dropped significantly in the last three decades, particularly so in the Yellow River Basin. The decrease in SMC was attributed mainly to the decline in annual precipitation. During the monitoring period 2004–2014, total precipitation in 2005–2006 and 2009–2011 was consistently lower than mean value (Liu and Shao, 2016). Besides, the continuous application of chemical fertilizers favored biomass growth of crops or weeds, which in turn increased transpiration rates and reduced SMC. Compared with croplands, however, *C. korshinskii* fields in the northern Loess Plateau region have higher rates of SMC decline due to stronger soil water uptake. This implied that *C. korshinskii* requires more water than cultivated crops, especially deep soil water. Furthermore, the 1–4 m depth-averaged SMC was considerably lower and temporally less variable (i.e., below the minimum extractible soil moisture by *C. korshinskii*) after 8 years of growth (Fig. 6). Thus soil water use by *C. korshinskii* induced desiccation of the deep soil layer (>1 m) after 8 years of growth, thereby reducing available soil moisture. This observation was consistent with that report by Wang et al. (2004) that lands in the Loess Plateau under exotic species induced soil desiccation. It was therefore concluded that soil moisture decline in the Loess Plateau was driven more by afforestation than crop cultivations. Furthermore, the rapid proliferation of exotic tree species has led to the depletion of available soil water and deep soil layer drying in the region.

The limited precipitation is the sole source of soil moisture as groundwater levels in the Loess Plateau are generally 30–100 m below the land surface. The precipitation is unevenly distributed along the year and mostly occurs in summer. Although the planted forests reduced surface runoff or increased infiltration rate and soil water-holding capacity, high soil moisture loss due to transpiration (particularly exotic plant species and high-density planting fields) caused an imbalance in soil water availability and utilization by trees. Due to the imbalance in the water budget, dry soil layers have developed on the Loess Plateau (Wang et al., 2004, 2009, 2010, 2011b), in turn threatening the health of the ecosystem due to degeneration of the vegetation cover. The Loess Plateau is known for "small old trees" due to high soil drought, where some 30-year-old forest trees grow only to about 20% of their normal height. In Mizhi and Shenmu Counties with low SMC, for example, the heights of 22-year-old and 30-year-old *P. tabulaeformis* were only 5.1 and 3.5 m, respectively. Then in Yongshou County with a relatively high SMC, the height of 25-year-old *P. tabulaeformis* was 17.0 m (Table S2).

4.2. SMC variations with stand age under R. pseudoacacia

Notably, stand densities in the 5-year-old and/or 10-year-old *R. pseudoacacia* plantations were high but decreased with increasing age (Jin et al., 2011). Intense competition for limited soil moisture in the stand population (i.e., natural-thinning) and soil drying due to high soil water consumption by the trees influenced *R. pseudoacacia* stand density in the Loess Plateau (Jin et al., 2011). Canopy density, however, was constant, but high in young stands that generally decreased after 20 years of growth (Table S2). The trend in canopy density was the reverse of that in soil moisture, suggesting that a close interaction existed between soil moisture and vegetation. As SMC under *R. pseudoacacia* varied with stand age (Fig. 5), it was grouped under two periods—drying period and recovering period. During drying period, depth-averaged SMC decreased with increasing age due to high moisture use by plants. Although stand density gradually decreased, both the increase in single-tree transpiration and understory evapotranspiration still caused an imbalance in soil water supply and soil water use by plants (Gebhardt et al., 2014; Sun et al., 2014). Thus exotic plant species such as *R. pseudoacacia* induced desiccation of the soil. Severe soil desiccation in turn hindered *R. pseudoacacia* growth or even caused vegetation degeneration. This was evident in the death of tree branches and the development of *R. pseudoacacia* rampikes or dwarfs after 20 years of growth (Jin et al., 2011; Wang et al., 2011b). *R. pseudoacacia* height initially increased with stand age in 5–26-year-old stands and then decreased in 26–40-year-old stands in Fuxian County (Table S2). The decrease in height was attributed to branch death due to soil drought. Because of soil drought, stand density and/or canopy density decreased to new lows, thereby decreasing tree transpiration. Analysis showed that the LAI of *R. pseudoacacia* in Fufeng County significantly decreased within 20–30 years after planting (data not shown). This, in addition to the low interception and high soil water-holding capacity and water retention after 20 years of growth, resulted in the recovery of the profile SMC. It suggested that the imbalance in soil water availability and soil water use by plants apparently weakened.

4.3. Implications for future afforestation activities

It is important to note the limitations of this study due mainly to the scarcity data (long-term continuous SMC data) and the inability to quantify potential soil moisture recovery. Irrespectively, the use of *R. pseudoacacia*, *P. tabulaeformis* and *C. korshinskii* afforestation has caused soil moisture decline, compared with crops in agricultural fields on the Loess Plateau. Soil water shortage was increasingly obvious in the Loess Plateau due to the inappropriate afforestation and/or management of tree plants. The introduction of exotic tree species and high-density planting further intensified soil water depletion in the region (Wang et al., 2009, 2010; Jin et al., 2011). Dry soil layers have now developed in some areas of the Loess Plateau, with negative effects on tree growth. This in turn threatened ecosystem health and services such as carbon sequestration, soil/water conservation, etc. The current trends in afforestation coupled with inappropriate forest management practices have resulted in an excessive exploitation of deep soil water and a severe degeneration of vegetation. The Chinese government planned to expand forests by $\sim$220,000 km^2 by 2030. For sustainable ecological construction, there was the need to pursue alternative afforestation practices that have the potential to control soil erosion without endangering future soil water availability in the region. Afforestation strategies for sustainable development are documented for the Yellow River Basin in several recent studies. The exotic tree species currently used should be replaced with more water-saving native tree species. Thinning was required in high-density areas as critical measure to maintain a balance in soil water availability and water use by plants. Using soil water carrying capacity for vegetation (SWCCV) models (Xia and Shao, 2008) to assess the consumption process of soil water with vegetation growth, optimal plant density or biomass can be established to guide afforestation operations in the Loess Plateau.

5. Conclusions

Planting trees (e.g., *R. pseudoacacia*, *P. tabulaeformis* and *C. korshinskii*) constitute an important soil erosion control measure for the sustainability of the ecology in China's Loess Plateau Region. Compared with croplands, however, mean SMC in the top 5-m soil layers under artificial forests declined with time across the Loess Plateau study area. The decline in SMC induced soil desiccation that in turn limited tree growth or even induced degeneration of vegetation. Although SMC for *R. pseudoacacia* plantation apparently recovered with increasing tree age over 25 yr, SMC under *R. pseudoacacia* was consistently lower than that under cropland. Artificial forests might thus play a role of "water pump" in the Loess Plateau. Therefore, future afforestation efforts should consider planting tree species that use less water and require less thinning. Such forest trees could support sustainable soil conservation without compromising future water demand in the Loess Plateau. Future water resources studies should investigate runoff, canopy interception and evapotranspiration fluxes to further clarify the processes of soil moisture decline due to afforestation of the Loess Plateau.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2017.01.011.

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