Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-22, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 19 January 2016

Hydrology and Earth System Sciences
Discussions
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Spatial variations of deep soil moisture and the influencing factors in the Loess Plateau, China

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Abstract:

Soil moisture in deep soil layers is a relatively stable water resource for vegetation growth in the semi-arid Loess Plateau of China. Characterizing the spatial variations of deep soil moisture and its influencing factors at a moderate watershed scale is important to ensure the sustainability of vegetation restoration efforts. In this study, we focused on analyzing the spatial variation and factors influencing soil moisture content (SMC) in (0-500 cm) soil layers based on a soil moisture survey of the Ansai watershed, Yanan, Shannxi province. Our results can be divided into four main findings. (1) At the watershed scale, the higher spatial variation of deep SMC occurred at 0-20 cm, 120-140 cm and 480-500 cm in the vertical direction. At a comparable depth but in the horizontal direction, the spatial variation of deep SMC under native vegetation was much lower than that in human-managed vegetation and introduced vegetation. (2) The deep SMC in native vegetation and human-managed vegetation was significantly higher than that of introduced vegetation, and different degrees of soil desiccation occurred under all introduced vegetation types. (3) Taking the SMC condition of native vegetation as a reference for local control, soil could be divided into four layers: Ⅰ) shallow rapid change layer (0-60 cm); Ⅱ) main rainfall infiltration layer (60-220 cm); Ⅲ) transition layer (220-400 cm); and Ⅳ) stable layer (400-500 cm). Positive and significant correlations existed between SMC at layers Ⅱ, Ⅲ and Ⅳ, and the correlations of the neighboring layer ranges were clearly stronger than that of nonadjacent depth ranges, although the SMC at shallow rapid change layer Ⅰ showed a disconnect (i.e., no correlations) with those at the three other soil depth layers. (4) The influencing factors of deep SMC at the watershed scale varied with land management types. The main local controls of SMC variation were soil particle composition and annual average rainfall; human agricultural management measures can alter soil buck density, which contributes to higher deep SMC. In introduced vegetation, plant growth conditions, planting density, and litter water

holding traits showed significant relationships with deep SMC. The results of this study are of practical significance for vegetation restoration strategies and the sustainability of restored ecosystems.

1 Introduction

Soil moisture is an indispensable component of the terrestrial system and plays a critical role in surface hydrological processes, especially runoff generation, soil evaporation and plant transpiration (Baroni et al., 2013; Cheema et al., 2011; Chen et al., 2008a; Chen et al., 2007; Legates et al., 2010; Sun et al., 2015; Wang et al., 2012a; Wang et al., 2015b; Zhang et al., 2014; Zhao et al., 2013). Moisture in deep soil layers is essential and is closely connected to shallow soil moisture and deep groundwater. It also works as a reservoir for soil, which is important for plant growth in dry seasons (Jia and Shao, 2014; Yang et al., 2012b). This is particularly true in semi-arid areas, such as the Loess Plateau of China, where water resources are incredibly scarce. In such regions, deep soil moisture even becomes the main constraining factor of plant productivity and ecosystem sustainability (Wang et al., 2011a; Wang et al., 2010b).

The Loess Plateau of China is located in a semi-arid area. The average annual rainfall in this region ranges from 150 to 800 mm, which is far lower than the average annual pan evaporation (1400–2000 mm) (Wang et al., 2010a). Low precipitation and high evaporation results in lower soil moisture content in this region. The shallow soil moisture is not sufficient to meet the needs of introduced vegetation growth. Moreover, loess soil thickness in this area ranges from 30-80 m; at these depths, groundwater is not available for plants (Wang et al., 2013). Therefore, deep soil moisture, which is stored in unsaturated soil, becomes an important water resource for plant growth (Yang et al., 2012b). However, the vegetation introduced by the national Grain for Green project tends to have strong water consumption. Large-scale afforestation has resulted in the excessive consumption of deep soil moisture, and a large range of soil desiccation has been reported (Wang et al., 2008b; Wang et al., 2010a; Wang et al., 2010b; Wang et al.,

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2011b). Soil desiccation greatly reduces the capability of a "soil reservoir" to supply water to deep soil layers for plant growth in the Loess Plateau (Chen et al., 2008b). Introduced vegetation in desiccated land is easily degraded with low productivity, and "small aged tree" with a height of 3–5 m appeared widely. Therefore the sustainability of the restored ecosystem is being challenged. Moreover, traditional soil moisture studies, which have mainly focused on shallow depth layers (Baroni et al., 2013; Bi et al., 2009; Gómez-Plaza et al., 2001), clearly cannot reveal the sustainability need for vegetation restoration.

Studies on deep soil moisture have gradually drawn attention from many scientists in recent years. For example, it was recently found that deep soil moisture was excessively consumed by almost all the introduced vegetation, and high planting density was the main reason for the severe deficit of soil moisture (Yang et al., 2012b). It was also found that introduced vegetation diminished the spatial heterogeneity of deep soil moisture at the small catchment scale (Jia and Shao, 2014; Yang et al., 2014b). In recent years, several studies have been conducted on the spatial variation and influencing factors of deep soil moisture in the Loess Plateau (Jia and Shao, 2014; Liu et al., 2010; Sun et al., 2014; Wang et al., 2012b; Wang et al., 2013; Yang et al., 2014a). Deep soil moisture is an indispensable water source for vegetation growth in the semi-arid Loess Plateau; understanding the spatial variation and influencing factors of deep soil moisture is important for "timely, suitable, and moderate" vegetation restoration, and it can also help in developing proper measures that can help control soil desiccation. In fact, deep soil moisture content (SMC) is a result of long-term biophysical processes controlled by multiple factors (Vereecken et al., 2007). Several factors may impact soil moisture variation, such as vegetation traits, soil properties, topographical factors, climate factors, and human landscape management measures (Lu et al., 2007; Lu et al., 2008; Montenegro and Ragab, 2012; Qiu et al., 2001; Vivoni et al., 2008; Zhu and Lin, 2011). The dominant factors that affect deep SMC spatial variation depend on the research scale (Entin et al., 2000). For instance, deep SMC variation was found to be mainly dominated by the

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type of vegetation at the slope scale (0.1-1 km^2) (Jia et al., 2013). It was also found that vegetation and topography are key factors contributing to deep SMC variation at the small catchment scale (1-100 km^2) (Yang et al., 2012a). Meanwhile, Wang et al. (2012b) reported that deep SMC variation at the regional scale (i.e., the whole Loess Plateau, covering 640,000 km^2) is mainly determined by plant types and climatic conditions. Note that vegetation factors play an important role in the spatial variation of deep SMC at all scales (Western et al., 2004). While all spatial scales, from slopes and small catchments to regions are relevant to the understanding of deep SMC variation, some scales are more operational and meaningful than others. For example, slopes and small catchments based studies tend to be too small in spatial extent to incorporate all environmental factors and human-managed measures (soil traits, climate characteristics, and human-managed measures in one slope or small catchment are usually homogeneous) that most relevant to deep SMC variation (Bi et al., 2009; Gómez‐Plaza et al., 2000; Zhu et al., 2014a; Zhu et al., 2014b), whereas at the region scale, it is often impossible to assess essential mechanistic details (high variation of rainfall and temperature can cover the influencing effects of other factors) of deep SMC variation necessary for guiding local policies (Wang et al.,2010a; Wang et al., 2010b; Wang et al., 2012). A moderate scale, covering an area of approximately 100-1000 km^2 over a watershed or a geopolitically-defined area represents a pivotal scale domain for the research of deep SMC variation mechanism. In particular, it is the scale at which people and nature mesh and interact most acutely (Fang et al., 2015; Zhao and Fang, 2014), and thus is a more operational scale for sustainable vegetation restoration policy making. Up to date, however, little particular research of deep SMC variation has centered on such a moderate scale, and the variation mechanism of deep SMC at this kind of scale is still unclear.

In this study, we aimed to reveal the spatial variation of deep SMC and its influencing factors at a moderate watershed scale. According to previous studies, factors that control deep SMC variations are different under three land management types: native vegetation with a shallow root system, introduced vegetation with a deep root system, and vegetation with agricultural management measures (Jia et al., 2013; Jia and Shao, 2014; Yang et al., 2012b; Yang et al., 2014a). This study included all three land management types, covering eight specific vegetation types. We first explored the overall variation of SMC in this area and then compared the deep SMC of these three different land management types as well as identify variations in their profiles. Furthermore, the influence of various environmental factors on deep SMC under different vegetation types is discussed. The objectives of this study were to: (1) quantify the spatial variation characteristics of deep SMC; (2) explore the mechanisms for controlling deep SMC variability among different land management types at the watershed scale; (3) develop recommendations for land use management and the sustainability of vegetation recovery for the Loess Plateau.

2 Materials and Methods

2.1 Study area

The Yanhe watershed lies in the middle of the Loess Plateau in the northern Shaanxi Province. The Ansai watershed (108°47′-109°25′E, 36°52′-37°19′N) (Fig. 1) in this study is located in the upstream section of the Yanhe river, covering an area of approximately 1334 km^2, with a highly fragmented terrain; the elevation here ranges from 1057 m to 1743 m above sea level. This typical semi-arid loess hilly region has a mean annual temperature of 8.8 ℃ and an average annual precipitation of 505 mm. Most rainfall occurs in the form of thunderstorms during the summer months from July to September. Soil types in this study area include mainly loess soil with low fertility and vulnerability to soil erosion (Zhao et al., 2012).

The Ansai watershed is located on a warm forest steppe; the predominant land use types in the watershed are rain-fed farmland, orchard land, sparse native grassland, pasture grassland, shrub land, and forest (Feng et al., 2013). The native vegetation in the study area consists of sparse grasses with shallow roots dominated by species, such as bunge needlegrass, common leymus, and Altai heterpappus. Non-native species, such as alfalfa, black locust, David peach, sea buckthorn, and *Caragana korshinskii*, were predominantly used in the study area under the national

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Grain for Green project. The cultivated crops are predominantly maize, millet and broom corn millet. Being in a semi-arid climatic zone, water resources represent the major constraint of vegetation growth and agricultural crop production.

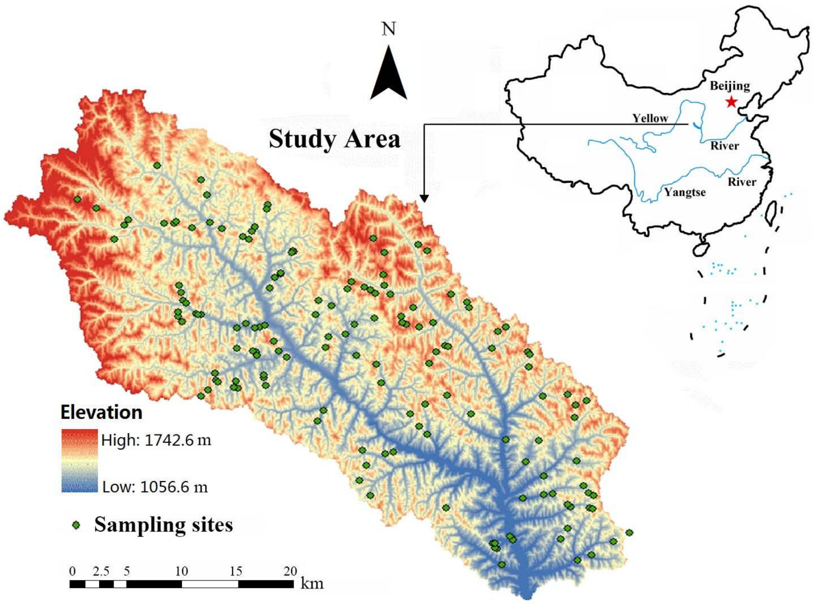

Figure 1. Location of the study area and sampling sites.

2.2 Sampling locations and description

In this study, three land management types were selected, including: (1) native shallow root vegetation: native grasses (NG); (2) introduced deep root vegetation: pasture grasses (PG), sea buckthorn (SB), *Caragana korshinskii* (CK), David peach (DP), and black locust (BL); (3) human-managed vegetation: farmland (FL) and apple orchard (AO). To fully explore the influencing factors of deep soil moisture, we identified the following four types of factors: topography factors, soil properties, vegetation traits, and climate factors, which further included 23 independent variables: average annual rainfall (AAR), altitude (Al), slope position (SP), slope aspect (SA), slope gradient (SG), clay (Cl), silt (Sl), sand (Sa), organic (Or), porosity (Po), soil bulk density (SBD), vegetation coverage (VC), grass biomass (GB), grass height (GH), planting density (PD), plant height (PH), diameter at breast height

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(DBH), crown width (CW), basal diameter (BD), litter max water holding (LMWH), litter biomass (LB), and clear bole height (CBH). The distance between each vegetation sampling site was at least 2 km. The sampling locations are shown in Fig. 1. The main characteristics and sampling numbers for each vegetation type are shown in Table 1.

Table 1. Main characteristics and sampling numbers for different vegetation types.

Vegetation conditions	Native vegetation	Managed vegetation		Introduced vegetation				
	NG [a]	FL	AO	PG	CK	SB	DP	BL
Sampling number	25	22	10	11	18	15	12	38
Altitude (m)	1392.60	1380.14	1370.10	1401.00	1350.61	1435.67	1377.58	1326.54
Slope aspect (°)	170.67	200.60	173.5	195.43	161.75	195.77	128.09	156.36
Slope gradient (°)	16.72	6.27	19.9	13.10	17.56	16.40	24.17	27.24
Sand (%)	44.87	39.44	38.22	55.33	46.42	46.19	52.66	39.96
Silt (%)	47.08	52.63	53.60	38.19	46.57	46.87	47.34	51.75
Clay (%)	8.06	7.93	8.18	6.49	7.01	6.95	7.40	8.30
Organic (g/kg)	7.04	5.31	5.75	6.30	13.30	8.91	5.99	8.10
Soil bulk density (g/cm^3)	1.26	1.29	1.25	1.28	1.26	1.23	1.26	1.23
Porosity	0.48	0.46	0.48	0.47	0.49	0.48	0.49	0.49
Mean canopy coverage (%)	57.36	53.27	39.70	67.82	45.61	66.07	33.75	59.58
Mean canopy height (m)	0.59	1.83	3.58	0.68	1.73	1.85	3.02	11.77
Mean tree DBH (cm)	-	-	6.32	-	-	-	4.98	10.37
Mean crown (cm)	-	-	398.39	-	199.65	184.85	293.40	455.25
Basal diameter (cm)	-	-	10.17	-	1.31	3.76	8.13	12.85
Planting density (/m^2)	-	-	30.5	-	129.67	262.40	36.17	58.66

[a] NG, FL, AO, PG, CK, SB, DP and BL refer to native grasses, farmland, apple orchard, pasture grasses, *Caragana korshinskii*, sea buckthorn, David peach and black locust, respectively.

2.3 Data collection and analysis

Each quadrat in the study area was covered by a single type of vegetation. Soil

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moisture measurements in the growing season were made for the 5 m profile in 20 cm increments from July to August in 2014. Soil samples were sealed and taken to the laboratory, and the gravimetric soil moisture content was determined using oven drying at 105 ℃ to constant weight. Three sampling profiles were randomly chosen to obtain the average soil moisture content for each sampling site. Meteorological data (Fig. 2) were obtained during the sampling period by the MILOS520 weather station located at the Ansai Research Station of Soil and Water Conservation (109°19′23″E, 36°51′26″N). The average annual rainfall (2006-2013) was provided by 29 rain gauges in or around the Ansai watershed, and the Ordinary Kriging method was performed by ArcGIS10.0 to obtain the average annual rainfall at each sampling site.

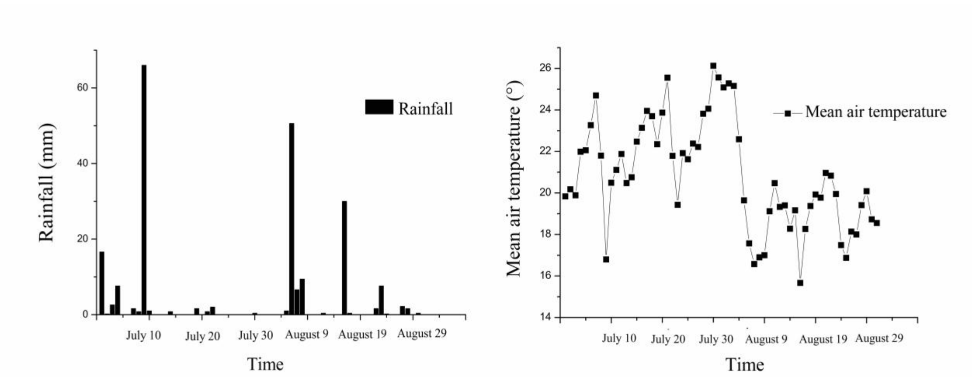

Figure 2. The rainfall (mm) and mean air temperature (℃) during the sampling period.

Longitude, latitude and altitude were collected for each experimental site using Garmin GPS (version eTrex 30). Slope gradients and slope aspects were determined using the compass method in field investigation; slope gradients were transformed into tan (slope), and slope aspects (clockwise from north) were transformed into cos (aspect). At each sampling site, six undisturbed soil cores were collected from the soil surface in metal cylinders (diameter 5 cm, length 5 cm) for measurements of bulk density and porosity (Wang et al., 2008a). Bulk density and porosity were determined from the volume–mass relationship for each core sample. Soil samples

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were also collected at each sampling site. Soil particle size distributions were measured using a laser scattering particle size distribution analyzer (BT-9300H, Dandong, China). The proportions of clay (<0.002 mm), silt (0.002-0.02 mm), and sand (>0.02 mm) content were then calculated. Soil organic matter content was determined using the dichromate oxidation method (Hu et al., 2010). At each sampling site, a vegetation investigation was also conducted. In forest sites, the stand density (plants/ha), tree height (m), diameter at breast height (DHB, cm), basal diameter (cm), under branch height (m), canopy width in a 20 m×20 m quadrat, and total canopy or coverage of each quadrat were recorded. In shrub sites, the stand density (plants/ha), plant height (m), basal diameter (cm), and canopy width in a 10 m×10 m quadrat were measured. Species composition, total herbaceous coverage, grass height (m), litters and grass biomass were measured in each herbaceous quadrat. The canopy cover was measured by visual estimation, and litter maximum water holdup was measured using the immersion method.

2.4 Statistical methods

In this study, the depth-averaged soil moisture content (SMC_d) of each sampling point was calculated using Eq. (1):

$$SMC_d = \frac{1}{k}\sum_{i=1}^{k} SMC_i , \qquad (1)$$

where k is the number of measurement layers at site j, and SMC_i is the mean soil moisture content in layer i calculated by using three random sampling profiles.

The depth-averaged soil moisture content for each vegetation type (SMC_s) was calculated using Eq. (2):

$$SMC_s = \frac{1}{m}\sum_{j=1}^{m} SMC_{i,j} \qquad (2)$$

where m is the number of sampling points for each vegetation type (Table 1), and SMC_{ij} is the depth-averaged soil moisture content in layer i at site j.

Soil moisture from each layer was pooled together for the 151 sampling locations to conduct a descriptive analysis. Basic population statistics, such as minimum values (Min), maximum values (Max), mean values (Mean), standard deviations (SD), and coefficients of variation (CV), were reported for both the overall soil moisture datasets and those by vegetation type. SD and CV were employed to reflect the degree of spatial variability of soil moisture in different layers and different vegetation types (Ruan and Li, 2002). One-way ANOVA was used to assess the contribution of different vegetation cover types to the overall variation in soil moisture variables. Multiple comparisons were made using the least significant difference (LSD) method. To determine the contributing factors to soil moisture dynamics, spearman correlation analysis was first used to examine the relationships between soil moisture and environmental variables. Then, principle component analysis was performed to reduce the linear correlation that may exist among selected environment variables and to further identify a minimum data set (MDS) of environmental variables for each vegetation type. All statistical analyses were performed using SPSS (Version 20.0).

3 Results

3.1 Summary statistics of soil moisture

The summary statistics of soil moisture at various depths are given in Table 2. Kurtosis, skewness, and the Kolmogorov–Smirnov test value indicated that soil moisture data sets were normally distributed. Thus, statistical analysis could be performed without data transformation (Shi et al., 2014). In general, the mean soil moisture, SD, and CV were highly dependent on depth. The profile distributions of mean soil moisture content, SD, and CV are given in Table 2 and Fig. 3. The highest mean value (10.65%) was observed at the 20-40 cm depth, the lowest (8.15%) was at the 120-140 cm depth, and the mean soil moisture below 300 cm was almost constant. However, both SD and CV showed waving trends with increasing depth (Fig. 3). The profile distributions of SD and CV were consistent. The highest values of both occurred at 0-20 cm, 100-120 cm, and 480-500 cm (Table 2), which indicated that soil moisture at these depth ranges had relatively higher spatial variability. Meanwhile, the lowest values occurred at 40-60 cm and 260-300 cm, which indicated lower spatial variability of SMC at these depth ranges.

Table 2. Summary statistics of soil moisture at various depths in the Ansai watershed.

Depth (cm)	n [a]	Mean (%)	SD [b] (%)	Minimum (%)	Maximum (%)	CV [c]	K [d]	S	K-S
0-20	151	9.78	3.87	2.76	20.73	0.40	-0.32	0.35	N(0.73) [e]
20-40	151	10.65	2.91	3.68	18.98	0.27	0.03	0.06	N(0.70)
40-60	151	10.20	2.91	2.30	17.52	0.29	-0.14	-0.12	N(0.59)
60-80	151	9.35	3.25	2.97	17.53	0.35	-0.50	0.04	N(0.93)
80-100	151	8.84	3.35	2.60	18.29	0.38	-0.45	0.28	N(0.95)
100-120	151	8.21	3.31	3.29	18.23	0.40	-0.27	0.57	N(1.36)
120-140	151	8.15	3.25	3.22	18.95	0.40	0.30	0.75	N(0.93)
140-160	151	8.16	3.09	3.37	18.56	0.38	0.40	0.80	N(0.99)
160-180	151	8.30	2.92	3.14	17.85	0.35	0.70	0.85	N(1.06)
180-200	151	8.47	2.70	3.22	17.89	0.32	1.48	1.01	N(1.13)
200-220	151	8.66	2.58	3.47	19.19	0.30	2.35	1.06	N(1.23)
220-240	151	8.83	2.54	3.59	19.72	0.29	2.99	1.05	N(1.02)
240-260	151	9.00	2.49	3.92	19.47	0.28	2.33	0.88	N(0.94)
260-280	151	9.00	2.37	4.08	18.46	0.26	1.94	0.74	N(1.11)
280-300	151	9.14	2.41	3.56	18.72	0.26	1.35	0.53	N(0.65)
300-320	151	9.15	2.46	3.26	18.08	0.27	1.45	0.54	N(0.73)
320-340	151	9.24	2.66	3.09	19.56	0.29	1.92	0.67	N(0.81)
340-360	151	9.36	2.83	2.98	19.38	0.30	1.31	0.59	N(0.91)
360-380	151	9.32	2.99	3.13	19.88	0.32	1.49	0.61	N(0.91)
380-400	151	9.35	3.09	2.81	20.85	0.33	1.99	0.60	N(1.00)
400-420	151	9.41	3.19	2.68	21.92	0.34	2.09	0.60	N(0.80)
420-440	151	9.33	3.21	2.70	20.97	0.34	1.43	0.55	N(0.57)
440-460	151	9.33	3.24	2.65	19.63	0.35	0.20	0.23	N(0.73)
460-480	151	9.35	3.43	2.67	19.88	0.37	-0.08	0.26	N(0.84)
480-500	151	9.45	3.58	2.43	19.98	0.38	-0.22	0.23	N(0.87)

Notes: [a] n refers to number of sampling points. [b] SD refers to standard deviation. [c] CV refers to coefficient of variation. [d] K, S, K-S refer to Kurtosis, Skewness, and the Kolmogorov-Smirnov test value, respectively. [e] N refers to normal distribution (significance level is in parentheses).

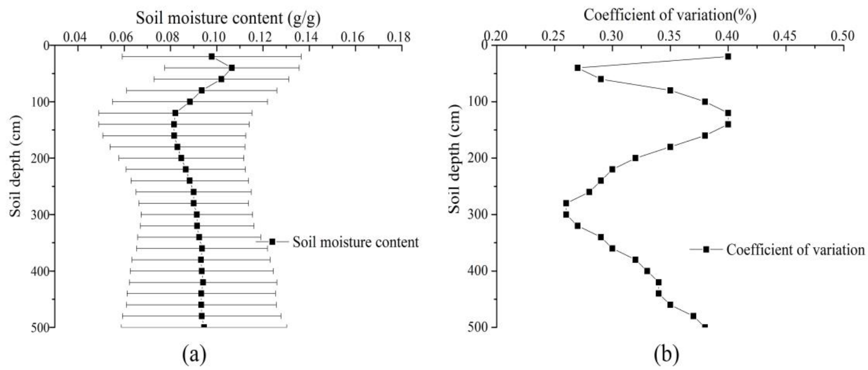

Figure 3. The profile distribution of soil moisture content and coefficient of variation.

Note: Error bar indicates standard deviation.

Moreover, different land management types greatly determined deep soil moisture variation; the soil moisture statistics of various vegetation types under different land management types are reported in Fig. 4. The results showed that the depth-averaged SMC of native vegetation and human-managed vegetation were significantly higher than that of introduced vegetation. In general, the mean soil moisture of different vegetation covers was in the order: FL>NG>AO>DP>SB>PG>BL>CK. The highest mean soil moisture existed in farmland and the lowest in *Caragana korshinskii*. This result indicated that human agricultural management measures can significantly improve soil moisture conditions and that *Caragana korshinskii* was the most serious water consuming species among the selected introduced vegetation types.

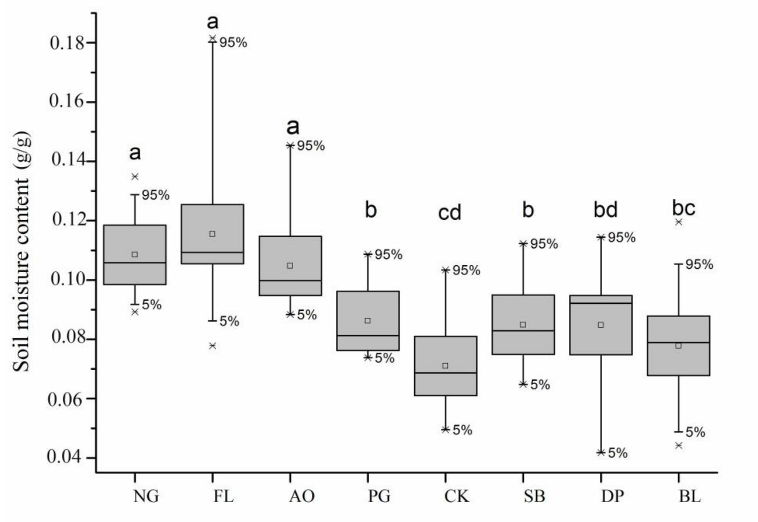

Figure 4. Soil moisture statistics for different vegetation types. Means with the same letter above the box are not significantly different at the 0.05 significance level (LSD test); NG, FL, AO, PG, CK, SB, DP and BL refer to native grasses, farmland, apple orchard, pasture grasses, *Caragana korshinskii*, sea buckthorn, David peach and black locust, respectively.

3.2 Profile distribution of soil moisture by vegetation types

According to a previous study, soil moisture profile characteristics are usually complex in vegetation covering zones (Jia et al., 2013). Thus, soil moisture profiles by vegetation types were chosen for analysis. As expected, the profile distribution characteristics of deep soil moisture varied by vegetation type (Fig. 5).

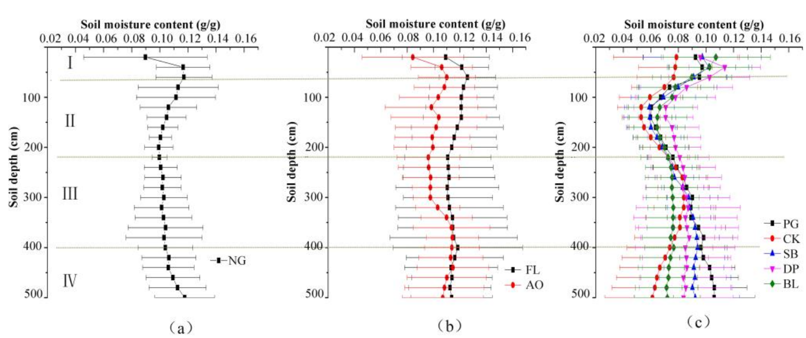

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Figure 5. Profile distribution of mean soil moisture contents for different vegetation types. Notes: (a) native grassland (NG-native grass), (b) human-managed vegetation (FL-farmland, AO-apple orchard), (c) introduced vegetation (PG-pasture grass; CK-*Caragana korshinskii*; SB-sea buckthorn; DP-David peach; BL-black locust). Error bar indicates standard deviation, Ⅰ-Ⅳ represent SMC at different soil layer depth ranges (Ⅰ: 0-60 cm, Ⅱ: 60-120 cm, Ⅲ: 120-400 cm, and Ⅳ: 400-500 cm), and the dashed lines are the boundaries of different soil layer depth ranges.

Deep SMC in native grassland zones is seldom affected by vegetation due to shallow root systems; thus, the deep SMC in native grasslands can be regarded as a reference for local control (Yang et al., 2012b). Based on the inflection point of SMC and the trending change of SD in native grasslands, the 5 m soil moisture profile was divided into 4 layers, from Ⅰ to Ⅴ. (Ⅰ) Shallow rapid change layer (0-60 cm); at this layer, SMC increased as soil depth increased, while SD decreased as soil depth increased. Moreover, this depth range is usually greatly influenced by rainfall events and evaporation and is characterized as “rapid change” (Cantón et al., 2004; Entin et al., 2000; Hébrard et al., 2006). (Ⅱ) Main rainfall infiltration layer (60-220 cm); at this layer, both SMC and SD decreased as soil depth increased, which indicated that this layer may be a main rainfall infiltration layer. Furthermore, as depth increased, the level of rainfall infiltration decreased. (Ⅲ) Transition layer (220-400 cm); SMC in this layer remained relatively constant as soil depth increased, but its SD increased with soil depth, which indicated that this layer is unstable. We characterize it as a transition layer. (Ⅳ) Stable layer (400-500 cm); this is a relatively stable layer whose SD is constant as soil depth increases, despite increasing SMC with soil depth. At this layer, SMC is seldom influenced by rainfall infiltration and evaporation. This vertical stratification method of the soil moisture profile may not be ideal, but it can reflect hydrological significance compared with previous studies (Yang et al., 2012a; Yang et al., 2012b; Yang et al., 2014a).

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The profile distribution characteristics of farmland were similar to those of native grasslands, except for layer Ⅳ. Perhaps this is because management measures increased the ranges of the rainfall infiltration layer. Similar profile distribution characteristics were also found for apple orchards, except for the 300-500 cm layer. As for vegetation-introduced, the profile distribution characteristics of the shallow rapid change layer (0-60 cm) were more complex due to differences in evaporation and rainfall redistribution caused by different vegetation coverage, while the deeper layer (60-500 cm) could be generally divided into three categories: (1) as soil depth increased, SMC decreased first and then increased (such as PG); (2) as soil depth increased, SMC decreased first, then increased and finally became stable (such as SB, DP, and BL); (3) as soil depth increased, SMC decreased first, then increased and finally decreased again (such as CK). Different profile characteristics can reflect different soil water consuming traits under different introduced vegetation.

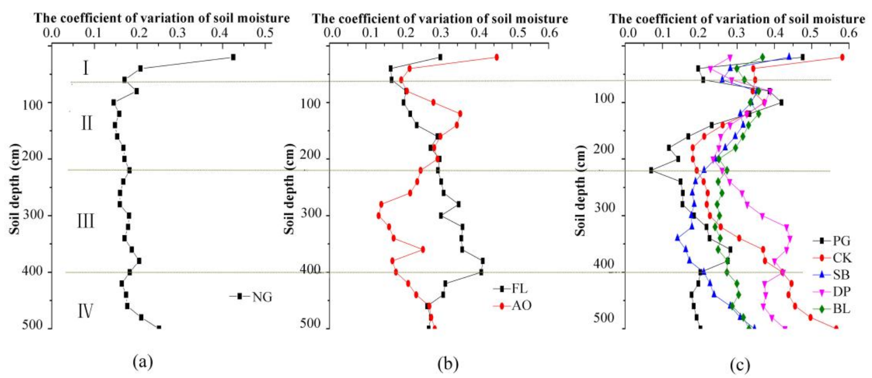

Figure 6. The coefficient of variation of soil moisture contents for different vegetation types. Notes: (a) native grassland (NG-native grass), (b) human-managed vegetation (FL-farmland, AO-apple orchard), (c) introduced vegetation (PG-pasture grass; CK-*Caragana korshinskii*; SB-sea buckthorn; DP-David peach; BL-black locust). Ⅰ-Ⅳ represent SMC at different soil layer depth ranges (Ⅰ: 0-60 cm, Ⅱ: 60-120 cm, Ⅲ: 120-400 cm, and Ⅳ: 400-500 cm); the dashed lines are the boundaries of different soil layer depth ranges.

The spatial variation of SMC under different vegetation types displayed different characteristics as well (Fig. 6). The spatial variation of native grassland was clearly less than that in human-managed vegetation and introduced vegetation, and the variation was relatively stable as depth increased, except for the shallow layer (0-60 cm). In human-managed vegetation (farmland and orchard), the variation was relatively higher and had a complex profile distribution due to different management measures. However, the spatial variation in introduced vegetation was, to some extent, consistent with the overall variation characteristics in this area (Fig. 5), which indicates that introduced vegetation plays an important role in the spatial variation of deep soil moisture in this area.

3.3 Relationships between soil moisture content at different depth ranges

According to previous studies, shallow SMCs at different depths are usually connected through infiltration and evapotranspiration processes (Shi et al., 2014). However, the SMC relationships between the shallow layer and various deeper layers have seldom been explored. Thus, the linear relationships of SMC at different depths ranges (Ⅰ-Ⅳ) were examined in the study area. The relationships between point measurements at these depth ranges are shown in Fig. 7. Scatter plots suggest that no correlations exist between the shallow layer (0-60 cm), moisture contents and various deeper soil layer ranges (R^2 from 0.045 to 0.134). However, there were positive and significant ($P<0.01$) correlations between moisture contents at different soil depth ranges (60-220 cm, 220-400 cm and 400-500 cm). The correlations of the neighboring layer ranges were relatively high, with R^2 from 0.68 to 0.78, while much lower correlations of soil moisture values were observed between nonadjacent depth ranges (R^2 = 0.47).

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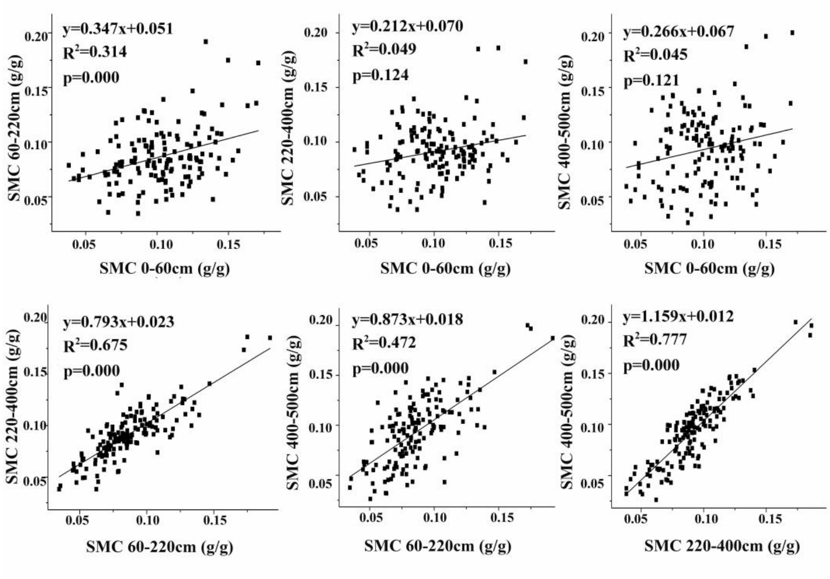

Figure 7. Correlations between point measurements at different depth ranges.

3.4 Comparison of deep soil moisture content under different vegetation types

Generally, soil moisture at comparable soil depths was lower in introduced vegetation (pasture grassland, shrub land and forestland) compared with native grassland and human-managed vegetation (farmland and orchard). Farmland (11.07-11.77%) had the highest SMC, followed by native grasses (10.47-11.19%). The LSD-test indicated that soil moisture content in native grasses and farmland was significantly higher than that in introduced vegetation ($P<0.05$, Table 3) at almost every soil depth. Soil moisture varied from 7.56% to 10.4% in pasture grassland, 7.42-9.75% in sea buckthorn, 6.49-8.07% in *Caragana korshinskii*, 7.46-7.66% in black locust, and 8.10-8.51% in David peach at layers of 60-500 cm. The LSD-test indicated that there were significant differences in soil moisture at depths of 400-500 cm between different introduced vegetation types. For example, *Caragana korshinskii* was significantly different from pasture grassland, sea buckthorn, and David peach, while black locust was significantly different from pasture grassland and sea buckthorn ($P<0.05$, Table 3).

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Table 3. Soil moisture of 0-50 cm soil layers for different vegetation types.

Land management types	Vegetation types	0-60 cm				60-220 cm				220-400 cm				400-500 cm			
		Min %	Max %	Mean %	SD %	Min %	Max %	Mean %	SD %	Min %	Max %	Mean %	SD %	Min %	Max %	Mean %	SD %
Native grasses	NG [a]	6.74	16.95	11.15ab	2.81	6.76	13.56	10.47a	1.95	8.35	12.84	10.52ab	1.62	8.17	14.72	11.19ab	2.03
Managed vegetation	FL	9.27	17.10	11.9a	2.19	6.91	19.19	11.07a	3.28	7.78	18.62	11.07a	3.20	7.53	20.01	11.77a	3.58
	AO	5.84	13.09	10.01abc	2.59	7.32	14.68	9.6ab	2.40	7.72	14.06	10.45abc	1.73	7.40	15.33	11.4ab	2.26
Introduced vegetation	PG	6.35	12.80	9.43bcd	2.15	6.81	8.36	7.56c	0.52	7.69	13.14	8.97bcd	1.55	8.49	14.29	10.4abc	1.85
	SB	4.52	14.51	9.44cd	2.77	5.15	10.74	7.42c	1.64	7.11	12.09	8.93cd	1.62	5.12	14.67	9.75bc	2.64
	CK	3.82	13.15	7.9d	2.84	5.05	10.50	7.25c	1.35	4.94	11.62	8.07d	2.11	2.63	12.50	6.49e	2.92
	BL	4.81	15.31	10.21bc	2.69	3.56	11.88	7.46c	2.05	4.16	10.94	7.66d	1.77	4.00	13.29	7.47de	2.47
	DP	7.16	13.00	10.4abc	2.04	3.47	10.80	8.1bc	2.11	3.82	13.9`5	8.51d	3.17	3.21	13.09	8.49cd	3.24

Notes: [a] NG, FL, AO, PG, CK, SB, DP, and BL refer to native grasses, farmland, apple orchard, pasture grasses, *Caragana korshinskii*, sea buckthorn, David peach and black locust, respectively. Means with the same letter in the same column are not significantly different at the 0.05 significance level (LSD).

As shown in Fig. 8, the SMC in farmland was higher than that in native grassland, and soil desiccation occurred in all introduced vegetation. However, soil desiccation varied among the vegetation types. In general, the soil moisture in layer Ⅱ (60-220 cm) was heavily consumed in almost all the introduced vegetation types. PG and SB consumed less soil moisture in layers Ⅲ-Ⅳ (220-500 cm) compared with the three other introduced vegetation types, while the soil moisture in layers Ⅲ-Ⅳ (220-500 cm) of DP and BL consumed more consistently. Double layer soil desiccation occurred in CK, indicating that the soil moisture in layers Ⅱ and Ⅳ of CK was heavily consumed, while the soil moisture in layer Ⅲ was less consumed. Furthermore, despite the deep root system of the apple orchard, soil desiccation did not occur across the soil profile from 0-500 cm; even in the 320-450 cm layer, the soil moisture in the apple orchard was higher than in native grasses.

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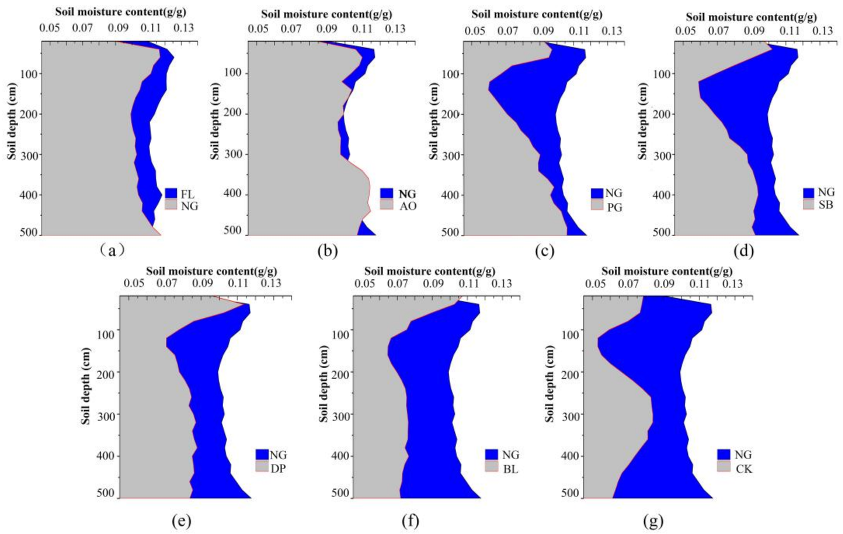

Figure 8. The comparison of soil moisture contents between human-managed vegetation, introduced vegetation and native grasslands. Notes: (a) farmland (FL) and native grasslands (NG), (b) apple orchard (AO) and native grasslands (NG), (c) pasture grasslands (PG) and native grasslands (NG), (d) sea buckthorn (SB) and native grasslands (NG), (e) David peach (DP) and native grasslands (NG), (f) black locust (BL) and native grasslands (NG), (g) *Caragana korshinskii* (CK) and native grasslands (NG).

3.5 Spearman correlation coefficients between soil moisture and selected environmental variables

Spearman correlation coefficients were used to determine the strength of possible relationships between soil moisture and selected variables. The correlation analysis results are presented in Table 4, Table 5, and Table 6. The correlation between soil moisture and environmental variations changed with soil depth and vegetation type. In native grassland, the SMC in the shallow layer (0-60 cm) showed significant correlations with average annual rainfall, while the SMC in the deep layer showed significant correlations with altitude (60-500 cm), slope gradient (220-500 cm), soil particle composition (60-500 cm), and average annual rainfall

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(220-400 cm).

In farmland, the SMC in the shallow layer (0-60 cm) showed significant correlations with altitude, clay content and bulk density, while the deep layers (60-220 cm) were only influenced by bulk density. In areas of introduced vegetation, apart from the significant correlations with topography, soil properties, and average annual rainfall, the SMC showed different correlations with vegetation growth traits. For instance, the SMC of BL showed significant negative correlations with plant height (at 60-220 cm depth) and diameter at breast height (at 400-500 cm depth), the SMC of DP showed significant negative correlations with crown width (at 0-60 cm depth) and basal diameter (at 0-60 cm depth), and the SMC of SB showed a significant negative correlation with plant density (at 60-500 cm depth). A significant correlation was found between aspect and SMC in some introduced vegetation in PG (at 400-500 cm depth) and BL (at 60-400 cm depth). Moreover, positive correlations existed between SMC and soil surface conditions; for instance, SMC of DP showed significant correlations with grass biomass (at 400-500 cm depth), SMC of AO showed significant correlations with litter biomass (at 400-500 cm depth), and SMC of CK showed significant correlations with litter max water holding (at 220-500 cm depth). Furthermore, in apple orchards, both soil buck density (at 60-400 cm depth) and porosity (at 60-220 cm depth) showed significant correlations with SMC.

Table 4. Spearman correlation coefficients between soil moisture (grassland, farmland and pasture grassland) and selected environmental variables.

	Native grasslands				Farmland				Pasture grassland			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
Altitude	0.27	-0.49	-0.56	-0.53	-0.51	-0.37	-0.30	-0.19	-0.04	-0.19	-0.06	0.08
Slope position	0.37	0.11	-0.11	-0.07	0.14	0.20	0.28	0.41	0.21	-0.14	-0.32	0.02
Cos (Aspect)	0.03	-0.22	-0.35	-0.44	-0.27	0.06	0.03	0.21	0.14	0.07	0.64	0.86
Tan (Slope)	0.04	0.36	0.67	0.59	0.09	-0.21	-0.07	0.21	0.02	-0.37	0.09	0.34
Clay	0.09	0.67	0.56	0.43	0.43	0.33	0.37	0.22	0.33	0.13	0.54	0.46
Silt	0.07	0.56	0.37	0.27	0.13	0.24	0.38	0.38	0.17	0.13	0.66	0.59
Sand	-0.09	-0.62	-0.42	-0.32	-0.17	-0.24	-0.35	-0.35	-0.25	-0.13	-0.58	-0.47
Organic	0.02	-0.18	-0.30	-0.19	0.08	0.08	-0.13	-0.23	-0.36	-0.04	-0.28	-0.64
Soil bulk density	-0.11	-0.06	-0.07	-0.04	0.49	0.45	0.31	0.34	-0.16	0.14	-0.01	-0.16

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Porosity	0.10	0.07	0.06	0.05	-0.35	-0.33	-0.26	-0.20	-0.08	-0.53	-0.26	-0.12
Annual average rainfall	-0.43	-0.01	0.46	0.37	0.20	-0.05	-0.11	-0.23	0.01	-0.47	0.15	0.36
Vegetation coverage	0.01	-0.19	-0.08	-0.02	0.39	0.15	0.11	0.26	-0.57	-0.38	0.37	0.11
Grass biomass	-0.38	-0.07	0.20	0.08	0.22	-0.05	-0.06	-0.06	-0.49	-0.01	0.28	-0.10
Grass height	0.35	0.33	0.01	0.00	0.20	0.04	0.06	0.15	-0.06	-0.23	0.46	0.32

Notes: I, II, III, and IV represent SMC at different soil layer depths; among them, I means SMC at 0-60 cm, II means SMC at 60-220 cm, III means SMC at 220-400 cm, and IV means SMC at 400-500 cm. Significant correlations (P<0.05) are shown in bold, and significant correlations (P<0.01) are shown in bold with underline.

Table 5. Spearman correlation coefficients between soil moisture (shrub land) and selected environmental variables.

	Caragana korshinskii Kom				Sea buckthorn			
	I	II	III	IV	I	II	III	IV
Altitude	0.06	-0.34	**<u>-0.70</u>**	**-0.59**	-0.15	**<u>-0.68</u>**	**-0.56**	-0.33
Slope position	0.34	0.27	-0.08	-0.11	0.10	-0.15	-0.25	-0.35
Cos (Aspect)	0.11	0.38	0.34	0.32	0.43	0.29	0.34	0.07
Tan (Slope)	-0.11	0.06	-0.10	-0.05	-0.06	-0.44	-0.19	0.00
Clay	0.23	0.09	-0.24	-0.09	**0.55**	0.24	0.22	-0.02
Silt	-0.04	0.14	0.32	**0.53**	0.29	**0.56**	**0.51**	0.41
Sand	-0.02	-0.14	-0.23	-0.45	-0.31	**-0.56**	-0.48	-0.37
Organic	-0.29	0.07	**0.47**	**0.49**	0.13	0.24	0.28	-0.20
Soil bulk density	0.22	0.12	-0.23	-0.24	0.01	0.06	-0.28	-0.18
Porosity	-0.04	-0.01	0.13	0.14	0.00	-0.07	0.20	0.02
Annual average rainfall	0.36	**0.56**	0.23	0.19	-0.28	0.16	0.22	0.18
Litter biomass	-0.23	-0.17	-0.04	0.10	0.44	-0.28	-0.33	-0.39
Litter max water holding	-0.02	0.31	**0.59**	**<u>0.60</u>**	-0.21	-0.13	0.09	0.08
Vegetation coverage	-0.07	-0.03	0.06	-0.03	0.15	-0.02	-0.14	-0.16
Grass biomass	0.03	0.20	0.42	0.45	-0.01	0.45	0.26	0.31
Grass height	0.01	0.22	0.35	0.43	-0.29	0.11	0.06	0.18
Plant height	0.03	0.26	0.24	0.23	-0.05	-0.02	0.25	0.09
Crown width	0.02	0.21	0.24	0.30	-0.48	-0.29	0.12	0.07
Basal diameter	**-0.49**	-0.23	0.31	0.40	-0.49	-0.28	0.06	-0.01
Plant density	-0.18	-0.28	0.08	-0.09	-0.31	**<u>-0.69</u>**	**-0.57**	**-0.56**

Notes: I, II, III, and IV represent SMC at different soil layer depths; among them, I means SMC at 0-60 cm, II means SMC at 60-220 cm, III means SMC at 220-400 cm, and IV means SMC at 400-500 cm. Significant correlations (P<0.05) are shown in

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bold, and significant correlations (P<0.01) are shown in bold with underline.

Table 6. Spearman correlation coefficients between soil moisture (orchard land and forest) and selected environmental variables.

	Apple orchard				Black locust				David peach			
	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅰ	Ⅱ	Ⅲ	Ⅳ
Altitude	0.14	-0.62	-0.25	-0.16	-0.12	-0.07	-0.07	0.20	0.43	-0.14	0.05	0.06
Slope position	-0.36	0.11	0.34	0.14	0.16	-0.20	-0.22	-0.21	-0.56	-0.34	-0.50	-0.55
Cos (Aspect)	0.38	0.02	-0.01	0.35	0.05	**0.34**	**0.34**	0.22	0.22	0.07	0.13	0.30
Tan (Slope)	**-0.77**	-0.28	0.26	0.33	-0.17	-0.07	-0.17	**-0.41**	-0.31	-0.15	0.19	0.07
Clay	0.50	**0.87**	0.42	-0.25	0.19	0.23	0.13	-0.09	**0.76**	0.30	0.15	0.06
Silt	0.16	**0.81**	**0.67**	0.08	0.25	0.27	0.14	-0.15	**0.69**	0.44	0.42	0.27
Sand	-0.16	**-0.81**	**-0.67**	-0.08	-0.25	-0.24	-0.14	0.13	**-0.69**	-0.44	-0.42	-0.27
Organic	0.31	**0.66**	0.38	0.13	-0.29	0.00	0.02	-0.22	0.48	-0.04	-0.12	-0.35
Soil bulk density	-0.27	**-0.65**	**-0.82**	-0.32	0.20	-0.27	-0.08	-0.06	-0.48	-0.25	-0.43	-0.41
Porosity	0.41	**0.86**	0.49	-0.06	-0.19	0.29	0.14	0.00	0.48	0.38	0.52	0.30
Annual average rainfall	0.08	0.29	-0.07	-0.38	-0.04	-0.02	0.26	-0.12	0.24	0.17	-0.11	-0.42
Litter biomass	-0.45	0.23	0.47	**0.72**	0.23	-0.05	0.13	-0.03	-0.06	0.01	0.08	0.08
Litter max water holding	0.18	0.32	0.08	0.33	-0.22	0.28	0.21	0.20	**0.59**	0.14	0.13	0.27
Vegetation coverage	-0.53	-0.54	0.10	-0.01	-0.03	-0.12	0.11	-0.03	-0.38	-0.39	-0.47	-0.41
Grass biomass	**-0.66**	-0.22	0.03	0.39	0.12	0.03	0.07	0.30	0.15	0.46	**0.80**	0.55
Grass height	0.18	-0.03	-0.17	-0.62	0.28	-0.01	0.02	0.08	-0.02	-0.50	-0.01	-0.01
Plant height	0.41	0.26	-0.09	-0.49	-0.29	**-0.35**	0.11	0.05	-0.56	-0.34	-0.11	-0.01
Diameter at breast height	0.16	0.62	0.31	0.04	-0.20	-0.29	-0.03	**-0.34**	-0.57	-0.36	-0.24	-0.15
Crown width	0.03	0.49	0.29	0.15	-0.10	-0.26	0.07	-0.07	**-0.59**	-0.50	-0.36	-0.29
Basal diameter	0.13	0.54	0.22	0.07	-0.17	-0.23	0.03	-0.25	**-0.61**	-0.42	-0.20	-0.07
Plant density	-0.35	-0.56	-0.20	-0.15	0.15	0.05	0.03	0.18	0.09	0.07	0.05	-0.08

Notes: Ⅰ, Ⅰ, Ⅲ, and Ⅳ represent SMC at different soil layer depths; among them, Ⅰ means SMC at 0-60 cm, Ⅱ means SMC at 60-220 cm, Ⅲ means SMC at 220-400 cm, and Ⅳ means SMC at 400-500 cm. Significant correlations (P<0.05) are shown in bold, and significant correlations (P<0.01) are shown in bold with underline.

3.6 Principal component analysis (PCA)

Based on spearman correlation analysis, only environmental variables that showed significant correlations (P<0.05) with SMC were retained for further analysis. There were 9 environmental variables for grassland and farmland (Group 1), 9 environmental variables for shrub land (Group 2), and 15 environmental variables for forestland and orchard (Group 3). Among these variables, some were linearly correlated. Thus, the dimensionality of these data sets could be reduced. Following Hu et al. (2010) and Xu et al. (2008), principal component analysis was performed to obtain a MDS of environmental variables; the results are listed in Table 7. Note that only principal components (PCs) with eigenvalues N>1.0 and only variables with highly weighted factor loading (i.e., those with absolute values for factor loading within 10% of the highest value) were retained for the MDS (Mandal et al., 2008; Shi et al., 2014). For Group 1, the PCA identified four PC that accounted for 80.04% of the variance, of which the first three PCs accounted for most of this variance (68.32%); for Group 2, four PCs, accounting for 84.39% of the variance, were identified; for Group 3, five PCs, accounting for 74.54% of the variance, were identified. In grassland and farmland, PC#1 included 3 variables that had highly weighted factor loadings, including clay, silt, and sand, which indicates that soil particle composition was the most important factor influencing soil moisture variation. Under PC#2, PC#3, and PC#4, only one variable for each principal component had a high factor loading: slope aspect, annual average rainfall, and soil buck density, respectively. In shrub land, the highly weighted factor loadings of PC#1 were clay, silt, and sand, while altitude and plant density were the highly weighted factor loadings for PC#2. Under PC#3 and PC#4, only one variable from each had a high factor loading: litter max water holding and organic, respectively. In forest and orchard land, diameter at breast height, basal diameter, and sand content accounted for the highly weighted factor loadings of PC#1; porosity was the only variation that accounted for the highly weighted factor loadings of PC#2. As for PC#3, there were four variations that were highly weighted: clay, silt, soil buck density, and litter max water holding. Under PC#4 and PC#5, only one variable from each had a high factor loading: slope aspect and slope gradient, respectively.

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Table 7. Principle component analysis (PCA) of environmental attributes

	Group 1: grassland and farmland				Group 2: shrub land				Group 2: orchard, and forest				
Principal component	PC[a]#1	PC #2	PC #3	PC #4	PC #1	PC #2	PC #3	PC #4	PC #1	PC #2	PC #3	PC #4	PC #5
Eigenvalue	3.58	1.45	1.13	1.05	2.99	2.32	1.27	1.01	4.51	2.62	1.80	1.17	1.08
% of variance	39.75	16.07	12.50	11.71	33.25	25.74	14.16	11.25	30.09	17.49	11.97	7.78	7.23
Cumulative %	39.75	55.82	68.32	80.04	33.25	58.98	73.14	84.39	30.09	47.57	59.54	67.32	74.54
Factor loading/eigenvector													
Annual average rainfall	0.21	-0.50	**0.71**	0.06	0.23	-0.52	0.41	-0.56					
Altitude	-0.46	0.23	0.53	0.51	-0.08	**0.83**	-0.17	-0.05					
Slope aspect	-0.16	**0.81**	0.24	-0.07					-0.06	-0.05	0.21	**0.64**	-0.10
Slope gradient	0.64	-0.43	-0.04	-0.23					0.55	0.22	0.07	0.01	**-0.70**
Clay	**0.86**	0.25	-0.13	0.15	**0.95**	0.11	0.01	0.10	0.64	-0.44	**-0.50**	-0.03	-0.04
Silt	**0.93**	0.27	0.05	0.09	**0.97**	0.05	0.12	0.07	0.68	-0.44	**-0.45**	0.28	0.08
Sand	**-0.94**	-0.27	-0.02	-0.11	**-0.98**	-0.06	-0.11	-0.08	**-0.77**	0.39	0.37	-0.23	-0.17
Organic	-0.48	-0.03	-0.50	0.49	-0.15	-0.42	0.26	**0.80**	0.54	-0.23	0.28	-0.16	-0.12
Soil bulk density	-0.41	0.31	0.07	**-0.67**					-0.25	0.61	**-0.49**	0.29	-0.05
Porosity									0.38	**-0.74**	0.22	-0.37	-0.13
Litter biomass									0.54	0.43	-0.29	-0.04	0.20
Litter max water holding					-0.28	-0.13	**0.81**	0.00	-0.24	-0.48	**0.46**	0.31	0.50
Grass biomass									0.27	0.49	-0.17	-0.37	0.39
Plant height									0.69	0.31	0.34	-0.22	0.24
Diameter at breast height									**0.80**	0.34	0.31	0.14	0.05
Crown width									0.39	0.20	0.43	0.22	-0.09
Basal diameter					-0.13	0.74	0.53	-0.07	**0.75**	0.37	0.26	0.18	0.07
Plant density					-0.04	**0.77**	0.21	0.15					

Notes: [a] PC refers to principal component. Significant correlations ($P<0.05$) are shown in italics, and significant correlations ($P<0.01$) are shown in bold. Factor loadings in bold are considered highly weighted when within 10% of variation of the absolute values of the highest factor loading in each PC.

In total, 6 out of 9 environmental variables for grassland and farmland (group 1), 7 out 9 for shrub (group 2), and 10 out of 15 for forest and apple orchard (group 3) were selected as MDS variables. Moreover, the MDS variables for each vegetation type were selected (Table 8). It can be concluded that, at the watershed scale, the main influencing factors of SMC variation under native grasslands were soil particle composition (clay, silt, and clay content) and average annual rainfall. In farmland, the dominant influencing factors were clay content and soil buck density. For introduced vegetation types, the main influencing factors were more complex; apart from soil texture and physical characteristics, topographical factors and vegetation

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traits also strongly affected SMC variation. Moreover, the main influencing depth ranges of different environmental factors varied with vegetation types (Fig. 9). For example, in native grasslands and apple orchard land, soil particle size composition mainly influenced deep SMC at 60-220 cm, while in pasture grassland, the most significant influencing depths were 220-400 cm. This indicates that vegetation coverage or human management measures can alter the depths of environmental factors influencing SMC.

Table 8. The minimum data set of environmental variables.

Vegetation types	Influencing variables
Native grasses	Cl[a], Sl, Sa, AAR
Farmland	Cl, SBD
Apple orchard	SG, Cl, Sl, Sa, SBD, Po
Pasture grasses	SA, Sl
Sea buckthorn	Al, Sl, Sa, Cl, PD
Caragana korshinskii	Al, Sl, Or, LMWH
Black locust	SA, SG, DBH
David peach	Cl, Sa, BD, LMWH

Note: [a] Cl, SA, SG, Sl, Sa, Or, Po, SBD, DBH, BD, LMWH refer to clay, slope aspect, slope gradient, silt, sand, organic, porosity, soil bulk density, diameter at breast height, basal diameter, and litter max water holding, respectively.

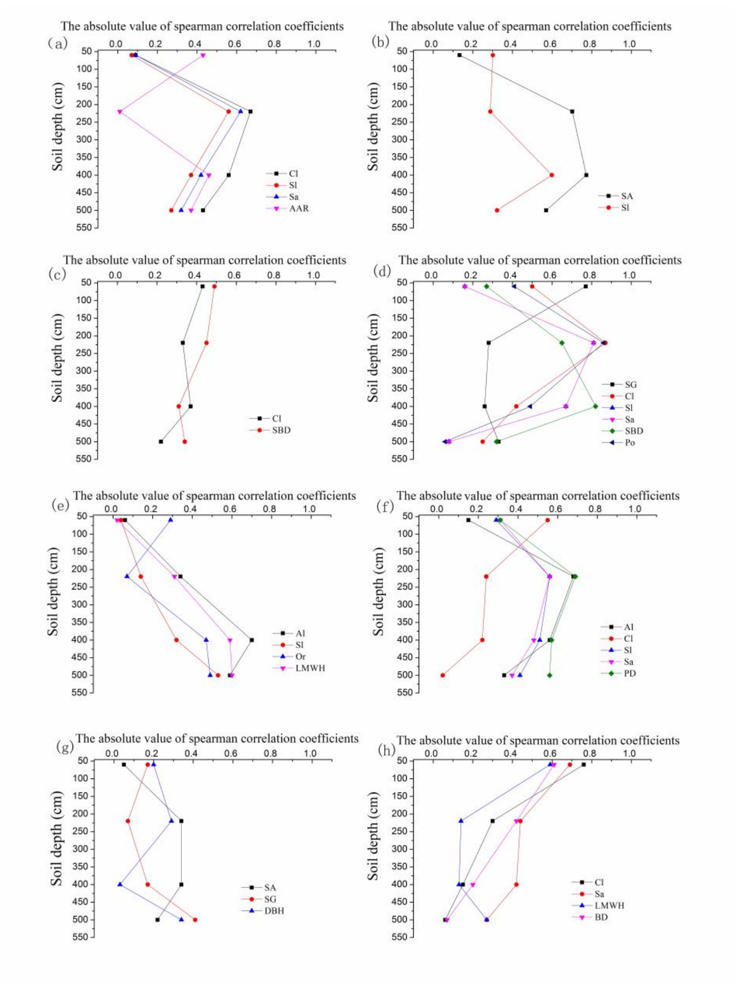

Figure 9. The influencing depths of the minimum data set of environmental variables for soil moisture content of different vegetation types. Notes: (a) Native grasslands: Cl-clay, Sl-silt, Sa-sand, AAR-annual average rainfall. (b) Pasture grasses: Sa-sand, Sl-silt. (c) Farmland: Cl-clay, SBD-soil bulk density. (d) Apple orchard: SG-slope gradient, Cl-clay, Sl-silt, Sa-sand, SBD-soil bulk density, Po-porosity. (e) *Caragana korshinskii*: Al-altitude, Sl-silt, Or-organic, LMWH-litter max water holding. (f) Sea buckthorn: Al-altitude, Cl-clay, Sl-silt, Sa-sand, PD-plant density. (g) Black locust: SA-slope aspect, SG-slope gradient, DBH-diameter at breast height. (h) David peach: Cl-clay, Sa-sand, BD-basal diameter, LMWH-litter max water holding.

4 Discussion

4.1 Spatial variation characteristics of deep soil moisture at the watershed scale

The spatial variation of deep soil moisture at the watershed scale varied with soil depth (Fig. 3 and Fig. 5). The shallow layer (0-60 cm) is more susceptible to soil evaporation or rainfall, and rainfall at this layer can be evapotranspired rapidly; thus, SMC at the surface layer increased as soil depth increased. At a soil depth of 60-220 cm, the influence of soil evaporation was relatively weak, rainfall infiltration could be stored in soil without the strong consumption of vegetation, and rainfall infiltration decreased as soil depth increased. Meanwhile, the soil layer at 220-400 cm was less influenced by rainfall infiltration; thus, SMC remained constant as soil depth increased. Soil depth below 400 cm was a deep stable SMC storage layer (Fig. 5). Moreover, compared with the rapid change of SMC caused by rainfall infiltration and evapotranspiration in the shallow layer, rainfall infiltration and evapotranspiration were usually slow processes in the deeper soil layers. This hysteresis process in deeper soil layers decreased the correlation relationship of SMC between the shallow and deeper layers (Fig. 7). However, the existence of deep rooted vegetation and human agricultural management measures altered the vertical SMC distribution rules, resulting in more complex spatial variation (Fig. 3). The highest variation of SMC at this watershed occurred at 0-20 cm, 100-120 cm, and 480-500 cm. Surface SMC (0-20 cm) was more prone to daily soil evaporation and rainfall events; different sampling climates and vegetation cover conditions contributed to the high variation (Cantón et al., 2004; Entin et al., 2000; Hébrard et al., 2006). However, the SMC was the lowest in the 120-140 cm layer, with high variation. This result is inconsistent with previous studies, which reported that high spatial variations usually appear in higher SMC and decrease when SMC becomes lower (Ibrahim and Huggins, 2011). This is likely because the most serious soil desiccation occurred in this layer for all introduced vegetation types (Fig. 5 and Fig. 8), increasing their difference with native grasses and human management vegetation types, eventually resulting in high variation. While the high variation at 400-500 cm may have been mainly caused by the different water consuming capacities of different vegetation types, this depth range is rarely influenced by rainfall event infiltration and soil evaporation (Chen et al., 2008a; Wang et al., 2009).

Soil moisture content spatial variation traits varied with vegetation types as well. In native grassland, only the surface layer displayed high soil moisture spatial variations (Fig. 5.), while the soil moisture variation at the deep soil layer was relatively low and stable. Usually, the roots of native grasses are distributed at 0-50 cm (Han et al., 2009). Thus, soil moisture below this depth is seldom influenced by vegetation transpiration, and local control, such as topography factors, soil factors, and climate conditions, may contribute to the spatial variation of SMC. In farmland, the SMC and its spatial variation were higher than that in native grassland, indicating that human agricultural measures can greatly increase SMC and its spatial variation. For introduced vegetation, the SMC was significantly lower than that in native grassland, indicating that soil desiccation occurred for all introduced vegetation. Moreover, different introduced vegetation showed different soil desiccation traits (Fig. 8). This result is different from that of a previous study (Yang et al., 2012b), which reported that no significant differences existed among different introduced vegetation. This was probably caused by the difference in annual precipitation; the mean annual precipitation of Yang's study area was 386 mm, which is far less than in our study area (505 mm). The lower annual precipitation resulted in plants not getting enough water, eventually leading to more homogeneous soil desiccation among the different introduced vegetation. Among the selected introduced vegetation types, *Caragana korshinskii* consumed the most water (Fig. 4.); this partly disagrees with most previous studies (Wang et al., 2010b; Wang et al., 2011b; Wang et al., 2009; Yang et al., 2012b), which reported that forest consumes more soil moisture than shrub land. This discrepancy may have been due to the higher planting density of CK in our study area. Moreover, the main difference in soil desiccation under introduced vegetation occurred at 60-220 cm and 400-500 cm (Table 3, Fig.

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8.); this contributed to the higher spatial variation of SMC at these two layers (Fig. 3).

4.2 Mechanisms of deep soil moisture spatial variability

The spatial variation of deep SMC is the combined result of topography factors, soil factors, vegetation factors, and climate conditions. In this study, vegetation coverage was an important factor influencing deep soil moisture variation. The effect of vegetation on soil moisture is shown in many aspects. First, due to the existence of a root system, soil moisture consumption in vegetation coverage zones is usually higher than that in zones lacking vegetation coverage (Savva et al., 2013), and different root systems determine different soil moisture consumption traits for various vegetation types (Fig. 8). For example, the roots of native grasses are usually distributed from 0-50 cm (Han et al., 2009), those of farmland from 0-40 cm (Feng et al., 2007), and those of Alfalfa and *Caragana korshinskii* can reach 3 m and 6 m, respectively (Wang et al., 2010b; Yang et al., 2014b). Thus, introduced vegetation with a deep root system consumes more and deeper soil moisture than farmland and native grasses (Table 3). Individual vegetation growth conditions and planting density can also influence deep SMC variation. For example, deep soil moisture in BL showed negative correlations with plant height and diameter at breast height, while SB showed negative correlations with plant density (Table 5 and Table 6). This phenomenon indicates that, in the deeper root system, forest individual growth conditions mainly explain SMC consumption, while planting density mainly accounts for SMC consumption in the less deep root system of shrubs. In addition to SMC consumption, the canopy interception system and surface coverage system can also have positive influences on soil moisture (Martínez-Fernández and Ceballos, 2003; Starks et al., 2006). Generally, a well-developed surface O-layer can hold more soil moisture; thick litter, humus layer and forest grass can retain more rainfall for infiltration as well as reduce soil evaporation (Vivoni et al., 2008). In this study, litter biomass, water holding capacity, and forest grass all showed different degrees of significant positive correlations with deep soil moisture for different vegetation types (Table 4, Table 5, and Table 6).

Climate factors that affect soil moisture are mainly determined by differences in rainfall infiltration and solar radiation (Savva et al., 2013). According to previous studies, deep soil moisture is relatively stable compared with the shallow layer, especially at depths below 200 cm. For example, Chen et al. (2008a) found that rainfall only affects the depth of 0-200 cm during drought years. Based on six years of observation in this region (Wang et al., 2009), it was also found that no significant changes occur in soil moisture below 200 cm. Thus, soil moisture in deeper layers is seldom influenced by rainfall events. However, in this study, SMC in the deep soil layer (60-220 cm in *Caragana korshinskii* and 220-400 cm in native grasslands) showed significant positive correlations with the six-year average annual rainfall, which indicates that deep SMC may be a long-term result of a water budget surplus.

Topography is another important factor that greatly affects the redistribution and consumption of soil moisture (Qiu et al., 2001; Zhu et al., 2014b). Slope position, altitude, and slope gradient mainly affect the lateral flow of soil moisture. Lower position or latitude usually has a higher soil moisture content (He et al., 2003; Zhu et al., 2014a), while slope gradient usually shows a negative correlation with SMC, indicating that a steep slope usually has a lower SMC than a gentle slope (Kim et al., 2007). As for the slope aspect, different aspects are usually caused by changes in solar radiation (Yang et al., 2012c), resulting in different rates of soil moisture evaporation. Thus, SMC on a sunny slope is usually lower than on a shady slope (Galicia et al., 1999; Wang et al., 2008a; Zhao et al., 2007). In this study, altitude had negative correlations with deep soil moisture; slope gradient showed significant positive correlations with SMC in grasslands (220 cm-500 cm), while significant negative correlations were found in black locust (400-500 cm). This indicates that the introduced vegetation can alter the topography factors' influence on SMC variation; this was also verified by Yang et al. (2012c), who found that introduced vegetation can lead to homogeneity of the deep SMC. This was true for slope aspect, which only showed positive correlations with SMC in pasture grasses (400-500 cm)

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and black locust (60-400 cm). Moreover, different soil traits determine different water transmission and conservancy characteristics, which may greatly influence the flow or storage of water in soil (Western et al., 2004). For example, Gómez-Plaza et al. (2001) found that soil porosity has a significant relationship with soil moisture in wet areas. Meanwhile, Vachaud et al. (1985) found that soil texture, especially clay content, is an important influencing factor of soil moisture variation. It was also found that soil layers with higher clay content usually have higher soil moisture (Ojha et al., 2014). In this study, soil particle composition was an important influencing factor of deep SMC variation at the watershed scale. Both clay and silt content showed significant positive correlations with soil moisture, and sand content showed negative correlations with deep SMC for most vegetation types. However, soil bulk density and porosity only showed significant correlations with deep SMC in farmland (0-220 cm) and apple orchard (60-400 cm). This result reflects that human agricultural management measures, or other factors that result in lower soil buck density and higher porosity conditions, can significantly improve infiltration capacity, thus increasing deep soil moisture content.

4.3 Implications for land use management and vegetation recovery.

A balance between soil water availability and water utilization by plants is key to maintaining ecosystem health, particularly in the arid and semi-arid Loess Plateau. The implementation of the “Grain to Green Program” has effectively controlled soil erosion (Chen et al., 2010; Wang et al., 2015a). However, according to this study, soil desiccation occurred in almost all introduced vegetation, while higher soil moisture content was found in native grassland and farmland (Fig. 8). These phenomena indicate that improper selection of vegetation type is a dominant reason for soil desiccation in this area. Thus, more attention should be paid to the selection of vegetation types based on the interactions between soil moisture and vegetation. Among these selected vegetation types, CK and BL caused the most serious soil desiccation (Fig. 4 and Fig. 5); thus, these two types are especially unsuitable for large scale plants in the study area, while SB, PG, and DP can be properly planted in

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good soil moisture conditions with suitable planting density and human management measures.

Furthermore, proper planting location should also be considered based on deep SMC conditions. Annual average rainfall spatial variations can significantly influence deep SMC conditions (Table 4 and Table 5). Thus, annual average rainfall is another important factor for determining planting location. In lower rainfall zones, vegetation enclosure and natural restoration may be good choices, while in higher rainfall zones, shrubs and forests could be rationally arranged. Even in the same rainfall regions, deep SMC is not evenly distributed: lower altitudes (such as a gully bottom or lower slope) usually had higher deep SMC (Table 4 and Table 5), while the deep SMC of native grasslands at steeper slopes was higher than that at gentle slopes (Table 4). Thus, shrubs or trees with high water consumption capacity can be arranged at these locations. At higher altitudes or upper slopes, where deep SMC is lower, native grass and low moisture consuming shrubs can be arranged.

The results of this study also indicate that human agricultural management measures can effectively improve deep SMC conditions. The SMC of farmland was highest among the selected vegetation types (Fig. 4); even though introduced vegetation has deep root systems, no soil desiccation was found in apple orchards (Fig. 8). Most of the farmlands we surveyed were level terraces and back-slope level benches with cultivation practices, while apple orchards were equipped with artificial rainwater gathering measures. All of the agricultural measures can significantly increase rainwater infiltration, eventually resulting in higher SMC in these vegetation zones. Moreover, in this study, forest grasses, litter biomass, and litter max water holding showed significant correlations with SMC (Table 5 and Table 6). Thus, increasing land surface cover (such as crop straw coverage, mix sowing shrub and grass) can be another effective measure for improving deep soil moisture recharge. Likewise, considering that plant density has significant negative correlations with SMC, vegetation control (when artificial forest and shrub are mature, the density should be reduced according to deep soil water conditions) may

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be an effective measure for helping reduce soil desiccation.

5 Conclusions

Based on the analysis of mean, SD, and CV of deep SMC at the watershed scale, the results indicate that the spatial variation of deep SMC varies with soil depth and vegetation types. In the vertical direction, the higher spatial variation of soil moisture occurred at three depth ranges: 0-20 cm, 120-140 cm, and 480-500 cm, while in the horizontal direction, the spatial variation in native grasses was far lower than that of farmland, apple orchard, and introduced vegetation at comparable depths. Based on the SMC and its variation characteristics, the SMC profile of local control natural grassland can be divided into four layers: Ⅰ. shallow rapid change layer (0-60 cm), Ⅱ. main rainfall infiltration layer (60-220 cm), Ⅲ. transition layer (220-400 cm), and Ⅳ. stable layer (400-500 cm), which can reflect the influencing depths of rainfall infiltration and evapotranspiration for SMC. Soil desiccation occurred in almost all the vegetation types; among them, CK and BL were the most serious, indicating that they are not suitable for large scale planting in this area. Moreover, the main rainfall infiltration layer Ⅱ had the most serious desiccation layer. The high SMC in farmland and apple orchard indicates that human management measures can greatly improve deep soil moisture, even for deep-rooted apple orchards, in which no soil desiccation was found. Although vegetation type is a dominant factor, the spatial variation characteristic of deep soil moisture in this area is actually the combined result of climate, vegetation, topography, soil, and human management measures. The SMC in native grassland, which can reflect native soil moisture conditions without human disturbance or soil moisture overconsumption, was found to be significantly related to topography, soil traits and annual average rainfall. For introduced vegetation, plant growth conditions, planting density, and litter water holding traits showed significant relations with deep SMC. In farmland and orchards, human management measures greatly increased the influence of soil traits on deep SMC, which increased rainfall infiltration and improved deep SMC. Based on the results of this study, proper selection of vegetation type, proper selection of planting location, and proper landscape management measures are suggested; considering the high SMC consumption capacity, CK and BL are unsuitable for large scale planting in the study area, while SB, PG, and DP can be properly planted in good soil moisture conditions with suitable planting density and human management measures. Good soil moisture condition areas usually include higher rainfall zones and lower altitude, while human management measures, such as macro-terrain reconstruction, artificial rainwater gathering, increased land surface cover and vegetation density control, are effective methods to control soil desiccation. The results of this study are of practical significance for vegetation restoration strategies and the sustainability of restored ecosystems.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 41390462) and the Program for Changjiang Scholars and Innovative Research Team in University (No. IRT_15R06). We are also grateful to the Ansai Research Station of Soil and Water Conservation, Chinese Academy of Sciences for their support and contributions to this fieldwork.

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Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-22, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 19 January 2016

Hydrology and Earth System Sciences Open Access Discussions

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