Hydrol. Earth Syst. Sci. Discuss., 9, 4553–4586, 2012
www.hydrol-earth-syst-sci-discuss.net/9/4553/2012/
doi:10.5194/hessd-9-4553-2012

Hydrology and Earth System Sciences Discussions

Spatial variation of shallow and deep soil moisture in the semi-arid loess hilly area, China

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Received: 27 March 2012 – Accepted: 29 March 2012 – Published: 5 April 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Soil moisture in deep soil layers is the only relatively stable water resource for introduced vegetation in the semi-arid Loess Plateau of China. Characterizing the spatial variation of deep soil moisture is significant for vegetation restoration with respect to the topographic conditions. In this study, we focused on analyzing the spatial variations and influencing factors of soil moisture content (SMC) in shallow (0–2 m) and deep (2–8 m) soil layers based on soil moisture observation in the Longtan watershed. The vegetation type of each sampling site for each comparison is same, while varies with slope position, slope gradient, or slope aspect. The following results are found: (1) compared with shallow SMC, slope position and slope aspect may affect shallow soil moisture more, rather than deep layers. Slope gradient however, affect both shallow and deep soil moisture significantly. It indicates that high difference of deep soil hydrological processes between shallow and deep soil moisture remains, which can be attributed to the introduced vegetation and topography. (2) The vegetation growth condition has significant negative relation with deep soil moisture. This result indicates that plants under different growth conditions may consume soil moisture differently, thus causing higher spatial variation of deep soil moisture. (3) The dynamic role of slope position and slope aspect on deep SMC has been changed by introduced vegetation in semi-arid environment. Consequently, vegetation growth condition and slope gradient may be the major factor contributing to the spatial variation of deep soil moisture.

1 Introduction

In the semi-arid Loess Plateau of China, soil moisture availability can be considered the only water source sustaining local ecosystems (Cao et al., 2009). This region has a loess cover with near 100 m thickness and loose soil structure (Chen et al., 2007b), and the groundwater levels in this region are generally at the depth of 30 to 100 m below surface (Mu et al., 2003). Little groundwater at these depths can be used as a supply for soil evaporation and plant transpiration. For this reason, plants in this area were forced to develop deep and robust root systems to utilize soil moisture stored in the deep soil layers (Chen et al., 2008a). Thus, deep soil moisture (usually 2 m below surface) becomes especially important for the sustainable growth of plants in this area (Chen et al., 2008a; Wang et al., 2011).

Meanwhile, to control serious soil erosion in the Loess Plateau, large-scale implementation of the “Grain to Green Program” (GTGP, also known as the Sloping Land Conversion Program and the Farm to Forest Program) initiated by the central government in recent years (Chen et al., 2010; Liu et al., 2008) and introduced vegetation thus has become the main vegetation type in this region (Wang et al., 2007). However, introduced vegetation usually need more soil moisture than local natural plants and could rapidly deplete the limited soil moisture resources stored in the deep layers (Wang et al., 2009, 2010b). Because of this reason, large-scale introduced vegetation restoration may be limited by the availability of soil water resources (Chen et al., 2010), and may have negative impacts on the sustainability of the restoration effort (Liu et al., 2010), agricultural production (Wang et al., 2008), watershed hydrological processes (Yang et al., 2008), and ecosystem services (Chazdon, 2008; Liu et al., 2008).

Several recent studies have been conducted on deep soil moisture depletion influenced by large-scale vegetation restoration in the Loess Plateau. For instance, it was found that soil moisture consumption rate was dependent on vegetation type (Wang et al., 2009, 2010b). Wang et al. (2011) also found that vegetation species have significantly influence on deep soil moisture balance. Liu et al. (2010) found a negative relationship between deep soil moisture content and the age of the plants. However, the issue of spatial variation of deep soil moisture in relation with the affecting factors has received limited attention due to arduous work required. As spatial variation of soil moisture has important implications on agriculture (Hebrard et al., 2006; Liu et al., 2010), soil erosion (Chen et al., 2007b; Fitzjohn et al., 1998) and vegetation restoration (Engelbrecht et al., 2007), understanding its dynamic role will provide a scientific basis for the optimization of spatial allocation in the vegetation restoration efforts. Specifically, because deep soil moisture is the only stable water source for introduced vegetation in the semi-arid Loess Plateau, understanding the spatial variation of deep soil moisture is fundamental for optimization of vegetation restoration.

In fact, factors affecting deep soil moisture are very complex. Besides vegetation, upslope contributing area, topographical factor, geographical location, land use and soil types all play key roles (Favreau et al., 2009; Fu et al., 2003; Gómez-Plaza et al., 2000; Qiu et al., 2003; Wang et al., 2010a). Specially, the detailed topographic variability as represented by the complicated hills and gullies in the Loess Plateau results in significant local redistribution of precipitation, solar radiation and surface runoff (Qiu et al., 2010; Zhu and Shao, 2008). This redistribution inevitably affects the spatial variation of soil moisture (Legates et al., 2011; Meerveld and McDonnell, 2006; Vivoni et al., 2008). Because the soil properties in the Loess Plateau is homogeneous (Yang and Tian, 2004), thus, vegetation and topography is the important factor contributing to the dynamics of soil moisture in the key semi-arid loess hilly region (Qiu et al., 2001).

Based on above discussion, although soil moisture in the semi-arid loess hilly region was significantly influenced by topography, does the topographic variability also affect soil moisture in deep layers? How do dynamics in deep soil moisture respond to the introduced vegetation restoration? All these questions indicate that understanding the dynamic of soil moisture between shallow and deep soil layers will provide a scientific basis for the optimization of vegetation restoration effort, especially for the semi-arid regions. In fact, this issue can be well studied on the watershed scale. Therefore, the objectives of this study are: (1) to analyze the spatial variation of shallow and deep soil moisture under different topographic factors; (2) to investigate whether the deep soil hydrological processes are same as the shallow under the influence of topography; (3) to elucidate the main affecting factor for the spatial variation of deep soil moisture.

2 Materials and methods

2.1 Study area

The study area is located in the Longtan watershed (35°43′–35°46′ N, 104°27′–104°31′ E) in Dingxi, Gansu province, covering an area of about 16.1 km^2, ranging in elevation from 1840 to 2260 m above sea level and with a highly fragmented landscape. It belongs to a typical semi-arid loess hilly region, with approximately 6.8° mean annual temperature and 386 mm mean annual rainfall. Most rainfall occurs in the form of thunderstorms during the summer months from July to September. The potential annual evaporation (pan evaporation) is about 1649 mm. All meteorological data were provided by the meteorological station 0.6 km from the watershed and represent 45-yr averages (1961–2006). The rainfall was uniform distribution in the watershed based on five spatial-distributed auto-recording rain gauges during 2008–2010. Soil types in this study area are mainly composed of loess soil with low fertility, and vulnerable to soil erosion. Such kind of soil has a loose structure, low soil moisture field capacity (18–24 %), and low organic matter content (ca. 0.2 %–2.9 %). The wilting point in the study area is 5.4 % (Chen et al., 2007a). Soil thickness varies from 40 to 60 m.

The predominant land use types are sparse native grassland and rain-fed farmland, and then pasture grassland, shrubland, and forestland. The native vegetation in the study area is sparse grass with annual plants and shallow roots, dominated by species bunge needlegrass (*Stipa bungeana* Trin.), common leymus (*Leymus secalinus* (Georgi) Tzvel.), Altai heterpappus (*Heteropappus altaicus* (Willd.) Novopokr.), etc. The introduced vegetation types are alfalfa (*Medicago Sativa*), korshinsk peashrub (*Caranana korshinskii*), Siberian apricot (*Armeniaca sibirica* (L.) Lam.), Chinese red pine (*Pinus tabulaeformis* Carr.), and others. As it is located in the semi-arid climatic zone, water shortage is actually the major constraint to vegetation growth and agriculture production.

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2.2 Observation and analysis

2.2.1 Experimental sites design

Based on vegetation distribution characteristics in the study area, the native nature grassland, farmland and planted vegetation lands were selected for analysis. Furthermore, five typical introduced vegetation types were selected: alfalfa (*M. sativa*), korshinsk peashrub (*C. korshinskii*), Chinese arborvitae (*Platycladus orientalis*), Chinese red pine (*P. tabulaeformis*) and Siberian apricot (*A. sibirica*) (Table 1).

(1) Native grassland: the native grassland is the dominant native species community in this region. The main species are native low water demanding grasses and herbs, including: common leymus (*L. secalinus*), bunge needlegrass (*S. bungeana*), Altai heterpappus (*H. altaicus*), capillary wormwood (*Artemisia capillaris* Thunb.), Mongolian thyme (*Thymus mongolicus* Ronn.), and others. According to local farmers and stakeholders, the natural grasslands had kept from human disturbance for at least 50 yr.

(2) Farmland: crops was planted annually in the farmlands. In year 2009 to 2010, sites of farmland were planted with potatoes. Crops were sown in April and harvested manually at the end of September or beginning of October. Then, a fallow period was followed from October to March of the next year. Abandoned farmland as a vegetation restoration type was fallowed from 2002, followed with native grasses and herbs grown. The soil moisture conditions in farmland could be considered as the reference condition before introduced vegetation planted.

(3) Lands with introduced vegetation: the lands with introduced vegetation were converted from farmland. The lands with introduced vegetation include pasture grassland (planted with alfalfa), shrub (planted with korshinsk peashrub) and forest (planted with Chinese arborvitae, Chinese red pine and Siberian apricot). The alfalfa was planted in 2003 after the “Grain-to-Green” project was initiated. In rainfall-deficit years, alfalfa was cut only once because of its poor growth, and it was cut twice in rainfall-rich years. The korshinsk peashrub were planted in 1984. The Chinese arborvitae, Chinese red

pine and Siberian apricot were planted with the same density in 1980, 1972 and 1960, respectively.

Eight typical transects with different vegetation covers (NG, PO, AF, AL, KP, CP, CA, and SA) were selected to compare soil moisture varied on different slope positions. The transects were selected based on upslope contributing area and flow direction. The upslope contributing area and flow direction were calculated by ArcGIS® 9.3 (ESRI Inc. Redlands, USA) based on DEM with a resolution of 10 m. All transects were covered with the same vegetation from the top to the foot of the hillside along with the flow direction and increasing of upslope contributing area. There were three separate sampling sites in each transect on the upper, middle and downhill slope. Each transect had the same slope aspect, and most transects had the similar slope gradient. To elucidate the dynamic role of slope aspect on shallow SMC and deep SMC, six groups of NG, PO, AF, AL, KP on different slope aspects were selected to compare SMC affected by the slope aspect. Each site selected in the same group was on same position and slope gradient and same vegetation growth conditions, but varied by slope aspects. Meanwhile, slope gradient was particularly highlighted in this study. Four groups of NG, AL, CP, and CA forestland in different slope gradients were selected to compare the SMC affected by slope gradient. Each site in a group was on the same slope position and aspect, but varied by slope gradients. For the limitation of vegetation distribution characteristics in the study area, not all the eight different types of vegetation can be found in different slope aspect or gradient. In this study, the dynamic role of slope aspect and gradient was analyzed by these two comparing groups.

2.2.2 Shallow and deep SMC measurement

The shallow SMC were collected biweekly from 0 to 2 m in 20 cm intervals from April to October of 2009 and April to September of 2010. Soil samples were taken by a drill and gravimetrically SMC was determined by the oven-drying method (24 h at 105 °C). At each sampling time, three sampling points were randomly chosen to obtain the average SMC each time at each experimental site. In this study, 26 times in total shallow

SMC data were collected. The depthaveraged SMC of each experimental site at each measuring time was calculated by Eq. (1)

$$\mathrm{SMC}_j = \frac{1}{i}\sum_{i=1}^{i}\mathrm{SMC}_i \tag{1}$$

where i is the number of measurement layers at the site j. The number of measurement layers of shallow SMC is 10.

The temporal-averaged shallow SMC of each experimental site was calculated by Eq. (2)

$$\mathrm{SMC}_n = \frac{1}{n}\sum_{n=1}^{n}\mathrm{SMC}_j \tag{2}$$

where n is the number of measurement times at the site j. The number of measurement times of shallow SMC is 26.

In August 2010, the deep SMC in the 28 m layers was measured at each site. Soil samples in the depth of 2–8 m were taken by a drill (5 cm in diameter). The soil samples were sealed in airtight aluminum cylinders and brought to the laboratory for determination of gravimetrically SMC. A total of 30 soil samples were collected from each sampling points. Three sampling points were randomly chosen to obtain the average SMC each time at each experimental site in the same way. The depthaveraged deep SMC of each experimental site at each measuring time was calculated by Eq. (1), and the number of measurement layers of deep SMC is 30.

2.2.3 Soil properties and vegetation characteristics

The latitude, longitude and elevation were determined for each experimental site using a Garmin GPS60 (German International Inc., Olathe, USA), while the site slope and aspect were determined using a compass. At each site, undisturbed soil cores were collected for measurement of soil bulk density for soil surface (0–5 cm) and subsurface layers (20–25 cm) in metal cylinders (diameter 5 cm, length 5 cm). Soil bulk density and porosity was determined from the volume-mass relationship for each core sample. Disturbed soil samples were collected to a depth of 1 m at 0.2 m intervals using a soil auger for each sampling point. All soil samples were passed through a 2 mm sieve before laboratory analysis. Soil particle sizes were evaluated using the MasterSizer 2000 apparatus manufactured by Malvern. The proportion of clay (<0.002 mm), silt (0.002–0.02 mm), and sand (>0.02 mm) contents were then calculated. Soil organic matter content was determined by the dichromate oxidation method.

At each experimental site, a vegetation investigation was also conducted. At forest sites, the stand density (plants ha^{-1}), tree height (m) diameter at the breast height (DHB, cm), canopy width in a 10 m × 10 m quadrat and the total canopy or coverage of each quadrat was recorded. At shrub sites, plant height (m), canopy width in a 10 m × 10 m quadrat and the total closeness of each quadrat were measured. Species composition, total herbaceous coverage, plant height, biomass were measured in each herbaceous quadrat.

2.3 Statistical methods

The basic statistical features as mean values (Mean), standard deviation (S.D.) were analyzed and reported for each site. One-way ANOVA was used to assess the contribution of different topography factors to the overall variation of the soil moisture variable. Multiple comparisons were made using the least significant difference (LSD) method. SPSS® (Version 18.0) was used for all of the statistical analyses.

3 Results

3.1 Spatial variation of SMC on different slope positions

No significant difference in SMC was found between different slope positions in shallow layers, no matter what the vegetation covers were (Table 3). The SMC in alfalfa transect increased from top to foot of the hillside. Interestingly, the highest SMC was found on upper position in native grassland transect and then followed by downhill and middle positions. Specially, mean SMC on downhill positions usually had the lowest value in transects with shrub and forest covers (Table 3, Fig. 2). Relatively higher SMC was found in top soil layers in lands with introduced vegetation; however, relative lower value appeared in the deeper layers.

Compared with shallow layers, significant differences in SMC between different slope positions appeared in deep layers in some transects (Table 3). On native grassland transect, SMC on middle position was significantly lower than that on other positions. In korshinsk peashrub and Siberian apricot transects, SMC on upper positions was significantly higher than those on the middle and downhill positions. Interestingly, higher SMC appeared on middle position in Chinese arborvitae transect. However, significant difference was still not found in farmland, alfalfa grassland and Chinese red pine transects. The difference in SMC between different slope positions was enlarged along with increasing soil depth in natural grassland, korshinsk peashrub, Chinese arborvitae and Siberian apricot transects. For the example in Siberian apricot transect SMC on upper position was 16.2 % and 13.7 % higher than that on middle and downhill positions below the depth of 4.6 m, respectively. On the contrary, no significant difference appeared in depth of 2–4.6 m.

3.2 Spatial variation of SMC on different slope aspects

In shallow soil layers, mean SMC on shady slopes were higher than that on sunny slopes in different vegetation covers (Table 4). Furthermore, the difference in SMC between different slope aspects varied with vegetation types. However, the difference between two slope aspects seemed no statistical significant in some vegetation covers. From the comparison of SMC in vertical distribution, SMC on shady slope usually had higher value than that on sunny slopes (Fig. 5). The result can reflect that the slope aspect was also an important affecting factor for soil moisture in shallow layers.

However, the comparison of mean value and vertical distribution of deep SMC showed the difference with shallow SMC. Generally, no significant difference in SMC was found between shady and sunny sloping lands, except the abandoned farmland (Table 4). This result was also proved by the vertical distribution of SMC in deep layers, no matter what the vegetation covers were (Fig. 6). Result of comparison reflected that slope aspect can only affect SMC in shallow layers, but the influence cannot reach the deep soil layers. Specially, relatively higher SMC was found on shady slope in abandoned farmland than that on sunny slope.

3.3 Spatial variation of SMC in different slope gradients

Generally, SMC in gentle slopes were much higher than that in steeper slopes in the shallow layers (Table 5), although not all the differences were significant. For example, no significant difference was found between the Chinese arborvitae forestland in slope gradient of 12° and 23°, however, Fig. 6d showed that the values in gentle slope were obviously higher than steeper slope in most layers. On the contrary, the highest mean SMC appeared in steepest slope in natural grassland. The differences in SMC between lands with different slope gradients decreased along with increasing soil depth on vertical distribution (Fig. 6). For example, the difference between alfalfa grassland in 8° and 13° in the depth of 0.2 m was 3.25 %, but decreased to 1.42 % in the depth of 1.8 m.

Consistent with shallow soil layers, obvious differences can also be found in deep layers (Table 5, Fig. 7). SMC in gentle slopes was significantly higher than that in steep slopes, especially in deep soil layers. Furthermore, such difference varies with vegetation types. The result reflects that slope gradient can affect SMC both in shallow and deep soil layers. Interestingly, different with vertical distribution characters of shallow soil moisture, the difference in SMC between different slope gradients was enlarged along with increasing soil depth.

4 Discussion

4.1 Vertical distribution and temporal variation characteristics of SMC in semi-arid Loess Plateau

Shallow soil moisture was more prone to be affected by vegetation transpiration and soil evaporation (Meerveld and McDonnell, 2006; Seneviratne et al., 2010). These two kinds of soil hydrological processes could return about 60 % or even 90 % of the whole precipitation back to the atmosphere (Oki and Kanae, 2006; Wang et al., 2011). Furthermore, soil moisture in this depth was usually intensively affected by the plant root system (Cong et al., 1990; February and Higgins, 2010). The loess has homogeneous soil texture and full of capillary pore which has strong capacity of evaporation, stable low shallow SMC was always found in this region (Yang and Tian, 2004). For these reasons, SMC in this area was always low in shallow layers. In this study, mean SMC in shallow layers was obviously lower than that in deep layers (Tables 3–5). For the soil evaporation's effect on soil moisture is lessened with the increasing in soil depth and the decreasing of plants' root networks, the SMC increased with soil depth in deeper layers. Previous studies have found that low spatial and temporal variation usually appeared in lower SMC, while increased when SMC became higher (Ibrahim and Huggins, 2011; Western and Blöschl, 1999). It can explain why the differences of shallow SMC were lower than deep SMC. No significant difference appeared in shallow SMC on different slope positions and aspects. In contrast, significant difference appeared in deep soil layers (Tables 3, 4). Low SMC in shallow layers led the low statistical significance. However, significant difference appeared in deep layers due to the increasing SMC. This phenomenon also reflected that topographic factors can affect SMC in wet conditions more than dry conditions in the semi-arid areas.

In the semi-arid Loess Plateau, SMC varies inter-annually in the depth of 0–2 m, depending on the annual precipitation. However, due to the thickness of loess cover in the Loess Plateau, vertical distribution and temporal variation of SMC is different with other semi-arid areas in the world. Wang et al. (2009) have found that no significant inter-annual changes in the depth below 2 m based on six years observation in the loess hilly region. Chen et al. (2008b) also found the depth of soil affected by the rainfall was only 0–2 m in the drought year by natural and simulated rainfall experiment. In fact, the annual rainfall infiltrate depth could hardly reach 1 m in the study area by the field soil moisture observation (Yang et al., 2011). In this area, the S.D. of SMC on each experimental site was relatively high in 0–1 m, but the value became low under the depth of 1 m during observation of 2009–2010 (Figs. 2, 4, 6). This result indicated that SMC only varied with rainfall in the shallow layers, but keeps stable in deep layers for several years. In such cases, therefore, we consider that the temporal-averaged shallow SMC data can provide accurate characterization of the temporal changes in SMC and represent the soil moisture conditions in shallow layers in this area. Because the deep SMC was relative stable during years, the one-year deep SMC data is sufficient in reflecting the stable soil moisture conditions in deep profiles.

4.2 Different dynamic rules between deep and shallow SMC

Topography factors such upslope contributing area, slope aspect and gradient is commonly considered as an important factor for the spatiotemporal variation of soil moisture (Venkatesh et al., 2011; Western et al., 1999, 2004). The general spatial pattern of SMC on the watershed-scale is the value increased along with surface flow direction from top to foot on a hill slope. The sunny slope usually suffers more solar radiation than shady slope, and this can lead more soil moisture transpiration. Thus, SMC in upper soil layers on sunny slope is usually lower than that on shady slope (Galicia et al., 1999) Furthermore, steep slope usually has lower SMC than gentle slope. The spatial distribution characters of SMC in these patterns have been proved by lots of previous studies (Francis et al., 1986; Legates et al., 2011; Western and Blöschl, 1999) and models (Cantón et al., 2004; Western et al., 1999). In the key loess hilly region, spatial variation of SMC in 0 ~ 0.7 m affected by the topographic factors was also corresponding to this spatial pattern (Qiu et al., 2001, 2010). Similar patterns were also captured in deep soil moisture. For example, He (2003) held the view that slope gradient, aspect and position all could affect deep SMC Wang (2008) and Zhao (2007) found that SMC in shady slope was higher than that in sunny slope in forestland and grassland. In this study, the deep SMC on middle position was lower than that on downhill position in native grassland (Fig. 3a), and SMC on gentle slopes was lower than that on steep slopes (Fig. 7a), and SMC on shady slope was higher than that on sunny slope (Fig. 5a). The result reflected that the spatial pattern of deep SMC with local native vegetation was corresponding to the spatial distribution patterns.

However, the spatial variation of deep SMC in introduced vegetation was different with that in native plants. In this study, measured data and statistical analysis provided evidences that topographic factor such as slope aspects can only affect shallow soil layers to a certain extent (Fig. 4), but cannot reach deep soil layers (Fig. 5). The result reflected that dynamics of deep SMC were different with shallow SMC under the influence of slope position and aspect. However, comparison of SMC in gentle and steep slopes indicated that lower gradient was related to higher SMC (Figs. 6, 7). This result was consistent with previous findings that slope gradient and SMC had a negative relationship in the semi-arid region (Cantón et al., 2004; Gómez-Plaza et al., 2001; Qiu et al., 2001). It thus can explain why deep SMC on upper position of native grassland transect was higher than other positions. The slope gradient on upper position was 9°, and slope gradients on middle and downhill positions were 30° and 32°, respectively. Thus, the lower slope gradient on upper position the higher SMC will be. Slope gradient as an important topographic factor in the loess hilly region can affect SMC not only in shallow layers but also in deep layers.

4.3 Relations between plant growth and deep SMC variation under introduced vegetation covers

Vegetation has a significant influence on SMC (Peel, 2009; Schymanski et al., 2009). In the Loess Plateau, dense vegetation plantation with high productivity consumes too much water stored in deep layers. It was the major possible reason of severe soil moisture deficit in deep soil layers. For example, using WinEPIC model Li et al. (2008) simulated changes in SMC and productivity of black locust (*Robinia pseudoacacia)* forestlands, and found that the higher planting density the faster decrease of deep SMC. In the semi-arid loess hilly regions, introduced vegetation with high planting density not only drastically decreased deep SMC, but also changed the dynamics of soil moisture in shallow and deep layers. In this study, taking Siberian apricot transect as an example, deep SMC on upper position was higher than that on middle and downhill positions, and the planting density may be the main reason. The planting density of Siberian apricot was 900 plant ha^{-1} on upper position. Although the same planting density of Siberian apricot appeared on middle and downhill positions, korshinsk peashrub with a planting density of 1670 plant ha^{-1} was also planted with Siberian apricot on these two positions. Therefore, the total planting density of introduced vegetation on middle and downhill positions were much higher than upper position. Thus, high planting density leaded the lower deep SMC on these positions (Figs. 2h, 3h). In Chinese arborvitae transect, planting density on upper and downhill positions was the same (2600 plant ha^{-1}), while the mean height of Chinese arborvitae on upper and downhill positions was 4.18 m and 3.65 m, respectively. The Chinese arborvitae plants on middle position had been cut in 1998, and now the planting density was 1300 plant ha^{-1}, and the mean height was 3.38 m. The lower planting density on middle position led to higher deep SMC (Fig. 3g).

In the semi-arid region, more soil moisture evaporation usually appears on upper positions due to suffering more solar radiation and wind, which affects plant's growth as a result. According to local filed investigation, the mean height of korshinsk peashrub plants on upper position was 1.02 m, but mean height on middle and downhill positions was 1.28 m and 1.23 m, respectively. Owing to the developed root system poor growth of korshinsk peashrub on upper position will lead to less soil moisture consumption, especially for deep SMC. This could explain why deep SMC on upper position was significantly higher than other positions (Table 2, Fig. 2e). In Chinese red pine transect, the mean height of pine trees in downhill position was 4.90 m, and mean DBH was 8.1 cm. In contrast mean height of pine trees in upper and middle positions was 4.55 m and 4.48 m, and mean DBH 7.4 cm and 6.9 cm, respectively. Better growing conditions of pine trees on downhill position associated with lower deep SMC Alfalfa also was found to have deep root systems, which could consume deep soil moisture drastically (Wang et al., 2010b). In this study, the fresh weight of alfalfa on upper and downhill positions of alfalfa transect was 246.3 $\mathrm{g\,m^{-2}}$ and 248.1 $\mathrm{g\,m^{-2}}$, respectively. In contrast, the fresh weight of alfalfa on middle position reached 314.0 $\mathrm{g\,m^{-2}}$. High biomass of alfalfa leads SMC on middle position to be lower than that on other positions.

Based on above discussion, the results indicated that introduced vegetation even can alter the contributions of topography to the specific soil moisture dynamics. Otherwise the effects of introduced vegetation on dynamics of soil moisture were not only limited to shallow soil layers but also deep layers. In fact, the plant growth conditions can be considered as the main factor affecting the spatial variation of deep SMC. For practice, vegetation restoration with alien species in the semi-arid environments should be strongly based on soil moisture conditions. On the other hand, the soil moisture data observed in shallow layers is insufficient in evaluating soil moisture conditions for the purpose of vegetation restoration in the semi-arid areas. Attention on available soil water source in deep layers, however, should be paid. Furthermore, since the dynamic role of topographic factors on soil moisture has been changed by introduced vegetation, the detailed location and density of plants on watershed-scale should be scientifically evaluated and determined according to local soil moisture viability in order to ensure a success of eco-construction projects.

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5 Conclusions

Based on the comparison between soil moisture dynamics in shallow and deep layers, the results indicated that topographic factors such as slope position and slope aspect only affect SMC in shallow layers, and no direct influence on deep soil moisture in introduced vegetation. Slope gradient, on the other hand, has significant influence on both shallow and deep SMC. Due to the role of vegetation plantation and restoration on the soil moisture, dynamic role of topographic factors on SMC was different between deep and shallow layers. The growth condition of planted vegetation have negative relationship with deep SMC, which is considered as the main factor for spatial variation of deep SMC. In practice, therefore, vegetation restoration in the semi-arid environments should be strongly based on soil moisture conditions. Moreover, in order to ensure a success of such eco-construction projects, the detailed location and density of plants on watershedscale should be taken into consideration seriously.

Acknowledgement. This study was supported by the National Natural Science Foundation of China (40925003, 41071122, and 40801041).

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Table 1. General information about the experimental sites.

Land use	Land cover subclasses	Vegetation type	Abbreviation	Year
Native grassland	Native grassland	Native grasses and herbs	NG	>50
Farmland	Farmland	Potato (*Solanum Tuberosum*)	PO	–
	Abandoned farmland	Native grasses and herbs	AF	8
Lands with introduced vegetation	Pasture grassland	Alfalfa (*Medicago sativ.*)	AL	7
	Shrubland	Korshinsk peashrub (*Caranana korshinskii*)	KP	26
	Forestland	Chinese red pine (*Pinus tabulaeformis*)	CP	38
		Chinese arborvitae (*Platycladus orientalis*)	CA	30
		Siberian apricot (*Armeniaca sibirica*)	SA	40

Table 2a. Basic description of each experimental site.

Sampling sites	Topographical properties Slope gradient (°)	 Slope aspect (°)	 Slope position	Bulk density (g cm^{-3})	Porosity (%)	Soil properties Clay (%)	 Silt (%)	 Sank (%)	 SOM (g kg^{-1})	Vegetation growth conditions
Transects for different slope positions										
NG-U	9	1	Upper	1.05	55.83	7.94	80.43	11.63	16.32	Native grasses and herbs, mean height of grasses was 0.1 m and the coverage was 75 %
NG-M	30	358	Middle	1.05	54.82	6.63	84.07	11.63	15.18	Native grasses and herbs, mean height of grasses was 0.1 m and the coverage was 75 %
NG-D	31	358	Downhill	1.07	52.73	6.56	84.41	9.03	17.16	Native grasses and herbs, mean height of grasses was 0.1 m and the coverage was 75 %
PO-U	3	180	Upper	1.12	49.01	5.53	83.71	10.77	11.92	Potato with crown width of 0.45 m × 0.45 m, and the coverage was 45 %
PO-M	3	180	Middle	1.11	48.03	6.39	84.06	9.55	11.57	Potato with crown width of 0.45 m × 0.45 m, and the coverage was 45 %
PO-D	3	180	Downhill	1.12	49.83	6.61	84.00	9.40	12.28	Potato with crown width of 0.45 m × 0.45 m, and the coverage was 45 %
AF-U	3	65	Upper	1.00	56.26	6.32	82.27	11.40	13.09	Native grasses and herbs, mean height of grasses was 0.15 m
AF-M	3	65	Middle	1.06	50.79	5.38	88.47	6.15	15.53	Native grasses and herbs, mean height of grasses was 0.11 m
AF-D	3	65	Downhill	1.04	55.07	7.35	85.87	6.78	16.35	Native grasses and herbs, mean height of grasses was 0.14 m
AL-U	13	180	Upper	1.10	53.06	6.66	74.73	18.61	9.98	Alfalfa with aboveground biomass 246.31 g m^{-3}
AL-M	14	181	Middle	1.09	54.52	7.16	80.80	12.04	10.94	Alfalfa with aboveground biomass 248.06 g m^{-3}
AL-D	14	183	Downhill	1.08	55.36	7.82	78.08	14.10	11.82	Alfalfa with aboveground biomass 314.00 g m^{-3}
KP-U	32	180	Upper	1.10	50.56	5.47	79.46	15.07	9.71	Korshinsk peashrub with planting density of 1900 plant ha^{-1}, mean hight was 1.02 m and mean crown width was 1.67 m × 1.37 m, undergroth vegetation was sparse native grass
KP-M	32	180	Middle	1.14	48.99	5.40	78.41	16.19	9.76	Korshinsk peashrub with planting density of 1900 plant ha^{-1}, mean hight was 1.28 m and mean crown width was 1.83 m × 1.37 m, undergroth vegetation was sparse native grass
KP-D	30	180	Downhill	1.14	49.01	4.95	82.78	12.27	8.19	Korshinsk peashrub with planting density of 1900 plant ha^{-1}, mean hight was 1.23 m and mean crown width was 1.48 m × 1.37 m, undergroth vegetation was sparse native grass
CP-U	7	345	Upper	1.01	52.08	5.48	81.69	12.83	9.68	Chinese red pine with planting density of 2400 plant ha^{-1}, the mean hight and DBH was 4.55 m and 7.4 cm. Undergroth vegetation was sparse native grass
CP-M	22	340	Middle	1.05	54.76	5.95	77.92	16.13	7.45	Chinese red pine with planting density of 2400 plant ha^{-1}, the mean hight and DBH was 4.48 m and 6.9 cm. Undergroth vegetation was sparse native grass
CP-D	23	359	Downhill	0.88	51.91	4.94	82.10	12.96	11.04	Chinese red pine with planting density of 2400 plant ha^{-1}, the mean hight and DBH was 4.90 m and 8.1 cm. Undergroth vegetation was sparse native grass
CA-U	23	174	Upper	1.08	52.07	5.57	78.49	15.94	10.72	Chinese arborvitae with planting density of 2600 plant ha^{-1}, the mean hight and DBH was 3.82 m and 3.6 cm. Undergroth vegetation was sparse native grass
CA-M	25	149	Middle	1.13	51.81	5.03	82.32	12.65	10.69	Chinese arborvitae with initial planting density of 2600 plant ha^{-1}, the mean hight and DBH was 4.18 m and 3.2 cm. The trees were cut in 1998 and the plant density became 1300 plant ha^{-1}. Undergroth vegetation was sparse native grass.
CA-D	24	150	Downhill	1.16	51.02	5.43	80.51	14.05	5.81	Chinese arborvitae with planting density of 2600 plant ha^{-1}, the mean hight and DBH was 3.65 m and 3.7 cm. Undergroth vegetation was sparse native grass
SA-U	26	165	Upper	1.19	48.91	5.14	82.66	12.20	9.37	Siberian apricot with planting density of 900 plant ha^{-1}, the mean hight and DBH was 3.24 m and 7.64 cm. Undergroth vegetation was sparse native grass
SA-M	24	126	Middle	1.06	50.31	5.81	77.51	16.68	7.95	Siberian apricot with planting density of 900 plant ha^{-1}, the mean hight and DBH was 3.33 m and 7.45 cm. Undergroth vegetation was Korshinsk peashrub with planting density of 1670 plant ha^{-1}.
SA-D	22	135	Downhill	1.23	47.59	4.88	84.88	10.24	13.89	Siberian apricot with planting density of 900 plant ha^{-1}, the mean hight and DBH was 3.34 m and 7.32 cm. Undergroth vegetation was Korshinsk peashrub with planting density of 1671 plant ha^{-1}

Table 2b. Continued.

Sampling sites	Topographical properties			Soil properties						Vegetation growth conditions
	Slope gradient (°)	Slope aspect (°)	Slope position	Bulk density ($g\,cm^{-3}$)	Porosity (%)	Clay (%)	Silt (%)	Sank (%)	SOM ($g\,kg^{-1}$)	
Groups for different slope aspects										
NG-Shady	9	1	Upper	1.05	55.83	7.94	80.43	11.63	16.32	Native grasses and herbs, mean height of grasses was 0.1 m and the coverage was 75 %
NG-Sunny	9	180	Upper	1.07	52.42	6.22	81.28	12.50	16.61	Native grasses and herbs, mean height of grasses was 0.1 m and the coverage was 75 %
PO-Shady	2	8	Middle	1.05	49.53	4.52	82.00	13.48	6.73	Potato with crown width of 0.45 m × 0.45 m, and the coverage was 45 %
PO-Sunny	3	180	Upper	1.12	49.01	5.53	83.71	10.77	11.92	Potato with crown width of 0.45 m × 0.45 m, and the coverage was 45 %
AF-Shady	14	295	Upper	1.09	53.00	5.46	84.74	9.80	14.63	Native grasses and herbs, mean height of grasses was 0.25 m
AF-Sunny	16	181	Upper	1.10	53.43	5.24	80.27	14.49	14.85	Native grasses and herbs, mean height of grasses was 0.12 m
AL-Shady	15	289	Middle	1.10	53.21	5.27	87.19	7.55	7.74	Alfalfa with aboveground biomass 246.31 $g\,m^{-3}$
AL-Sunny	14	181	Middle	1.09	54.52	7.16	80.80	12.04	10.94	Alfalfa with aboveground biomass 246.31 $g\,m^{-3}$
KP1-Shady	29	276	Middle	1.26	49.75	6.92	75.73	17.35	11.53	Korshinsk peashrub with planting density of 1900 plant ha^{-1}, mean height was 1.28 m and mean crown width was 1.72m × 1.32 m, undergrowth vegetation was sparse native grass
KP1-Sunny	32	180	Middle	1.14	48.99	5.40	78.41	16.19	9.76	Korshinsk peashrub with planting density of 1900 plant ha^{-1}, mean height was 1.21 m and mean crown width was 1.83m × 1.37 m, undergrowth vegetation was sparse native grass
KP2-Shady	27	300	Downhill	1.23	50.48	5.65	84.04	10.31	10.52	Korshinsk peashrub with planting density of 1900 plant ha^{-1}, mean height was 1.28 m and mean crown width was 1.42m × 1.37 m, undergrowth vegetation was sparse native grass
KP2-Sunny	30	180	Downhill	1.14	49.01	4.95	82.78	12.27	8.19	Korshinsk peashrub with planting density of 1900 plant ha^{-1}, mean height was 1.23 m and mean crown width was 1.48m × 1.37 m, undergrowth vegetation was sparse native grass
Groups for different slope gradients										
NG9	9	1	Upper	1.05	55.83	7.94	80.43	11.63	16.32	Native grasses and herbs, mean height of grasses was 0.1 m and the coverage was 75 %
NG13	13	174	Upper	1.16	50.73	4.85	82.02	13.13	11.40	Native grasses and herbs, mean height of grasses was 0.1 m and the coverage was 75 %
NG24	24	150	Upper	1.14	51.11	4.35	84.92	10.73	12.21	Native grasses and herbs, mean height of grasses was 0.1 m and the coverage was 75 %
AL8	8	90	Upper	1.23	49.99	5.70	82.45	11.85	9.39	Alfalfa with aboveground biomass 246.31 $g\,m^{-3}$
AL13	13	180	Upper	1.10	53.06	6.66	74.73	18.61	9.98	Alfalfa with aboveground biomass 246.31 $g\,m^{-3}$
AL24	24	66	Upper	1.06	55.36	6.24	85.06	8.70	19.12	Alfalfa with aboveground biomass 246.31 $g\,m^{-3}$
CP7	7	345	Upper	1.01	52.08	5.48	81.69	12.83	9.68	Chinese red pine with planting density of 2400 plant ha^{-1}, the mean hight and DBH was 4.55 m and 7.4 cm. Undergroth vegetation was sparse native grass
CP23	23	330	Upper	1.03	52.87	4.57	82.02	13.41	8.51	Chinese red pine with planting density of 2400 plant ha^{-1}, the mean hight and DBH was 4.12 m and 7.4 cm. Undergroth vegetation was sparse native grass
CA12	12	180	Upper	1.02	54.78	5.74	84.80	9.46	10.50	Chinese arborvitae with planting density of 2600 plant ha^{-1}, the mean hight and DBH was 3.82 m and 3.6 cm. Undergroth vegetation was sparse native grass
CA23	23	174	Upper	1.08	52.07	5.57	78.49	15.94	10.72	Chinese arborvitae with planting density of 2600 plant ha^{-1}, the mean hight and DBH was 2.91 m and 3.6 cm. Undergroth vegetation was sparse native grass

Table 3. Temporal- and depth-averaged shallow SMC and depth-averaged deep SMC on different slope positions together with *F* test and *t* test.

Soil layer	Slope positions	NG (%)	S.D.	PO (%)	S.D.	AF (%)	S.D.	AL (%)	S.D.	KP (%)	S.D.	CP (%)	S.D.	CA (%)	S.D.	SA (%)	S.D.
Shallow SMC (*N* = 26)	Upper	6.49a*	1.69	8.96a	1.61	9.05a	1.31	5.48a	1.37	5.54a	1.00	7.07a	1.17	5.69a	1.13	6.23a	107
	Middle	5.76bc	1.55	8.58a	1.18	8.62a	1.28	5.54a	1.19	5.55a	1.03	6.52a	0.93	5.58a	1.06	6.02a	0.98
	Downhill	6.28ac	1.21	8.54a	1.65	8.22a	1.23	5.59a	1.02	5.27a	1.02	6.58a	0.98	5.17a	0.99	5.65a	0.84
	p value	0.083		0.824		0.449		0.659		0.787		0.740		0.256		0.507	
Deep SMC (*N* = 30)	Upper	9.93a	2.18	11.28a	1.84	12.01a	2.20	8.18a	1.64	8.37a	1.65	6.83a	0.81	6.83a	1.02	7.79a	1.42
	Middle	8.70b	1.96	11.54a	1.54	12.29a	1.34	7.97a	1.61	7.04b	0.72	7.07a	0.98	7.07b	0.92	7.03b	0.92
	Downhill	10.38a	1.29	11.25a	1.53	12.64a	1.99	8.26a	1.52	6.87b	0.89	6.86a	0.84	6.50c	0.94	6.96b	1.21
	p value	0.002**		0.748		0.427		0.766		0.000**		0.501		0.000**		0.013**	

Note: The shallow SMC was temporal- and depth- averaged from April 2009 to September 2010 during growing reason, and the number of samples was 26. The deep SMC was depth-averaged during August 2010, and the number of samples was 30.
*: Means with the same letter in the same column are not significantly different at the 0.05 level (LSD test).
**: Means significantly different at the 0.05 level (*F* test).

Table 4. Temporal- and depth-averaged shallow SMC and depth-averaged deep SMC on different slope aspects together with *t* test.

Soil layer	Slope aspect	NG (%)	S.D.	PO (%)	S.D.	AF (%)	S.D.	AL (%)	S.D.	KP1 (%)	S.D.	KP2 (%)	S.D.
Shallow	Shady	6.66a*	1.46	8.73a	1.31	8.22a	1.25	7.38a	1.17	5.94a	1.08	6.58a	1.14
SMC	Sunny	5.97b	1.25	8.70a	1.18	6.57b	1.14	6.40a	1.19	5.54a	1.03	5.24b	1.02
($N = 26$)	*p* value	0.045**		0.686		0.010**		0.103		0.448		0.024**	
Deep SMC	Shady	10.10a	2.23	11.28a	1.44	12.74a	1.34	7.63a	1.33	7.42a	1.12	6.83a	0.86
($N = 30$)	Sunny	10.22a	2.37	11.40a	2.14	10.56b	2.43	7.97a	1.34	7.04a	0.72	6.87a	0.89
	p value	0.828		0.780		0.000**		0.358		0.140		0.871	

Note: The shallow SMC was temporal- and depth- averaged from April 2009 to September 2010 during growing reason, and the number of samples was 26. The deep SMC was depth-averaged during August 2010, and the number of samples was 30.
*: Means with the same letter in the same column are not significantly different at the 0.05 level (*t* test).
**: Means significantly different at the 0.05 level (*t* test).
KP1 and KP2 are sampling sites on the middle and downhill positions of korshinsk peashrub transect.

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Table 5. Temporal- and depth-averaged shallow SMC and depth-averaged deep SMC in different slope gradients together with F test and t test.

Vegetation types	Slope gradient (°)	Shallow SMC (%, $N = 26$)	S.D.	Deep SMC (%, $N = 30$)	S.D.
NG	9°	7.00a*	1.46	10.10a	2.23
	13°	6.59a	1.00	8.69b	1.27
	24°	6.66a	1.06	7.96b	0.91
p value		0.388		0.000**	
AL	8°	7.68a	1.03	8.25a	1.50
	13°	5.68b	1.37	8.18a	1.64
	24°	5.99b	1.13	7.43b	1.31
p value		0.000**		0.060	
CP	7°	7.07a	1.17	6.83a	0.81
	23°	5.75b	1.01	6.48a	1.11
p value		0.046**		0.165	
CA	12°	5.81a	1.15	7.80a	1.09
	23°	5.69a	1.13	6.73b	0.72
p value		0.660		0.000**	

Note: The shallow SMC was temporal- and depth- averaged from April 2009 to September 2010 during growing reason, and the number of samples was 26. The deep SMC was depth-averaged during August 2010, and the number of samples was 30.

*: Means with the same letter in the same column are not significantly different at the 0.05 level (LSD test).

**: Means significantly different at the 0.05 level (F test).

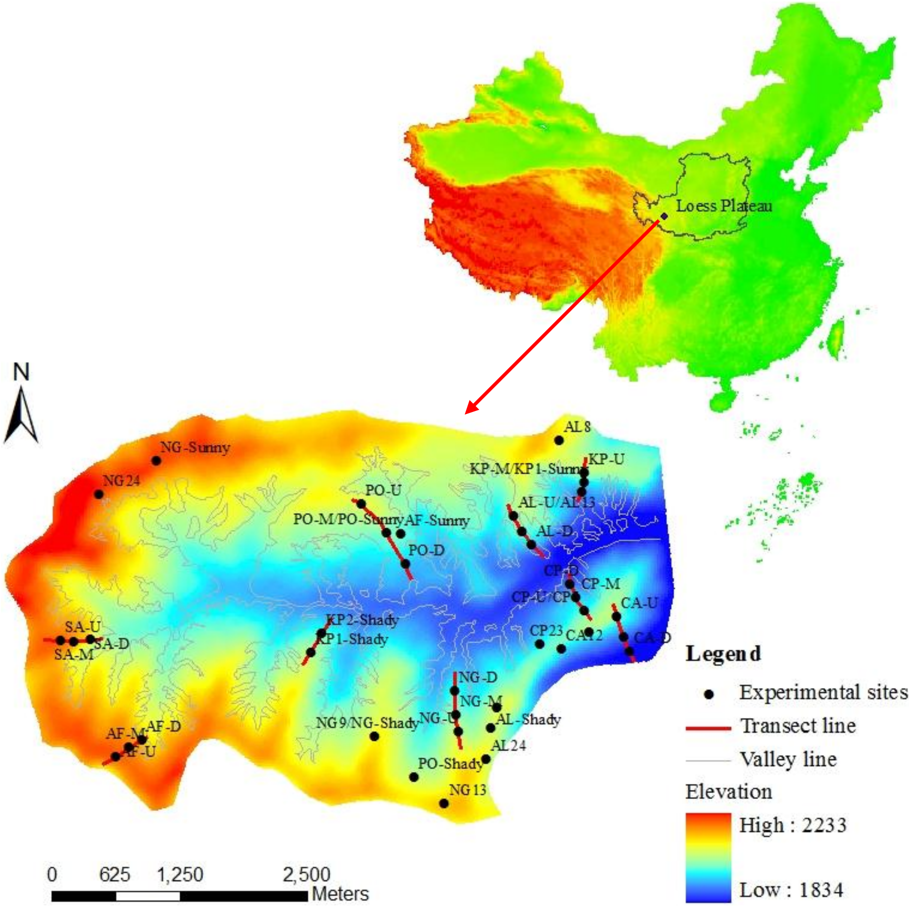

Fig. 1. Location of the study area and experimental sites.

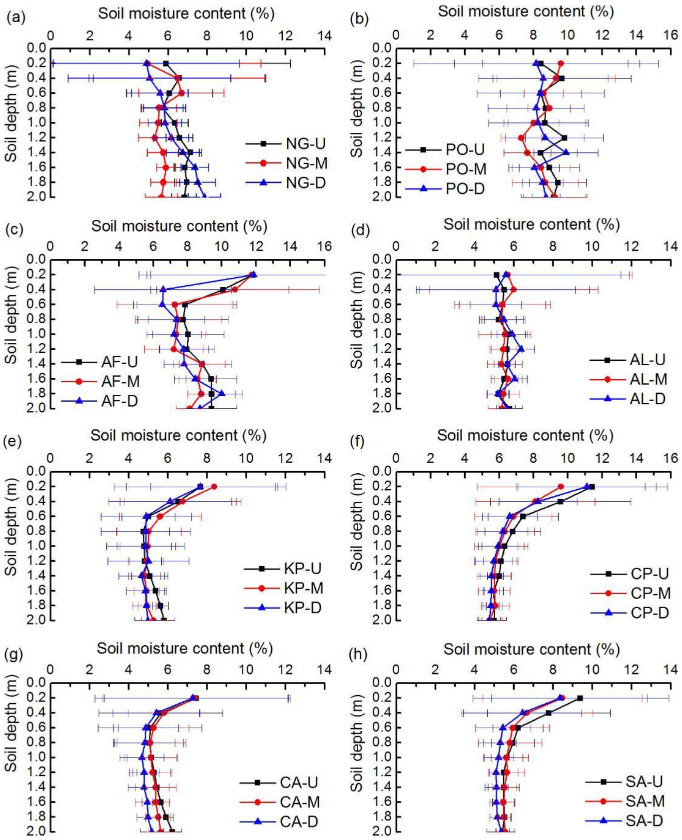

Fig. 2. Comparison of temporal-averaged shallow SMC on different slope positions. Note: The number of samples of shallow SMC was 26. The last letter U refers to upper position, M refers to middle position and D refers to downhill position. For example, NG-U NG-M and NG-D refer to upper position of natural grassland, middle position of natural grassland and downhill position of natural grassland, respectively.

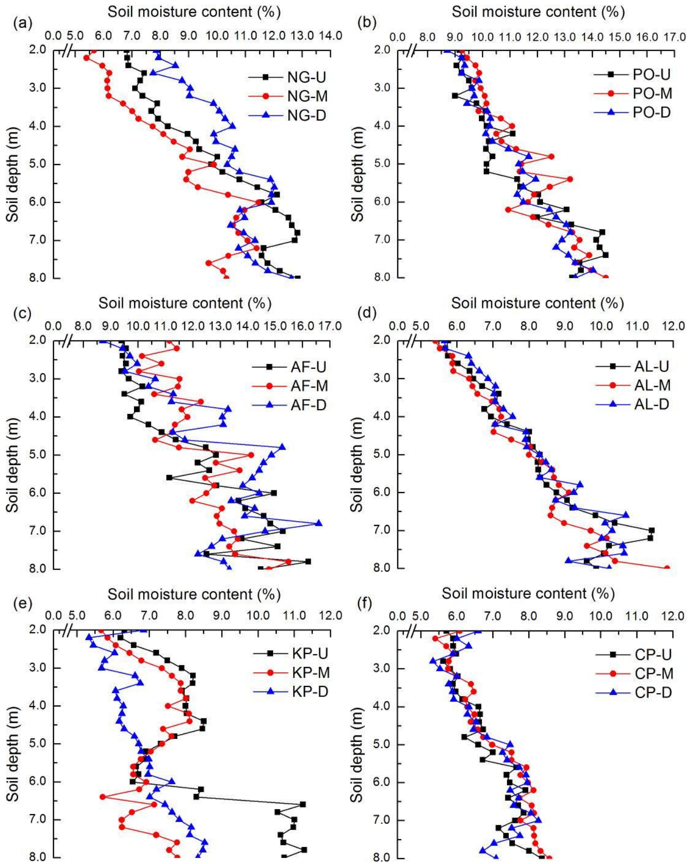

Fig. 3. Comparison of deep SMC on different slope positions. Note: The last letter U refers to upper position, M refers to middle position and D refers to downhill position. For example, NG-U NG-M and NG-D refer to upper position of natural grassland, middle position of natural grassland and downhill position of natural grassland, respectively.

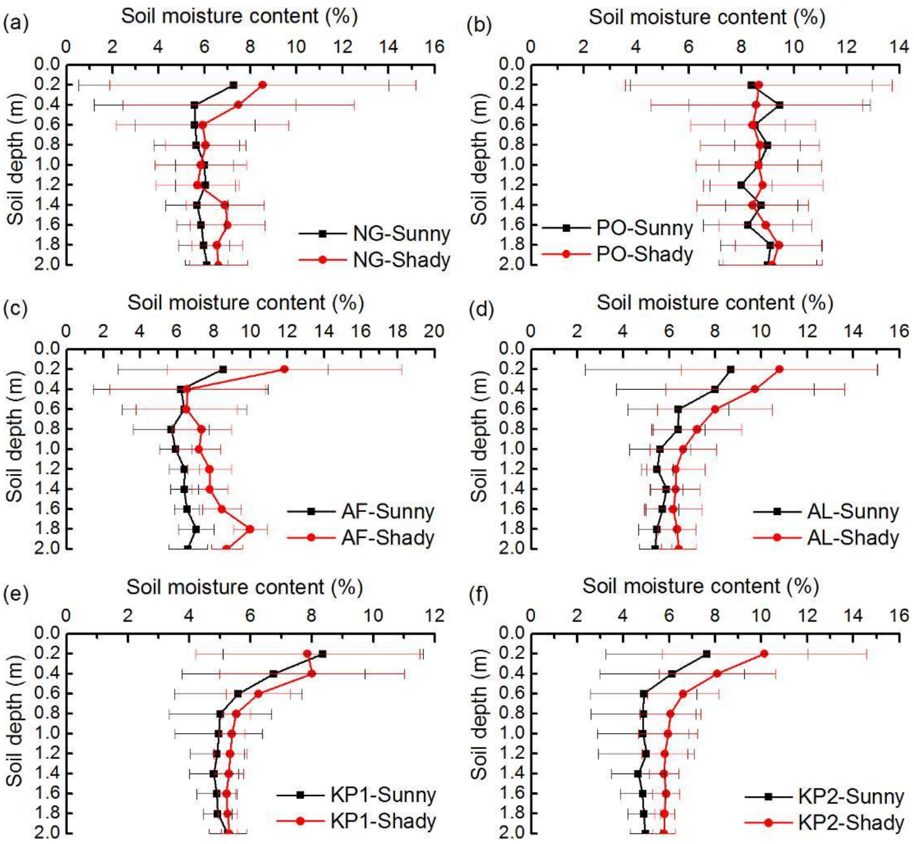

Fig. 4. Comparison of temporal-averaged shallow SMC on different slope aspects. Note: The number of samples of shallow SMC was 26. Sunny refers to sunny slope and Shady refers to shady slope. For example, NG-Shady refer to native grassland on shady slope, and NG-Sunny refer to native grassland on sunny slope.

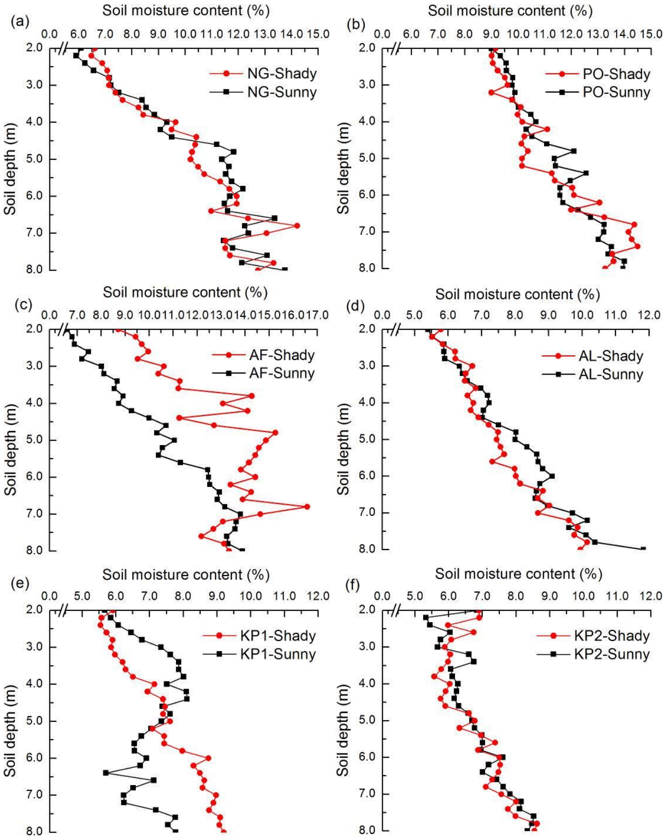

Fig. 5. Comparison of deep SMC on different slope aspects. Note: Sunny and Shady refers to sunny slope and shady slope, respectively. For example, NG-Shady refers to native grassland on shady slope, and NG-Sunny refers to native grassland on sunny slope.

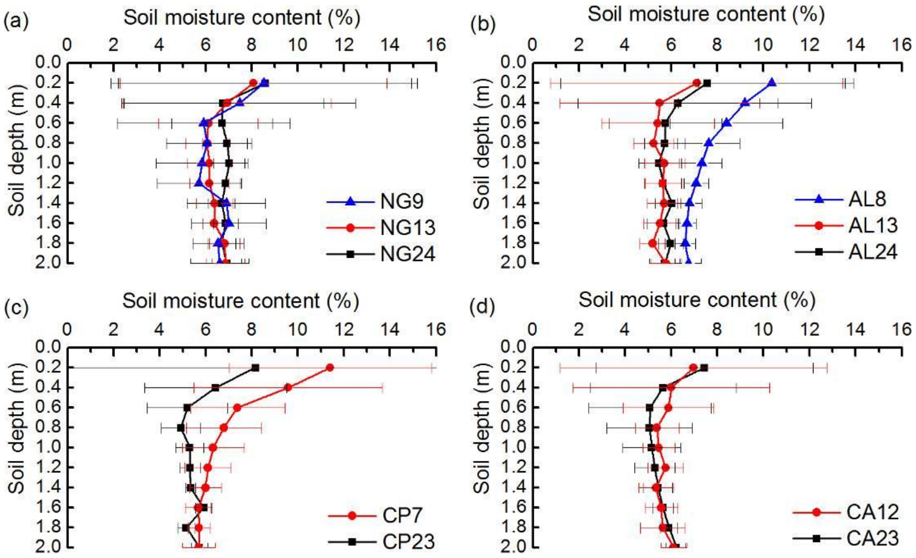

Fig. 6. Comparison of temporal-averaged shallow SMC in different slope gradients. Note: The number of samples of shallow SMC was 26. The last number refers to slope gradient. For example NG9 refer to native grassland with slope gradient of 9°, NG13 refer to natural grassland with slope gradient 13° and NG 24° refer to natural grassland with slope gradient 24°.

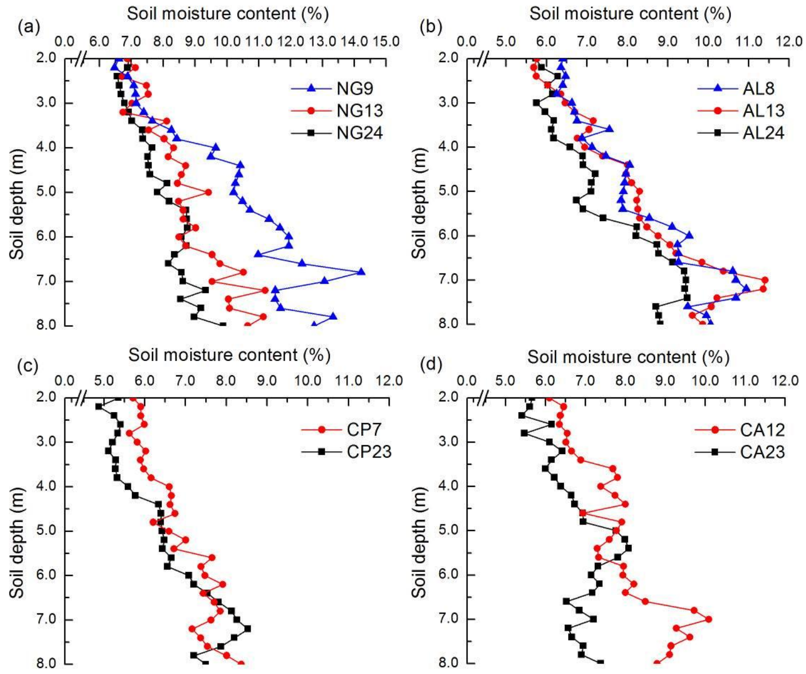

Fig. 7. Comparison of deep SMC in different slope gradients. Note: The last number refers to slope gradient. For example NG9 refer to native grassland with slope gradient of 9°, NG13 refer to natural grassland with slope gradient 13° and NG 24 refer to natural grassland with slope gradient 24°.