Hydrol. Earth Syst. Sci., 15, 2519–2530, 2011
www.hydrol-earth-syst-sci.net/15/2519/2011/
doi:10.5194/hess-15-2519-2011

Hydrology and Earth System Sciences

Hydrologic feasibility of artificial forestation in the semi-arid Loess Plateau of China

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Received: 7 December 2010 – Published in Hydrol. Earth Syst. Sci. Discuss.: 19 January 2011
Revised: 20 July 2011 – Accepted: 8 August 2011 – Published: 15 August 2011

Abstract. Hydrologic viability, in terms of moisture availability, is fundamental to ecosystem sustainability in arid and semi-arid regions. In this study, we examine the spatial distribution and after-planting variations of soil moisture content (SMC) in black locust tree (*Robinia pseudoacacia* L.) plantings in the Loess Plateau of China at a regional scale. Thirty sites (5 to 45 yr old) were selected, spanning an area of 300 km by 190 km in the northern region of the Shaanxi Province. The SMC was measured to a depth of 100 cm at intervals of 10 cm. Geographical, topographic and vegetation information was recorded, and soil organic matter was evaluated. The results show that, at the regional scale, SMC spatial variability was most highly correlated with rainfall. The negative relationship between the SMC at a depth of 20–50 cm and the stand age was stronger than at other depths, although this relationship was not significant at a 5 % level. Watershed analysis shows that the after-planting SMC variation differed depending upon precipitation. The SMC of plantings in areas receiving sufficient precipitation (e.g., mean annual precipitation (MAP) of 617 mm) may increase with stand age due to improvements in soil water-holding capacity and water-retention abilities after planting. For areas experiencing water shortages (e.g., MAP = 509 mm), evapotranspiration may cause planting soils to dry within the first 20 yr of growth. It is expected that, as arid and semi-arid plantings age, evapotranspiration will decrease, and the soil profile may gradually recover. In extremely dry areas (e.g., MAP = 352 mm), the variation in after-planting SMC with stand age was found to be negligible. The MAP can be used as an index to divide the study area into different ecological regions. Afforestation may sequentially exert positive, negative and negligible effects on SMCs with a decrease in the MAP. Therefore, future restoration measures should correspond to the local climate conditions, and the MAP should be a major consideration for the Loess Plateau. Large-scale and long-term research on the effects of restoration projects on SMCs is needed to support more effective restoration policies. The interaction between afforestation and local environmental conditions, particularly water availability to plants, should be taken into account in afforestation campaigns in arid and semi-arid areas.

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1 Introduction

Over the past century, afforestation and reforestation (artificial forestation) have been implemented extensively (Del Lungo et al., 2006), and increasing attention has been paid to their ecological impact. Artificial forestation was initially undertaken as an effective way to alleviate water loss and soil erosion, control desertification and conserve biodiversity (Lugo, 1997; Parrotta et al., 1997; Chirino et al., 2006; Barlow et al., 2007; Porto et al., 2009). It has recently gained attention as a potential mechanism for carbon sequestration (Wright et al., 2000; Fang et al., 2001; Pacala and Socolow, 2004; Marin-Spiotta et al., 2009). According to Fang (2001), the increase in biomass resulting from artificial forestation in China from the mid-1970s to 1998 has sequestered 0.45 petagrams of carbon. Today, reforestation and afforestation are acknowledged as effective ways to increase carbon storage in soil (Resh et al., 2002). Moreover, the decreases in bulk density and increases in soil organic matter (SOM), porosity and aggregation associated with tree planting (Kahle et al., 2005; Ilstedt et al., 2007; Li and Shao, 2006) can improve soil properties. In other cases, the rapid growth rates of

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planted trees as compared to those of the native vegetation and the frequent removal of biomass can lead to a depletion of soil nutrients (Merino, 2004; Berthrong et al., 2009). However, one of the major issues that is currently of concern with respect to artificial forestation is the relationship between plantings and their effect on water resources.

The hydrological ramifications of artificial forestation have been studied extensively over the past two decades (Andreassian, 2004; Jobbagy and Jackson, 2004; Nosetto et al., 2005; Sahin and Hall, 1996; Van Dijk and Keenan, 2007). Several reviews have clearly detailed the close relationship between tree planting and runoff reduction (Brown et al., 2007, 2005; Bruijnzeel, 2004; Farley et al., 2005). This association may be very critical in arid and semi-arid areas (Farley et al., 2005), which are highly susceptible to land degradation (Puigdefàbregas and Mendizabal, 1998). In arid and semi-arid areas, tree planting has been widely adopted as a means of ecosystem restoration (Boix-Fayos et al., 2009; Hu et al., 2008). Given the close correlation between water yields and available water resources, most researchers in this field have focused on the effects of planted trees on water yields. However, changes in soil moisture after the planting of trees are of great significance for vegetation restoration and ecosystem sustainability in dry climate conditions (Schume et al., 2004; Wang et al., 2004b; Zhao and Li, 2005; Yang et al., 2010).

Planted trees affect the soil moisture content (SMC) through leaf interception of rainfall, root uptake of soil moisture, litter-layer buffering and changes in soil water-retention properties. Litter increases soil water retention by increasing the hydraulic conductivity of the duff layer (Robichaud, 2000). The physical and chemical properties of the soil (such as the SOM, bulk density, porosity and hydraulic conductivity) influence the transformation of precipitation into soil moisture and the soil water-retention capacity. These soil properties can be improved through natural and artificial re-vegetation (Ilstedt et al., 2007; Li and Shao, 2006), but artificial forestation can also decrease soil moisture due to the effects of leaf interception and root uptake. Gordon (1998) reviewed studies on Melaleuca and Sapium in Florida and found that high evapotranspiration rates can dry soil and drain wetlands. According to Chirino et al. (2001), 23–35 % of the total annual rainfall is intercepted by *Pinus halepensis* canopies in the Ventos-Agost catchment (Alicante, Spain).

Soil moisture can vary after the planting of trees under different conditions. According to previous studies, the effects of planted trees on topsoil moisture at depths of 0–15 cm have been reported to be either significantly negative (Breshears et al., 1997), positive (Joffre and Rambal, 1998), negligible (Koechlin et al., 1986) or undetectable (Maestre et al., 2003). More recent studies have focused on short-term local-scale variations (Breshears et al., 1997; Cao et al., 2006; Koechlin et al., 1986; Li et al., 2004; Maestre et al., 2003); however long-term regional-scale studies are rarely reported.

The Loess Plateau has a typical semi-arid climate and suffers from ecosystem degradation due to severe water loss and soil erosion (Chen et al., 2001). The Chinese government has aggressively invested in soil and water conservation and restoration programmes for the nation's ecosystems since the 1950s (Fu et al., 2002). Although extensive afforestation is currently taking place on the Loess Plateau, some negative effects of afforestation have been reported (McVicar et al., 2007; Yang et al., 2010). In some areas, afforestation has led to the emergence of a dry soil layer (Shangguan, 2007). Given the importance of the SMC to plants in arid and semi-arid areas, a better understanding of the spatial distribution and after-planting variation in SMCs is crucial for the sustainability of a restored ecosystem. This research will also help direct ecosystem restoration in other arid and semi-arid areas of the world.

This study was designed to investigate the interaction between water resources (rainfall and soil moisture) and afforestation in the study area in order to support more effective restoration policies in arid and semi-arid areas. Optimal research methods should be based on regional, long-term monitoring of SMCs. However, this type of monitoring is time-consuming and difficult. Instead, a regional, short-term study was conducted as an alternative. We examined the following: (1) the spatial distribution of SMCs on a regional scale; (2) the stand-structure variations of planted trees along the water gradient; and (3) the after-planting SMC variations with stand age and between watersheds.

2 Methods

2.1 Study sites

The study area is located on the Loess Plateau in the northern part of the Shaanxi Province (35.16° N–37.86° N, 108.11° E–110.22° E; 916–1586 m above sea level; Fig. 1). The area has a continental monsoon climate. Within the study area, the mean annual temperature (MAT) varies from 9.2–11.5°, and the mean annual precipitation (MAP) varies from 352–618 mm. These statistics were calculated from 7-yr-averaged temperature and precipitation records taken from 2000 to 2006 at 174 well-distributed climate stations on the Loess Plateau.

The most widely distributed soil type in the Loess Plateau is loess soil (Guo, 1992). The vegetation zone changes from temperate forest steppe in the southeast of the Loess Plateau to temperate steppe (Wu, 1980) in the northwest. Most of the native vegetation has been cleared in this region, and much of the land has been afforested. The most common tree species in the area are black locust (*Robinia pseudoacacia* L.), Chinese pine (*Pinus tabulaeformis* Carr.) and Korshinskii peashrub (*Caragana korshinskii* Kom.). *R. pseudoacacia* is an exotic nitrogen-fixing tree that is native to southeastern North America. It has been widely cultivated

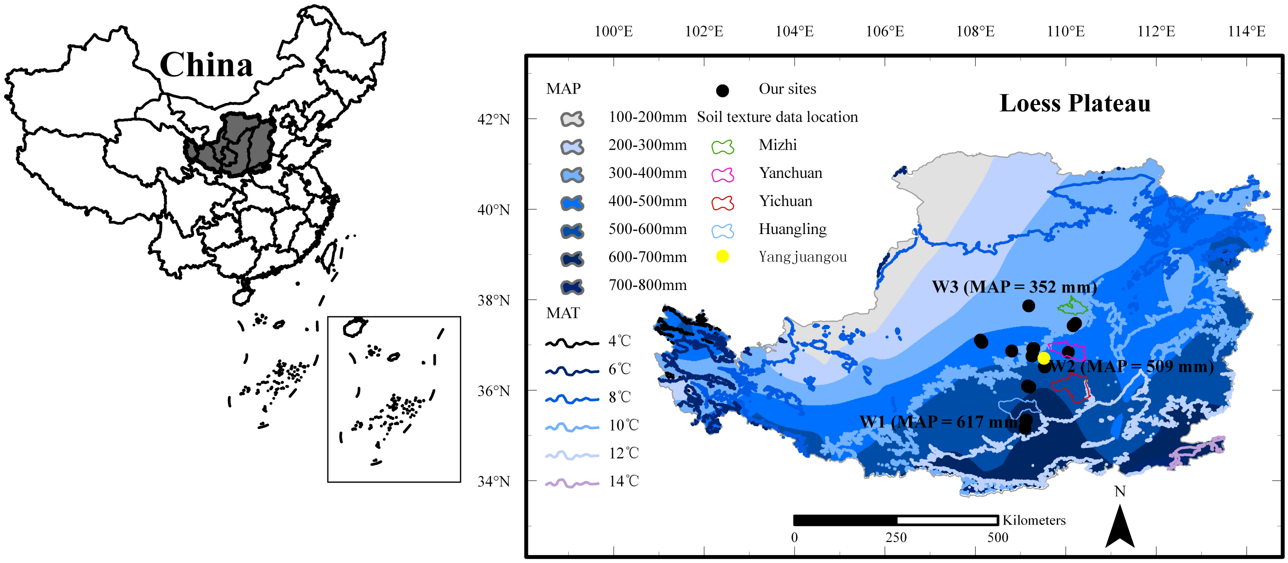

Fig. 1. Map of the study area on the Loess Plateau in central China and the distributions of the mean annual temperature (MAT) and mean annual precipitation (MAP). A total of 30 sites were selected. Sites W1, W2 and W3 are three watersheds located in the northern, middle and southern parts of the study area, respectively.

for restoration due to its drought resistance, high survival rate, ability to improve the soil-nutrient status and remarkable growth rate (Li et al., 1996; Shan et al., 2003). The most commonly used stand densities for afforestation in the study area are 5000 (1×2 m) and 3333 (1.5×2 m) plants hm^{-2}, determined by interviewing local inhabitants. At the present time, *R. pseudoacacia* is the most widely cultivated species on the Loess Plateau.

The most important consideration for short-term regional research is to determine how to lessen the effect of individual rainfall events on SMC measurements. This will ensure that the data measured at different study sites are comparable. Undulating terrain and short, violent rainfall events on the Loess Plateau greatly reduce the impact of rainfall events on SMCs, particularly in upslope areas where afforestation has been applied. Historically, *R. pseudoacacia* saplings are usually planted in fish-scale pits. To minimise the effects of planting methods and slope variation (Querejeta et al., 2001), fish-scale pits in upslope areas were selected for planting. To further eliminate the influence of rainfall events on SMC measurements, the SMCs were measured at least five days after a rainfall event had occurred. To focus on the interaction between afforestation and SMC, the experiment was conducted during the growing season (late July through early August, 2008).

At the regional scale, 30 sites were selected, spanning a total area of 300 km by 190 km (Fig. 1). There is a wide range in annual precipitation between the study sites, from 352 to 617 mm. In some watersheds, only one or two planting sites exist, so watershed analysis was impossible. Twelve sites in three watersheds (W1, W2 and W3) were selected for analysis of the after-planting SMC variation within different watersheds. As shown in Fig. 1, study site W1 is located at the southern boundary of the Loess Plateau and is located in the wettest and warmest area in the region, with a MAT of 11.0° and a MAP of 617 mm. The landscape at W1 is typical of plateau topography and is relatively flat as compared to the northern part of the Loess Plateau in Shaanxi Province. W2 is located in a typical loess hilly-gully region with a MAT of 10.4° and a MAP of 509 mm. W3 is located in the transitional zone between the desert area in the north and the Loess Plateau hilly-gully area in the south. It has the lowest MAT (9.5°) and MAP (352 mm) of the three sites.

2.2 Sample collection and analysis

The stand ages of the plantings were determined by interviewing local inhabitants. The latitude, longitude and elevation were determined for each study site using a Garmin GPS60 (Garmin International Inc., Olathe, KS, USA), while the site slope and aspect were determined using a compass. The slope aspect is positive and increases clockwise from 0° to 360°: a north-facing slope has an aspect of 0°, 90° is east-facing, 180° is south-facing and 270° is west-facing. The aspect degree was further divided into four classes according to Qiu et al. (2001): (1) 135–225°, (2) 225–315°, (3) 45–135° and (4) 315–360° and 0–45°. Grade 1 represents the slope aspect with the highest solar radiation reception, while Grade 4 has the lowest. To prepare for field measurements, a 10×10 m quadrant was established at each study site, and three 2×2 m sub-quadrants were chosen along a diagonal of each 10×10 m quadrant. In each of the 10×10 m quadrants,

Table 1. Correlation analyses between depth-averaged SMC and spatial parameters ($N = 30$; $^{**}P < 0.01$).

	Latitude (degree)	Longitude (degree)	Elevation (m)	Slope (degree)	Slope aspect
SMC (0–100 cm, $N = 30$)	−0.806(**)	0.149	0.171	−0.322	0.224

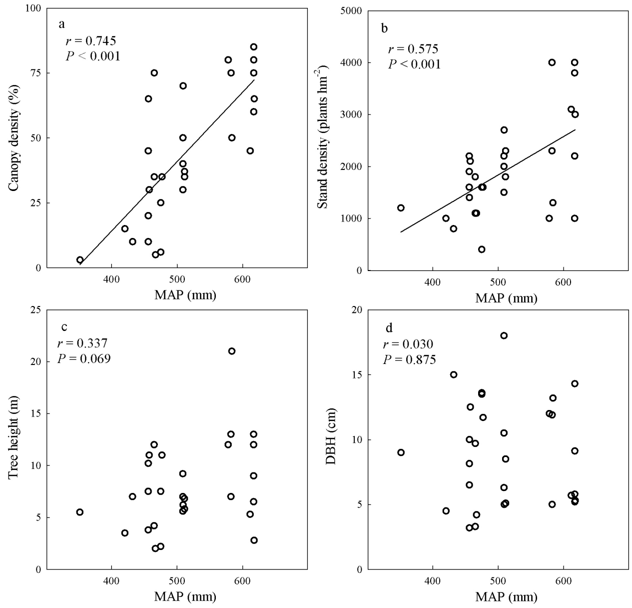

Fig. 2. Plots of canopy density, tree density, tree height and diameter at breast height (DBH) variation with respect to the MAP.

the stand density (plants hm^2), canopy density (the percentage of area covered by tree canopy) and the average tree diameter at breast height (DBH) were recorded. For each of the three 2×2 m sub-quadrants, the percentage of herbaceous cover were recorded, and soil samples were collected to a depth of 100 cm at 10 cm intervals using a soil auger. SMCs were measured using the oven-drying method. Soil organic carbon (SOC, mg g^{-1}) was determined using the $K_2Cr_2O_7$ titration method (Lu, 1999) for soils at depths of 0–10 cm, 10–20 cm and 50–60 cm, and the soil organic matter was derived as $1.7 \times$ SOC. All laboratory experiments were conducted at the Research Centre for Eco-Environmental Sciences, Chinese Academy of Science.

2.3 Statistical analysis

The data in this study were analysed on two different scales. At the regional scale, the data from all 30 sites were combined. Bivariate correlation analysis was used to determine the variation of SMC with latitude, longitude, elevation, slope and slope aspect, and it was also used to identify stand-structure variations with the MAP and the relationship between SMCs at different depths and stand ages (from 5 to 45 yr).

At the watershed scale, the data for W1, W2 and W3 were used. Descriptive statistics were used to give the mean and standard deviation of SMCs at different depths for each site. A comparison of plantings with different stand ages in the same watershed and of the watershed-averaged SMCs of the three watersheds was performed using one-way ANOVA, and post-hoc multiple comparisons were made using the least significant difference (LSD). The relationship between the SMC and SOM in different watersheds was determined by bivariate correlation analysis. The following logarithmic regression was used to test the effect of self-thinning in different watersheds:

$$\log w = \log k + a \log N \quad (1)$$

where w is the plant size, with DBH (cm) as an indicator of plant size; k is a species-specific constant that has an interspecific range; a is a constant that is generally thought to lie between −1.3 and −1.8 and has an ideal value of −1.5 (Adler, 1997); N is the stand density (plants hm^{-2}).

All statistical analyses were performed with the statistical software package SPSS 16.0 (SPSS Inc., Chicago, Illinois, USA).

3 Results

3.1 Spatial distribution of depth-averaged SMCs

The depth-averaged SMC varied widely at the regional scale. It decreased from 18 % to 3 % from the south to the north of the study area. As shown in Table 1, it decreased significantly with increasing latitude, with a high correlation coefficient. No significant relationships were found between the SMC and longitude, elevation, slope, or slope aspect.

3.2 Variation in R. pseudoacacia stand-structure

3.2.1 Regional scale

The canopy density and stand density decreased significantly with decreasing MAP (Fig. 2a, b). The tree height and MAP exhibited a weaker relationship, which was not statistically significant at the 0.05 level ($P = 0.069$) (Fig. 2c). The DBH and MAP exhibited the weakest relationship (Fig. 2d).

Table 2. Correlation analyses between SMCs measured at different depths and stand ages on the regional scale (correlation coefficients and P values).

Soil depth (cm)	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100	Depth-averaged
$N = 30$	−0.201	−0.348	−0.406	−0.399	−0.398	−0.364	−0.358	−0.353	−0.355	−0.350	−0.384
	(0.286)	(0.059)	(0.026)	(0.029)	(0.029)	(0.048)	(0.052)	(0.056)	(0.054)	(0.058)	(0.036)
$N = 29$	−0.174	−0.276	−0.351	−0.354	−0.351	−0.310	−0.300	−0.290	−0.288	−0.319	−0.327
(Values after elimination of 45-year-old site)	(0.367)	(0.148)	(0.062)	(0.059)	(0.062)	(0.102)	(0.114)	(0.127)	(0.129)	(0.092)	(0.083)

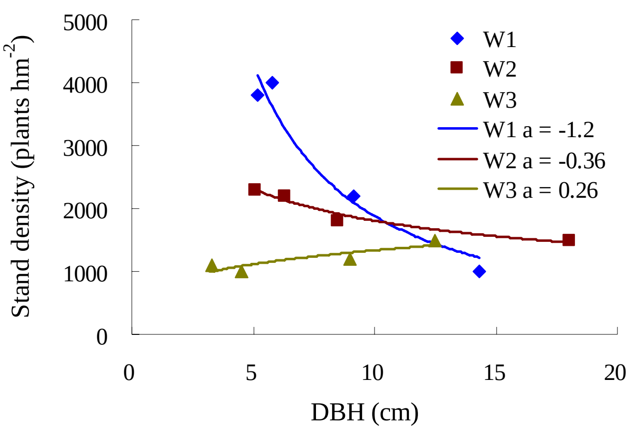

Fig. 3. Logarithmic regression between plant size and density.

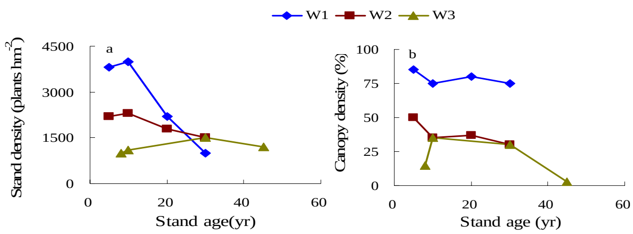

Fig. 4. Variations in stand density and canopy density with stand age in the different watersheds.

3.2.2 Comparisons between watersheds

From the logarithmic regression between DBH and stand density (equation 1, Fig. 4), the regression constant a values determined for sites W1, W2 and W3 were −1.20, −0.36 and 0.26, respectively. The regression constant a value of W1 was similar to the determined a value for self-thinning (−1.3 to −1.8, Fig. 3) (Adler, 1997).

In W1, the stand densities in the 5- and 10-year-old plantings were high, and the stand density decreased with increasing stand age. In W2, this trend lessened, while in W3, no trend was found (Fig. 4a). From W1 to W2, the canopy density decreased gradually. In W1, the canopy density was constant and high, while in W2 and W3, the canopy density was constant and low (Fig. 4b).

3.3 Soil moisture variation with stand age

3.3.1 Regional scale

The depth-averaged SMC had a significant negative correlation with stand age at the regional scale. However, the relationship between stand age and SMC was only significant at depths of 20–60 cm. At depths of 0–20 cm and 60–100 cm, there was no correlation (Table 2).

With a MAP of only 352 mm, W3 was the driest watershed and was also the only one in which 45-year-old plantings were present. To eliminate any bias, the relationship between stand age and SMC was further examined after excluding the 45-year-old site (Table 2). The SMC still had a negative correlation with stand age at the regional scale. Although no significant relationships were found, the absolute values of the correlation coefficients between SMCs at depths of 20–50 cm were higher as compared to the other depths, and the P values determined for depths of 20–50 cm were close to 0.05.

3.3.2 Comparisons between watersheds

SMCs in different watersheds

Large differences in SMC profiles were evident between the three watershed sites: W1, W2 and W3. The average SMC of W1 (Fig. 5a) was the highest of the three watersheds because it had the highest amount of precipitation (MAP = 617 mm). In the soil profile for W1, the SMC decreased slightly with depth (0–100 cm). The 30-year-old tree sites maintained a significantly higher SMC than the sites with younger trees.

In W2 (Fig. 5b; MAP = 509 mm), two distinct SMC layers were evident in the soil profile. In the top layer (0–40 cm), the SMC decreased rapidly with depth. In the lower layer (40–100 cm), the SMC was relatively constant with depth, with the exception of locations in which the youngest (5-

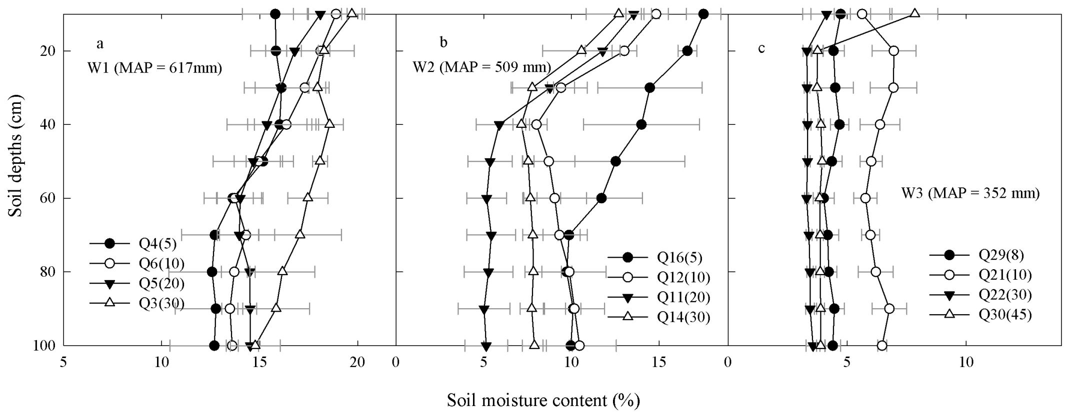

Fig. 5. Soil moisture profiles for watersheds **(a)** W1, **(b)** W2 and **(c)** W3. The bars indicate the standard deviations of the means ($N = 3$). In the legends, the numbers in the parentheses after W1, W2 and W3 indicate stand ages.

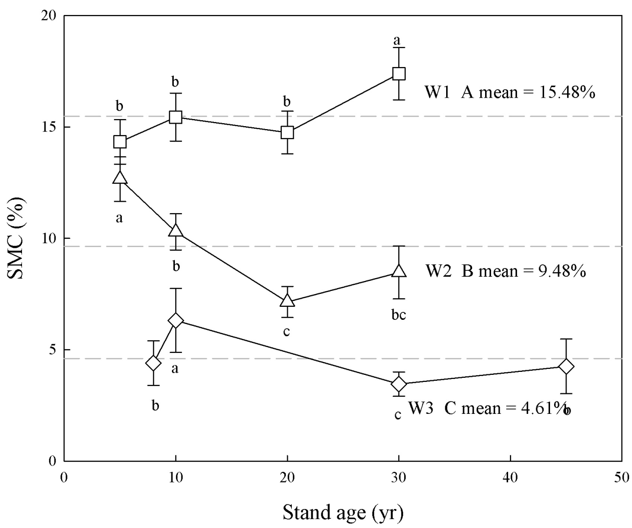

Fig. 6. SMC versus stand age for the different watersheds. The bars indicate the standard deviations of the means. Lowercase letters indicate differences between depth-averaged SMCs with different stand ages for a given watershed, significant at the 0.05 level. Uppercase letters after W1, W2 and W3 indicate differences between watershed-averaged SMCs significant at the 0.05 level.

year-old) trees were present. At these locations, the SMCs decreased gradually along the top 70 cm of the profile.

In the driest watershed, W3 (Fig. 5c), the SMC was low (MAP = 352 mm). In the 8-, 30- and 45-year-old stands, the SMC was less than 5 % and varied minimally across the entire soil profile (except for the SMC at the soil surface in the 45-year-old stand, which maintained a relatively high value of approximately 7.8 %). The SMC in the 10-year-old stand was slightly higher (a depth-averaged value of approximately 6 %) and varied minimally with depth.

As shown in Fig. 6, the SMCs were the highest in W1 and the lowest in W3. This corresponds to the precipitation distribution. The SMCs, however, also varied with stand age. In W1, the SMC levels were high (approximately 15 %) for stands younger than 20 yr, but they were significantly higher (approximately 17 %) for 30-year-old stands. The SMC decreased significantly from 12.7 % to 10.3 % to 7.1 % in W2 with corresponding increases in stand age from 5 to 10 to 20 yr. The SMC increased slightly from 7.1 % to 8.5 % as the stand age increased from 20 to 30 yr; however, the difference in SMC was smaller than the difference between 10- and 20-year-old stands. In W3, the SMC levels were considerably lower (4–6 %) and did not appear to change with stand age. The watershed-averaged SMC value of 4.6 % is similar to the permanent wilting point of the soil (Li et al., 1996; Wang et al., 2004b).

The relationship between SMC and SOM

The correlations between the SMC and SOM (0–10, 10–20 and 50–60 cm depth) for the different watersheds are given in Fig. 7. The SMC and SOM show a significantly positive relationship for W1 (Fig. 7a), while no significant relationship was found for W2 or W3 (Fig. 7b, c). When the data point with the highest SOM was removed from the W2 data set (this point is thought to reflect a saturation response of the SMC when the SOM content is greater than approximately 25 mg per gram of soil), the SMC and SOM were significantly correlated ($r = 0.735$, $P = 0.01$). This relationship, however, was derived from variations of these two factors with soil depth (SMC: $r = -0.775$, $P < 0.01$; SOM: $r = -0.914$, $P < 0.01$). When depth was used as a control factor, the partial correlation coefficient between the SMC and SOM was 0.102 ($P = 0.779$). In comparison, the partial correlation coefficient between the SMC and SOM in W1 was 0.786 ($P < 0.01$), which reflects the effect of the SOM on SMC in W1.

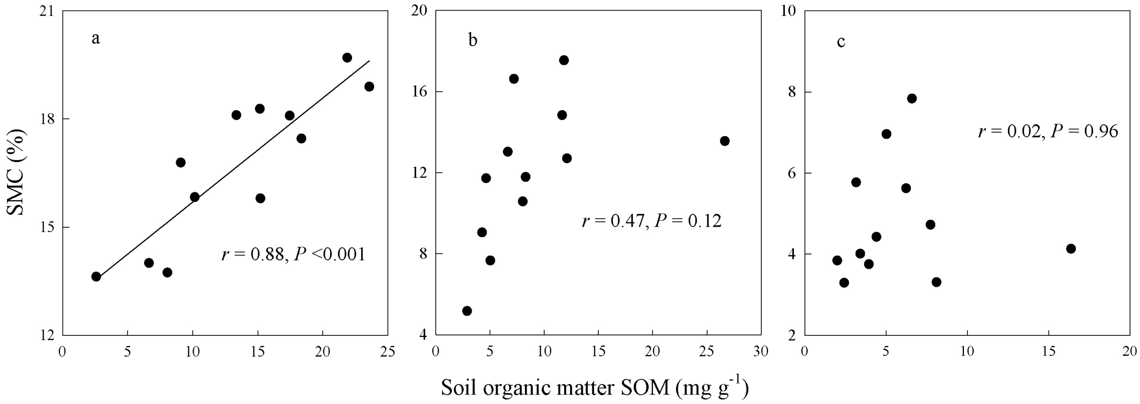

Fig. 7. Correlations between the SMC (soil moisture content) and SOM (soil organic matter) in watersheds **(a)** W1, **(b)** W2 and **(c)** W3.

In watershed W1, the topsoil organic matter content was highly correlated with increasing stand age (0- to 10-cm depth: $r = 0.49$, $P < 0.01$; 10- to 20-cm depth: $r = 0.551$, $P < 0.01$).

4 Discussion

4.1 Spatial distribution of SMCs

The SMC is the most important source of water used directly by plants and should be a primary consideration in the afforestation of arid and semi-arid areas. Given the wide range of afforestation programmes in the Loess Plateau, research on the spatial distribution of the SMC is necessary in this region. Most research on the Loess Plateau has been restricted to the watershed scale, but some factors may influence the SMC at other scales. The decisive role that MAP levels have played in determining SMCs at the regional scale on the Loess Plateau is not surprising. Due to the deep groundwater levels, precipitation is the only source of soil moisture, which strengthens the relationship between the SMC and MAP. An upslope position can lessen the effect of the terrain on the SMC because the effect of runoff is eliminated and the shade effect from undulating terrain is also lessened. In this study, the slope and aspect shape exert insignificant effects on the SMC at the regional scale. As with latitude and longitude, elevation was found to not directly affect the SMC, but to indirectly affect the SMC via other factors (e.g., temperature and precipitation). In this study, the MAP and MAT did not have significant relationships with elevation (MAP: $r = 0.054$, $P = 0.778$; MAT: $r = 0.277$, $P = 0.138$). Therefore, no significant relationship was found between altitude and SMC. Due to the homogeneous texture of the soils in the Loess Plateau (refer to Supplement Figs. 1 and 2 for soil texture data at the regional and watershed scales and Fig. 1 for the locations relating to soil texture data), soil properties are unlikely to be dominant factors for determining SMCs at the regional scale. Based on the above analysis, the MAP can be used as a major factor to determine the spatial distribution of SMCs, which may be used along with vegetation species to the divide the Loess Plateau into different ecological regions.

4.2 Stand-structure variations of R. pseudoacacia populations along the rainfall gradient

Rampike and dwarf forms of *R. pseudoacacia* were frequently found in the northern area of the study site. The emergence of rampike and dwarf trees was reflected through a trend of decreasing stand density and tree height with decreasing MAP (Fig. 2). The results from this study suggest that afforestation measures should be regulated according to the environmental gradient in which they are implemented. However, unified measures are often adopted for a variety of areas. For example, the stand densities most commonly used in afforestation of the Loess Plateau are 5000 (1×2 m) and 3333 (1.5×2 m) plants hm^{-2}. However, a density of less than 1000 plants hm^{-2} has been found to be appropriate under different MAP levels, which is far less than the initial adopted stand density (Table 3). In watershed W1, a high MAP led to a high tree survival rate, but subsequent growth made competition within the stand population more intense. As shown in Fig. 3, the regression constant a value determined for W1 (-1.20) was found to be very similar to the regression constant a value for self-thinning (-1.3 to -1.8) (Adler, 1997). In addition, the constant high canopy density resulted in space and resource competition among individual trees in W1 (Fig. 4a). However, the high stand densities in young stands and the decreasing trend of stand density with stand age (Fig. 4b) imply a density-dependent mortality. Therefore, the self-thinning observed in watershed W1 was probably an important process accompanying afforestation. In W2 and W3, the stand densities and canopy densities were low, and drought led to a high mortality of planted saplings. Drought, as opposed to self-thinning, was found to be the main factor affecting mortality rates in W2 and W3.

Table 3. Appropriate stand density for the Loess Plateau.

MAP (mm)	Appropriate stand density (plants hm^{-2})	Stand age (yr)	Criterion for judging appropriation	Method	Literature
576	1500–3000	45	No soil desiccation	WinEPIC model	Li et al. (2008b)
576	2000	11	Maximum forest biomass	Measured data and logistic model	Sun et al. (2006)
576	876	13	Low water stress for plants	Measured data and water balance model	Wu et al. (2007)
535	1500	45	No soil desiccation	WinEPIC model	Li et al. (2008b)
487	833	18	Maximum forest biomass	Measured data and power function model	Wang et al. (2005)
416	< 833	11 and 18	Maximum forest biomass	Measured data and regression model	Yin et al. (2008)

4.3 The cumulative effects of afforestation on SMCs

4.3.1 The effect of the R. pseudoacacia root system on SMCs

R. pseudoacacia is a shallow-rooted species. Although the greatest vertical root depths vary from 190 cm (Wang et al., 2004a) to 120 cm (Liu et al., 2007) in the Loess Plateau, the effective roots are concentrated at a depth of 0–60 cm and at a depth of 20–60 cm in particular (Cao et al., 2006; Liu et al., 2007; Wang et al., 2004a). This implies that this species will largely absorb soil moisture at a depth of 20–60 cm. Although no statistically significant relationships were found after eliminating the 45-year-old site data for W3, the negative correlations between the SMC and stand age at the 20- to 50-cm depth were stronger than those at other depths at the regional scale after the exclusion of the 45-year-old site. However, the intensity and nature of the relationship between the SMC and stand age may be affected by other environmental factors, and the relationship between the SMC and stand age differed between watersheds.

4.3.2 After-planting SMC variation in different watersheds

Watershed W1

W1 (MAP = 617 mm) had a higher SMC than the other watersheds. The consistently high SMC levels demonstrated good water supplementation across the soil profile (Fig. 5a). A previous study has also shown that the SMC in the growing season in this region is effectively maintained by natural rainfall (Li, 1983). The watershed-averaged SMC in this study, 15.48 %, is roughly equivalent to the average water-holding capacity previously found for the soil (15.00 %; Li et al., 2008a). Under such conditions, the effect of tree root uptake on the SMC is lessened by intermittent supplementation from precipitation, and the SMC largely depends on the soil water-holding capacity. Joffre (1988) revealed that the soil water content in woodland sites in southern Spain (MAP = 650 mm) is greater than that in grass sites due to improvements in soil permeability and water-holding capacity after the planting of trees.

Soil water-holding capacity and water-retention ability are mainly related to SOM, soil texture, porosity and bulk density (Husein Malkawi et al., 1999). The soil texture in the Loess Plateau is derived from parent materials, and the soil is relatively uniform in space and over time (Li and Shao, 2006). SOM promotes the formation of soil aggregates by binding soil particles together, increasing soil porosity and, thus, improving soil structure and decreasing bulk density (Husein Malkawi et al., 1999; Langdale et al., 1992; Li and Shao, 2006; Soane, 1990; Watts and Dexter, 1997). Therefore, SOM is a good indicator of soil water-holding capacity and soil water-retention ability (Franzluebbers, 2002; Li and Shao, 2006).

In watershed W1, the topsoil organic matter content increased significantly with increasing stand age, consistent with the results of Paul et al. (2002). The SMC was found to have a significantly positive correlation with SOM (Fig. 7a). Therefore, it is expected that the soil moisture status should improve with stand age in W1. In watersheds W2 and W3 (Fig. 7b, c), the insignificant relationship between the SMC and SOM indicates a weaker effect of the soil water-holding capacity on the SMC.

Watershed W2

In W2, precipitation and root uptake may play an important role in determining the SMC. Precipitation was found to wet only the upper soil layer (Fig. 5b). Water use by planted species (especially those selected for rapid growth) initially increases quickly and then gradually decreases with age (Almeida et al., 2007; Farley et al., 2005). For *Eucalyptus sieberi*, a transpiration peak is reached when stands reach 15 yr of age (Roberts et al., 2001; Vertessy et al., 2001). In the early stages of planting growth, afforestation has been found to dry the soil quickly, as evidenced by increasing water use in plantings. From the results shown in Fig. 6, it can be hypothesised that the peak water usage for *R. pseudoacacia* in this area occurs when stands reach between 20 and 30 yr of age. The decreased water usage of older trees might be another cause of the higher SMC at the 30-year-old tree site in W1. In comparison with W1, the effects of precipitation and root uptake on the SMC in W2 were distinct. Limited precipitation and concentrated root uptake at the 20- to 60-cm depth shaped the SMC of the soil profile in this watershed.

Watershed W3

In watershed W3 (Fig. 5c), the observed soil profile distribution of the SMC indicates the long-term absence of a water supply. In the 8-, 30- and 45-year-old stands, the SMCs nearly reached the species' wilting point (Li et al., 1996; Meng et al., 2008), indicating that water was not consistently available to the trees. In the 10-year-old stand, the SMC was slightly higher than the wilting point, and water could have been partially used by trees. This finding is supported by a slight decrease in SMC at the depth of 20–60 cm. No obvious trend was found between the SMC and stand age. Divergences in the SMCs of the different stands are likely to have come from differences in terrain (slope, aspect and slope position) given the uniform soil texture in this area. All four stands were located in upslope areas, and the SMC levels exhibited no significant trend with slope. Comparatively, the relationship between the SMC and aspect was clearer. The graded slope aspects of the 8-, 10-, 30- and 45-year-old stands were 3, 4, 1 and 3, respectively. The SMC was found to increase with decreasing solar radiation. In watershed W3, the slope aspect, which has a significant effect on solar radiation reception on slopes, also had an important effect on the SMC.

4.3.3 Implication for restoration activities in arid and semi-arid areas

As stated in Sect. 4.3.2, the after-planting SMC variations were largely dependent on the local rainfall. Therefore, a single standard is not appropriate for ecosystem restoration. In arid and semi-arid areas, water resources should be the central consideration of afforestation. Afforestation may only be practical when there is sufficient precipitation (e.g., MAP $>$ 617 mm on the Loess Plateau). Trees planted in some areas with water shortages might be able to grow well during the initial stage (e.g., MAP = 509 mm on the Loess Plateau); however large water uptakes by the plantings will dry the soil and lead to an unsustainable ecosystem. In extremely dry areas (e.g., MAP $<$ 352 mm on the Loess Plateau), insufficient SMCs often fail to support the growth of the plantings.

4.4 The trend of soil drying after tree planting and the potential effect on vegetation succession

A trend of after-planting soil drying was only found for W2, and this trend will recover gradually with planting age (Fig. 6). This trend was not found in watersheds with higher (W1) or lower (W3) MAPs. In W2, the initial drying trend may exert a negative effect on vegetation renewal and the associated ecosystem. The growth of afforested trees was limited by this drying trend, and many "dwarf" trees were found (Han and Hou, 1996; Hou and Huang, 1991). Furthermore, the undergrowth vegetation succession may be altered by this drying trend. Species that are adaptable to dry environments and have shallow roots can quickly become dominant (Francis and Parrotta, 2006; Li et al., 2004).

On the Loess Plateau, afforestation may exert the biggest impact on the SMC of sites with mid-range MAPs (e.g., W2 MAP = 509 mm). In this area, afforestation may lead to drought stress for the planted trees and deplete soil moisture, which is critical to vegetation restoration. Tree adaptability and the ecological significance of establishing plantings should be comprehensively considered in the afforestation process.

5 Conclusions

Afforestation is one of the most important restoration measures for arid and semi-arid ecosystems. However, it is largely limited by water availability in these ecosystems. The soil moisture content (SMC) is the most important water resource available to plants when grown in locations where groundwater tables are deep. The success of ecosystem restoration is largely dependent on the spatial and temporal variation of the SMC at the regional scale.

This study suggests that the mean annual precipitation (MAP) can be used to determine the SMC in the northern region of the Loess Plateau. Therefore, it can also be used as an index to define different ecological regions in the study area. In areas where the MAP was less than 400 mm (W3), the SMC was found to be near the wilting point (SMC = 5 %). Over-planting in such areas will not only lead to a waste of money and human power invested in afforestation restoration projects, but will also hamper the restoration of degraded ecosystems. The planting of fast-growing species may dry soils in areas with moderate MAPs (e.g., W2 MAP = 509 mm) in the initial stages. Less water-demanding species would be more suitable for ensuring the success of afforestation projects. In areas where the MAP is relatively high (e.g., W1 MAP = 618 mm), the SMC was found to approach the average water-holding capacity of the soil. The SMC in such areas is high enough to maintain the growth of planted trees during the growing season. plantings located in these areas are likely to improve the SMC due to the high water-holding capacity of the soils and will therefore promote the natural recovery of these areas.

The results from this study show that local environmental conditions, particularly water availability for plants, should been taken into account in the establishment of artificial plantings in arid and semi-arid areas. Further regional-scale and long-term research on the effects of restoration projects on SMCs is needed to ensure that more effective restoration policies are implemented.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci.net/15/2519/2011/hess-15-2519-2011-supplement.pdf.

Acknowledgements. We acknowledge the considerable assistance of Lei Yang and Xiao-Hui Ding with sampling and laboratory procedures. This research was supported by the National Basic Research Programme of China (No. 2009CB421104), the National Natural Science Foundation of China (No. 40930528 and 40871085), and the CAS/SAFEA International Partnership Programme for Creative Research Teams of "Ecosystem Processes and Services."

Edited by: Y. Fan

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