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

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Abstract

Hydrologic viability in terms of moisture availability is fundamental for ecosystem sustainability in arid and semiarid regions. This study was conducted to examine the regional scale and after-planting variations of soil moisture for planted Black Locust tree (*Robinia pseudoacacia* L.) plantations in the Loess Plateau of China. 30 sites spanning for 300 km long and 190 km wide in the Northern Shaanxi Province were selected in all. On the regional scale, SMC spatial variability was most closely correlated to rainfall. A large amount of herbaceous cover helped increase the moisture level in the topsoil (0–10 cm), and soil moisture in the deeper layer between 20 and 60 cm below the surface was mostly affected by plantations. The after planting SMC of artificial plantations in areas with sufficient precipitation (mean annual precipitation (MAP) 617 mm) may increase with stand age due to soil water-holding capacity and soil water retention ability improvements after planting. For areas in water shortage (MAP 509 mm), evapotranspiration caused the soil of the plantation to dry up in the first 20 years of growth. Then as the plantation aged, evapotranspiration decreased, and the soil profile recovered gradually. In areas where water was extremely lacking, soil moisture was too rare to be used by trees, and after-planting SMC variation with stand age was insignificant. For the sustainability of artificial ecosystem, the construction of artificial plantations needs to be thoroughly evaluated on regional scale based on the climate conditions (especially rainfall) and soil moisture conditions in arid and semiarid areas.

1 Introduction

Over the past century, afforestation and reforestation (artificial forestation) have been implemented extensively (FAO, 2006). Increasing attention has been paid to its ecological impacts. Artificial forestation was initially featured as an effective way to alleviate water loss and soil erosion, control desertification, conserve biodiversity (Lugo, 1997; Parrotta et al., 1997; Chirino et al., 2006; Barlow et al., 2007; Porto et al., 2009).

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Recently, it has also 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), artificial forestation since the mid-1970s to 1998 in China has sequestered 0.45 petagram of carbon for biomass increase. Now, reforestation and afforestation are acknowledged to be effective ways to increase carbon storage in soil (Resh et al., 2002). Moreover, the decrease of bulk density and the increase of SOM (soil organic matter), porosity, and aggregates associated with tree planting (Kahle et al., 2005; Ilstedt et al., 2007; Li and Shao, 2006) lead to improvement in soil properties. In other cases, the fast growth rates of planted trees compared to native vegetation and frequent removal of biomass can lead to soil nutrient depletions (Merino, 2004; Berthrong et al., 2009). Yet, one of the most concerned topics concerning artificial forestation may be the relationship between forest and water.

The hydrological ramifications of artificial forestation have been studied intensively 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 elaborated on the close relationship between tree planting and runoff reduction (Brown et al., 2005, 2007; Bruijnzeel, 2004; Farley et al., 2005). This association may be most critical in arid and semiarid areas (Farley et al., 2005), which are susceptible to degradation (Puigdefàbregas and Mendizabal, 1998). In arid and semiarid 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 yield and available water resources, most researches have focused on the effects of plantations on water yield. However, soil moisture changes after tree planting is of great significance for vegetation restoration and ecosystem sustainability in dry climate conditions (Schume et al., 2004; Wang et al., 2004; Zhao and Li, 2005; Yang et al., 2010).

Planted trees affect 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 detention by increasing the hydraulic conductivity values of the duff layer (Robichaud, 2000). Soil physical and chemical properties (such

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as SOM, bulk density, porosity, hydraulic conductivity, etc.) influence the transformation of precipitation into soil moisture and the soil water-retention capacity. These soil properties can be improved effectively through natural and artificial re-vegetation (Ilstedt et al., 2007; Li and Shao, 2006). However, artificial forestation can also decrease soil moisture due to the effects of leaf interception and root uptake. Gordon (1998) reviewed studies of Melaleuca and Sapium plantations in Florida and found that high evapotranspiration can dry soils and drain wetlands. According to Chirino et al. (2001), 23–35% of total annual rainfall is intercepted by *Pinus halepensis* canopies.

SMC after tree planting varied differently under different conditions. According to previous studies, the effects of plantations on topsoil moisture at 0–15 cm depths have been reported to be either significantly negative (Breshears et al., 1997), positive (Joffre and Rambal, 1998), neglectable (Koechlin et al., 1986), or not apparent (Maestre et al., 2003). Recently, most studies have focussed on short-term spot variation (Breshears et al., 1997; Cao et al., 2006; Koechlin et al., 1986; Li, X. R. et al., 2004; Maestre et al., 2003), and long-term regional scale studies are rarely reported.

The Loess Plateau, with a typical semiarid climate, suffers from ecosystem degradation due to severe water loss and soil erosion (Chen et al., 2001). Since the 1950s, the Chinese Government has invested aggressively to conserve soil water and restore the ecosystems (Fu et al., 2002). Currently, reforestation is extensive in the Loess Plateau, but some negative effects of reforestation have been reported (McVicar et al., 2007; Yang et al., 2010). In some areas, reforestation has led to the emergence of a dry soil layer (Shangguan, 2007).

This study is designed to investigate regional variability of soil moisture and soil moisture dynamics with stand age in artificial forestation by examining the following: 1) after-planting SMC variation with stand age in different watersheds and 2) environmental factors affecting soil moisture on a regional scale.

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2 Methods

2.1 Study sites

The study was conducted between late July and early August 2008 in the northern part of Shaanxi Province in the Loess Plateau (35.16° N–37.86° N, 108.11° E–110.22° E; 916–1586 m a.s.l.). The area has a continental monsoon climate. The mean annual temperature (MAT) is 9.2–11.5 °C and the mean annual precipitation (MAP) is 352–618 mm, as calculated from 7-year averaged temperature and precipitation records from 2000–2006 at 174 well-distributed climate stations in the Loess Plateau. The most widely distributed soil type is loessial soil (Guo, 1992). The vegetation zone changes from temperate forest-steppe to temperate steppe (Wu, 1980) from southeast to northwest. Indigenous vegetation is seldom found in this area due to human activities. Much of the land has been reforested to woodland. The most common tree species are Black Locust (*Robinia pseudoacacia* L.), Chinese Pine (*Pinus tabulaeformis* Carr.), and Korshinskii Pea-shrub (*Caragana korshinskii* Kom.). *Robinia pseudoacacia* L. is an exotic nitrogen-fixing tree native to Southeastern North America. It has been widely cultivated for restoration because of its drought resistance, high survival rate, ability to improve soil nutrient status and remarkable growth rate (Li et al., 1996; Shan et al., 2003). At the present, it is the most widely cultivated species in the Loess Plateau.

30 sites were selected for the study on the regional scale (Fig. 1), which cover 300 km long and 190 km wide. They span across a wide range of precipitation from 617 mm per year to 352 mm per year. 12 sites in three watersheds were picked out for the analysis of after-planting SMC variation in different watersheds. As shown in Fig. 1, watershed W1 is located at the southern margin of the Loess Plateau and is the wettest and warmest area in the region. The MAT is 11.0 °C and the MAP is 617 mm. The landscape is typical of the plateau topography and is relatively flat compared to the northern part of the Loess Plateau in Shaanxi province. Watershed W2 is a typical loess hilly-gully region with MAT 10.4 °C and MAP at 509 mm. Watershed W3 is located at the transitional zone between the desert area in the north and the Loess Plateau

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hilly-gully area in the south, having the lowest MAT at 9.5 °C and MAP at 352 mm.

The stand age was determined by questioning local inhabitants. Historically, reforestation was implemented mainly on high slopes that were previously cultivated for slope farmland, and the *Robinia pseudoacacia* L. saplings were usually planted in fish-scale pits. To minimize the side effects from planting methods and slope (Querejeta et al., 2001), plantation with similar landscape features were selected.

2.2 Sample collection and analysis

At each site, latitude, longitude, and elevation were determined using a Garmin GPS60 (Garmin International Inc., Olathe, KS, USA). Slope and aspect were determined using a compass. Four aspect classes were used in our analysis (Qiu et al., 2001): (1) 135–225 °C, (2) 225–315 °C), (3) 45–135 °C, and (4) 315–360 °C and 0–45 °C. To prepare for field measurement, a 10 m×10 m quadrat was established, and three 2 m×2 m subquadrats were chosen along the major diagonal of the 10 m×10 m quadrat. In the 10 m×10 m quadrat, stand density, canopy density, and the average diameter at breast height (DBH) were recorded. In the three 2 m×2 m subquadrats, herbaceous cover was recorded and soil samples were collected using a soil auger to a depth of 100 cm at intervals of 10 cm. SMC was measured using the oven dry method. Soil organic carbon (SOC, $mg\,g^{-1}$) was determined using the $K_2Cr_2O_7$ titration method for soils at depths of 0–10 cm, 10–20 cm, and 50–60 cm.

2.2.1 Statistical analysis

SMC was analyzed on two different scales. On the watershed scale, depth-averaged SMC with different stand ages in each watershed of the three typical watersheds was compared using a one-way ANOVA. Watershed-averaged SMC from the three watersheds was also compared using this method. Multiple comparisons were made using the least significant difference (LSD). On the regional scale, all data from the 30 sites were combined. To identify the relationships between SMC (depth-averaged SMC and

SMC at different depths) and environmental factors such as geographical (longitude, latitude, and altitude), slope (aspect and slope), and vegetation (tree density, stand age, and herbaceous cover) variables, a bivariate correlation was conducted. One-way ANOVA and bivariate correlations were all performed with SPSS 16.0.

Canonical correspondence analysis (CCA), a constrained ordination technique, was used to identify specific environmental variables at different depths. CCA was performed using the program CANOCO (Ter Braak, 1987) version 4.5. The following environmental variables, which showed significant correlations with SMC at different depths on the regional scale, were included in the CCA: latitude, stand age, herbaceous cover, canopy density, and stand density.

3 Results

3.1 Soil moisture variation with stand age in different watersheds

The SMC profiles in different watersheds exhibited large differences. In watershed W1 (Fig. 2a), the average SMC is generally the highest in the three watersheds due to the highest amount of precipitation. In soil profile, SMC decreased slightly along the soil depths (0–100 cm). The 30-year-old tree sites maintained a significantly higher SMC than sites of the younger trees. In W2 (Fig. 2b), the SMC is medium high as the precipitation is, but displayed two distinct layers. In the top layer from 0 to 40 cm, the SMC decreased rapidly with depth. In the lower layer, the SMC was relatively constant except for the youngest, 5-year old trees with which the SMC decreased gradually in the top 70 cm depth. In the driest watershed W3 (Fig. 2c), the SMC was very low (below 5%) and kept almost constant from top to bottom. The 10-year-old trees maintained higher moisture content of about 6% at all depths. The 45-year-old trees maintained the highest SMC (about 7.8%) at the soil surface.

As shown in Fig. 3, the SMC level is highest in watershed W1, medium in W2 and lowest in W3, corresponding to the distribution of precipitation. However, the SMC also

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changed with stand age. In W1, the SMC levels are high (at about 15%) for trees younger than 20 years, but are higher (at about 17%) for the 30-year-old trees. In W2, the SMC initially decreased from 12.7% to 7.1% for tree stand ages between 5 and 20 years, and then increased to 8.5% for the 30-year-old. In W3, the SMC levels are very low (4–6%) and seem to be unchanging with the stand age. The slightly higher SMC in the 10-year-old stand may come from different stable SMC in long drought condition resulting from soil texture and physicochemical property divergences. The watershed-averaged value (4.61%) is close to the permanent wilting point of the soil (Li et al., 1996; Wang et al., 2004).

3.2 Relationship between environmental factors and soil moisture on the regional scale

On the regional scale, the depth-averaged SMC was positively correlated with canopy density and stand density, and negatively correlated with latitude and stand age (Fig. 4a–d). No significant relationship was found between SMC and slope or aspect (Fig. 4e,h).

Changes in terrain (which changed from plateau to hilly-gully with the increasing latitude) were accompanied with the variation of canopy density, herbaceous cover, and stand density. Canopy density and stand density decreased with increasing stand age (Table 1).

3.3 Main environmental factors at different soil depths

The SMC is correlated to certain environmental factors at different soil depths (Table 2). Significant negative relationships between SMC and stand age were found only in the 20–60 cm depths (Table 2). In the 0–10 cm topsoil, SMC was positively correlated to herbaceous cover ($r=0.366$, $p<0.05$, Table 2).

Axes 1 and 2 represent 16.2 and 4.7% of the variation in the data (Fig. 5), respectively. Herbaceous cover was the dominant environmental variables correlating with

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the first CCA axis. The second axis was correlated with latitude, stand age, stand density, and canopy density. SMC values at ten different depths were assembled into three layers: 0–20 cm, 20–50 cm, and 50–100 cm. Herbaceous cover exerted a positive effect on the soil from 0 to 20 cm. Stand age most influenced SMC from 20 to 60 cm. SMC from 60 to 100 cm was similar. This result was consistent with the results of the bivariate correlations between SMC at different depths and environmental factors (Table 2).

4 Discussion

4.1 Variability of soil moisture

4.1.1 Variability with stand age in different watersheds

Although on a regional scale the depth-averaged SMC decreased with stand age (Fig. 4d), the relationship between SMC and stand age differed by watershed.

It can be seen that W1 (MAP=617 mm) had a high SMC than other sites. Steady high SMC levels demonstrated good profile water supplementation (Fig. 2a). A previous study showed that soil water in the growing season in this region is effectively maintained by natural rainfall (Li, 1983). We found that the watershed-averaged SMC was 15.48%, which is roughly equivalent to the average water-holding capacity of the soil (at about 15.00%, Li et al., 2008). Under such conditions, the root uptake effect on SMC was lessened by intermittent supplementation from precipitation, and the SMC depended largely on the soil water-holding capacity and soil water retention ability. Joffre's research (1988) in Southern Spain (mean annual rainfall 650 mm) revealed that soil water content in woodland sites were greater than grass sites with the improvement of soil permeability and water hold capacity after plantation.

Soil water-holding capacity and soil 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 has not changed significantly for a century (Li and Shao, 2006). The SOM promotes the formation of soil aggregates by binding soil particles together and increasing soil porosity and then 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). Thus, 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 increased significantly with increasing stand age (0–10 cm, $r=0.49$, $P<0.01$; 10–20 cm, $r=0.551$, $P<0.01$). This finding is consistent with that of Paul and Colleagues (2002). SMC had a significantly positive correlation with SOM. Therefore, the soil moisture status would probably increase with the stand age in W1. In W2 and W3 (Fig. 6b,c), relationships between SMC and SOM are less pronounced, indicating the diminished effect of soil water-holding capacity on SMC.

In W2 (Fig. 2b), insufficient profile water supplementation is responsible for the appearance of a turning point. The effects of precipitation and root uptake on SMC become sufficiently distinctive. Precipitation only wetted the upper soil layer. The concentration of effective roots for *Robinia pseudoacacia* L. at depths of 20 to 60 cm implied the intensive effect of roots on SMC in this layer (Cao et al., 2006; Liu et al., 2007; Wang et al., 2004). Water use by plantation 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 are 15 years old (Roberts et al., 2001; Vertessy et al., 2001). In the early stages of a plantation, reforestation dries up the soil quickly as evidenced by the increasing plantation water use. From Fig. 3, we can hypothesize that the peak water usage for *Robinia pseudoacacia* L. in this area occurs when the stand is between 20 and 30 years of age. Decreased water usage of aged trees might be another reason for the higher SWC of the 30-year old tree site in W1.

In watershed W3 (Fig. 3c), plantation evaporation and the limited precipitation led to a persistent severe soil water deficit (Meng et al., 2008). SMC was near the wilting point (Li et al., 1996). Therefore, water was not consistently available to plants. No obvious trend was found between SMC and stand age. The SMC variation probably came from differences in slope, aspect, and soil texture.

4.1.2 Spatial variability and environmental factors

Generally, spatial variability of SMC is decisively affected by precipitation which decreases with the increase in latitude (Fig. 7). Besides water availability, increasing proportion of the sand particles in the soil led to decreasing water-holding capacity and the stable SMC in the north of the studied area (Yang and Yu, 1990).

At the same initial stand density, the tree density of old reforestation plantations was lower than that of new plantations due to drought and niche competition (Guarín and Taylor, 2005; Negrón et al., 2009; Worrall et al., 2008). However, low stand density does not necessarily suggest low canopy interception and soil water uptake. According to a study by Wang et al. (2007), the root biomass of a 26-year-old *Robinia pseudoacacia* L. plantation was 8.1 times that of a 5-year-old plantation at 0–50 cm in depth. As stand age increased, although stand density and canopy density decreased significantly (Table 1), root biomass may increase and an increased amount of water could be transferred for transpiration. In addition, with increasing latitude, the water source decreases, leading to the decrease in canopy and stand density (Table 1). All of the reasons discussed above may have led to the positive correlations between SMC and canopy and stand density. When latitude and stand age were controlled, no significant relationship was found between SMC and canopy and stand density.

The soil surface layer is important for energy and matter exchange in the soil-plant-atmosphere system. Herbaceous cover exerts an effect on SMC via shielding and root uptaking. Loess soil shows strong evaporation potentials due to its uniform texture, developed capillary porosity, and low suction force for water (Hu and Shao, 2002). The shielding may affect the energy exchange between the soil and atmosphere and

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decrease the diurnal temperature and temperature variation in the topsoil (Tesaø et al., 2008; Verhoef et al., 2006). Low temperatures in the topsoil lead to decreased evaporation from bare soil and increased condensation (Alvarez et al., 2006). All of these factors improve soil moisture conditions in the topsoil, but the effect diminishes with soil depth. The shielding effect may be counteracted by plant root uptake for transpiration below the 10 cm soil profile. Only in the topsoil (0–10 cm), SMC was positively correlated to herbaceous cover significantly ($r=0.366$, $P<0.05$, Table 2).

Robinia pseudoacacia L. is a shallow-rooted species. Although the deepest vertical root depths found varied from 190 cm (Wang et al., 2004) to 120 cm (Liu et al., 2007) in the Loess Plateau, the effective roots were concentrated at a depth of 0–60 cm, especially at a depth of 20–60 cm (Cao et al., 2006; Liu et al., 2007; Wang et al., 2004). This implies that there is a severe water uptake layer at a depth of 20–60 cm. A dramatic increase in root density with stand age accounted for the negative relationship between stand age and SMC between 20 and 60 cm. However, the intensity and direction of the relationship between SMC and stand age may be affected by other environmental factors.

4.2 Potential effect of reforestation on later vegetation restoration

Although 30-year-old tree site maintained a significant higher SMC than sites of the younger trees in W1 (Fig. 2a), on a regional scale SMC decreased significantly with stand age during the growing season (Fig. 4d). This trend may exert a negative effect on the ecological environment and vegetation renewal. The growth of reforested trees was limited by this drying trend, thus many “dwarves” were found (Han and Hou, 1996; Hou and Huang, 1991). Furthermore, undergrowth vegetation succession may be accelerated. Species that are adaptable to dry environments and have shadowed roots would quickly dominate, and it would likely be decades before natural succession result in a new system of vegetation structure and species composition (Francis and Parrotta, 2006; Li et al., 2004).

Plantations in dry sites not only lead to drought stresses on the planted trees, it also depletes soil moisture which is critical to vegetation restoration. Tree adaptability and ecological significance of plantation should be comprehensively considered in the reforestation process.

5 Conclusions

Restoration of arid and semiared ecosystems is primarily water-limited. In the north of the Loess Plateau where MAP is less than 400 mm, and soil moisture was near the wilting point. Over-planting here will not only lead to a waste of invested money and human power but will also hamper the restoration of degraded ecosystems. On the contrary, high SMC in the south of the study area can maintain the growth of planted trees during the growing season. Plantations here can probably improve soil water statue and promote natural recovery. Therefore, local environmental conditions should been take into the count in the construction of artificial plantations. More Large-scale and long-term researches are needed badly to support a more effective restoration policy.

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Table 1. Bivariate correlation between environmental factors.

	Canopy density (%)	Aspect	Herbaceous cover (%)	Stand density (/100 m2)	Average DBH (cm)	Average tree height (m)	Longtitude (°)	Elevation (m)	Stand age (yr)	Slope (°)
Aspect	ns									
Herbaceous cover (%)	ns	ns								
Stand density (/100m2)	0.576**	ns	ns							
Average DBH (cm)	ns	ns	ns	−0.481**						
Average tree height (m)	0.454*	ns	ns	ns	0.541**					
Longtitude (°)	ns	ns	ns	ns	ns	ns				
Elevation (m)	ns	ns	ns	ns	ns	ns	−0.645**			
Stand age (yr)	−0.386*	ns	ns	−0.546**	0.719**	ns	ns	ns		
Slope (°)	−0.409*	ns	−0.438*	ns	ns	ns	ns	ns	ns	
Latitude (°)	−0.698**	ns	−0.369*	−0.588**	ns	ns	ns	ns	ns	0.541**

$N=30$.
* $P<0.05$.
** $P<0.01$.
ns means not significant.

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Table 2. Bivariate correlations between SMCs and environmental factors at different soil depths.

Soil depth (cm)	Stand age	Herbaceous cover	Tree density	Latitude	Canopy density
0–10 cm	n.s.	0.366*	0.581**	–0.750**	0.601**
10–20 cm	n.s.	n.s.	0.622**	–0.818**	0.650**
20–30 cm	–0.406*	n.s.	0.624**	–0.795**	0.656**
30–40 cm	–0.0399*	n.s.	0.588**	–0.793**	0.649**
40–50 cm	–0.398*	n.s.	0.571**	–0.809**	0.634**
50–60 cm	–0.364*	n.s.	0.538**	–0.783**	0.629**
60–70 cm	n.s.	n.s.	0.554**	–0.801**	0.623**
70–80 cm	n.s.	n.s.	0.533**	–0.795**	0.639**
80–90 cm	n.s.	n.s.	0.517**	–0.783**	0.629**
90–100 cm	n.s.	n.s.	0.543**	–0.794**	0.633**
Average	–0.384*	n.s.	0.569**	–0.806**	0.646**

$N=30$.
* $P<0.05$.
** $P<0.01$.
n.s. not significant.

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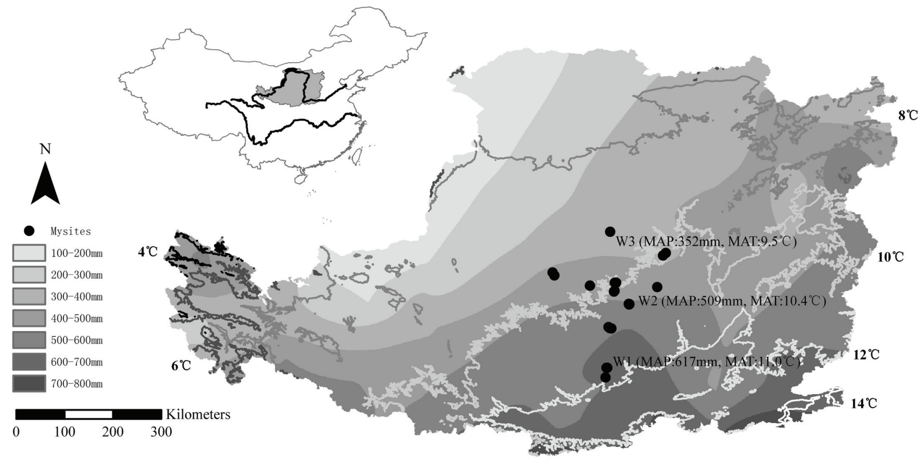

Fig. 1. Map of the study area and the distribution of the mean annual temperature (MAT) and the mean annual precipitation (MAP). 30 sites were selected in all. W1, W2 and W3 are three watersheds located, respectively in northern, middle, and southern part of the study area.

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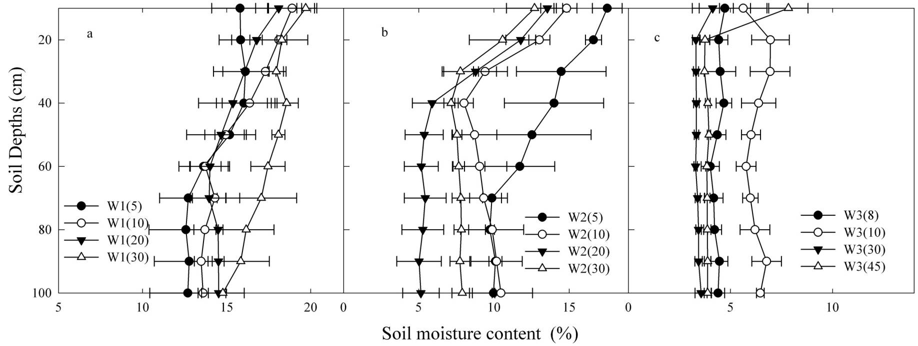

Fig. 2. Soil moisture profiles (mean±SD) in watersheds W1 **(a)**, W2 **(b)**, and W3 **(c)**.

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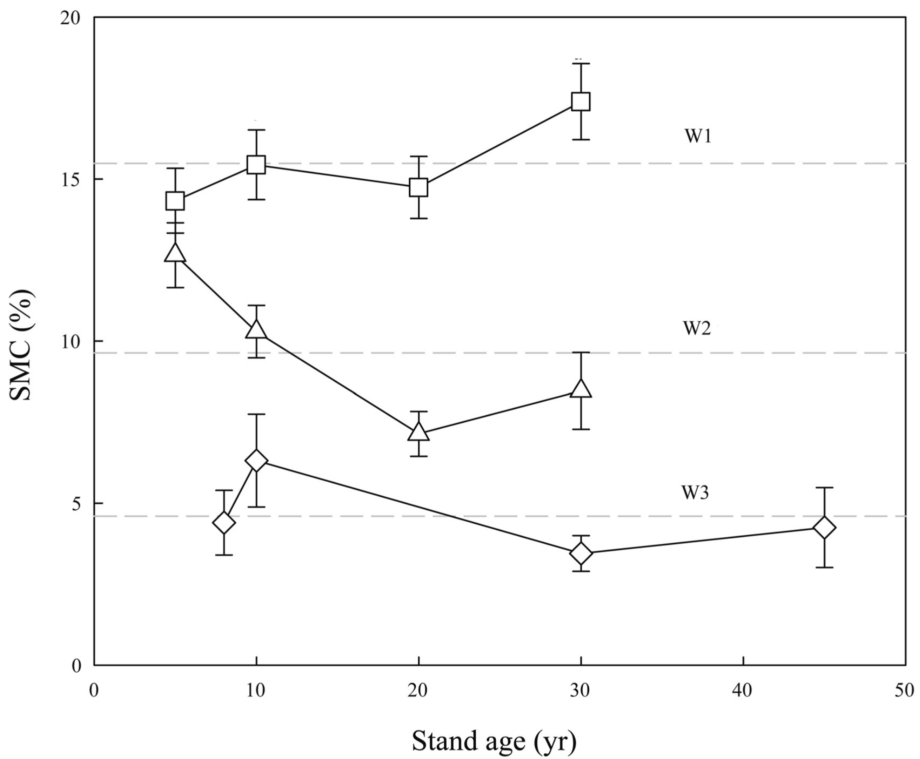

Fig. 3. Depth-averaged SMC in 0–100 cm depths in watersheds W1, W2 and W3. Bars indicate standard deviations of the means. Watershed-averaged SMC values from the three watershed were all significantly different from each other ($P<0.05$).

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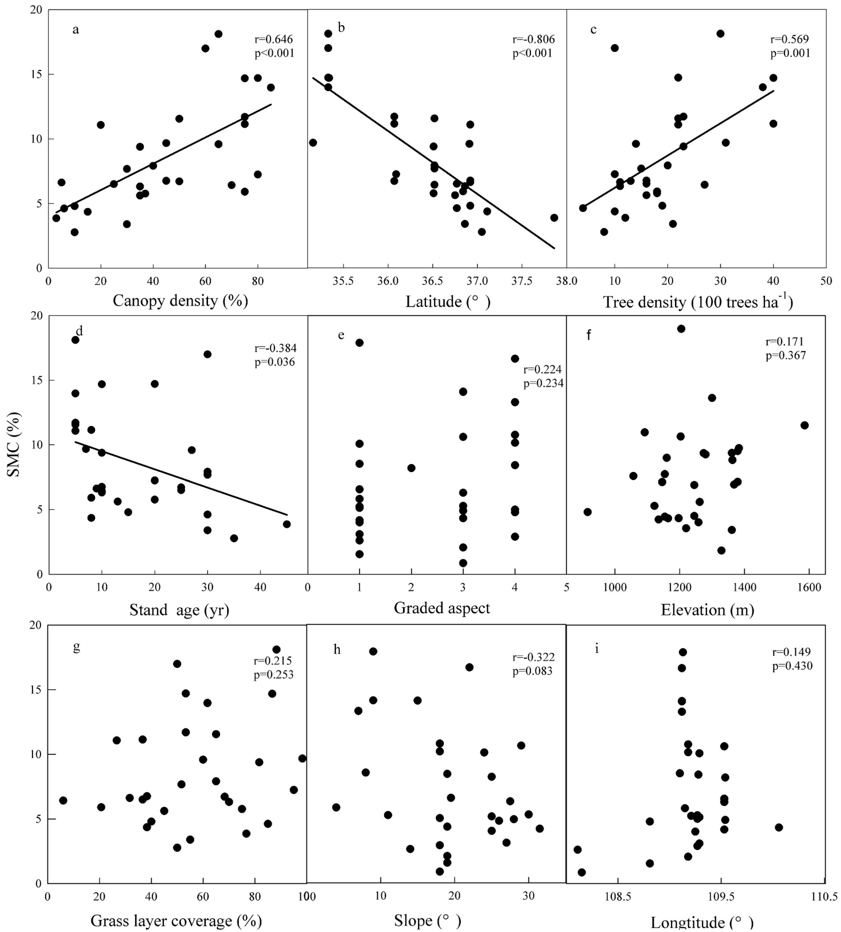

Fig. 4. Bivariate correlation between depth-averaged SMC (0–100 cm) and the relevant environmental factors.

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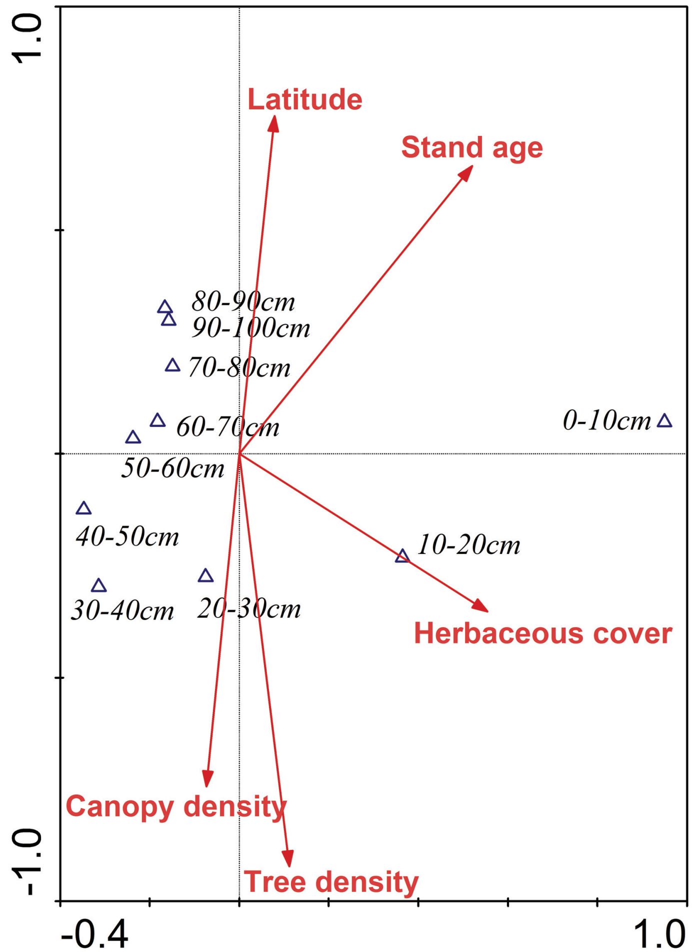

Fig. 5. CCA ordination biplot showing the relationship between SMC and environmental factors at different soil depths.

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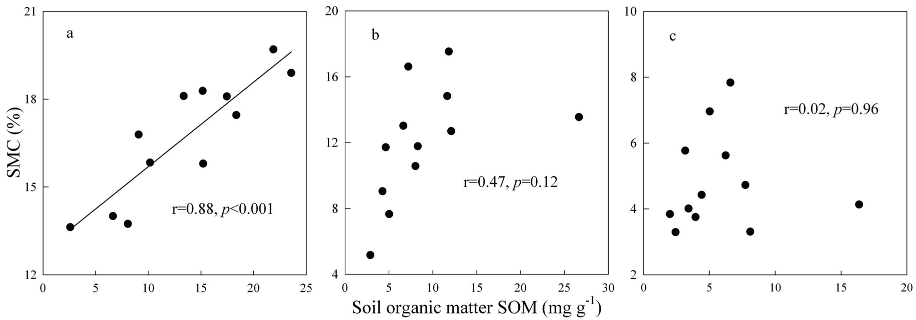

Fig. 6. Correlation between SMC and SOM (soil organic matter) in watershed W1 **(a)**, W2 **(b)**, and W3 **(c)**.

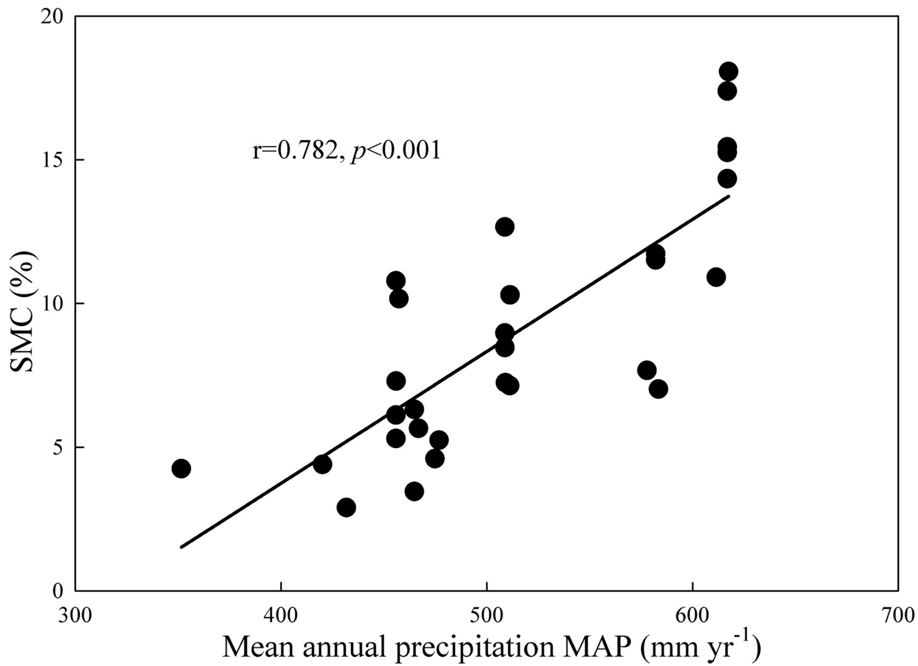

Fig. 7. Linear regression between mean annual precipitation (MAP) and SMC.

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