Responses to the Reviewers:

We thank the editor and reviewers very much for the time they spent evaluating our manuscript and providing constructive comments. Their detailed comments inspired us to improve the quality of this manuscript. We have carefully amended our original manuscript based on the suggestions and comments. Our detailed responses are provided below.

Responses to Reviewer #1:

Reviewer: *The researchers conclude that natural vegetation and croplands had the highest soil moisture content while introduced vegetation types have caused soil desiccation. The authors suggest that vegetation restoration in the study watershed has resulted in concerns of soil water resources depletion and this issue can explain the low productivity in planted forests. The data are valuable and findings have important implication in practices given the large-scale ecological restoration efforts in the study region.*

Authors: Investigating the deep soil moisture (DSM) dynamics under different vegetation types and its control mechanism at the watershed scale is indeed a valuable and challenging task. Thank you very much for your encouragement. We have carefully amended the manuscript based on the comments that you provided.

Reviewer: *The manuscript is well written. However, a thorough read by an English native speaker will increase the readability and presentation. There are too many grammar errors and clarifications are to be addressed.*

Authors: We have invited a native English speaker to revise the language of our manuscript to increase its readability.

Reviewer: *The title is misleading. The work does not address spatial variations of SMC. No maps are presented to show the differences in space across the watershed although work does examine how slope gradient, slope positions and climate (Precip) distribution result in difference in SMC.*

Authors: We have adjusted the title in the revised manuscript based on the collective suggestions from all the reviewers (please refer to the title section on page 1).

Reviewer: *The authors have identified Precipitation and Soil Particle size (soil texture)* *is the major driver. But, how different is the Precipitation and soil across the watershed is not clear. Also, I suggest a word of watershed should be added since the paper does not address SMC for the entire Loess Plateau!*

Authors: We agree that clarifying the differences in precipitation and soil particle size across the watershed is necessary. Thus, we have added relevant content to the revised manuscript and supplemental materials (please refer to lines 2-4 on page 7, lines 7-9 on page 7, and Figures S1 and S2 in the supplemental material). Following the reviewer's suggestion, we have added the word "watershed" in the title (please refer to the title section on page 1).

Reviewer*: Which layer is considered deep soil layer? This basic concept needs to be defined clearly.*

Authors: In this study, we define a deep soil layer as a layer where the soil moisture is not sensitive to daily evapotranspiration and regular rainfall events. We have defined "deep soil layer" clearly in the Introduction section of the revised manuscript (please refer to lines 15-26 on page 3 and lines 1-2 on page 4).

Reviewer: *The manuscript is overly long. I suggest the authors just present key findings that are useful for illustrate the 1) overall patterns of SMC on space by soil depth, 2) contrast SMC by land use 3) Illustrate key factors that justify the fact that the introduced vegetation had lower SMC than native grassland and crops was due to higher biomass and evapotranspiration loss NOT by other factor such as slope, aspects, soil etc. Several figs are not essential example, Fig 2 and Fig 9. Similarly reduce the number of Tables, such as Fig 7. In Table 4, only the significant correlations are needed to be reported.*

Authors: Following the reviewer's suggestion, we have checked the manuscript carefully and removed/condensed some content that was less relevant to the key findings, such as Figure 2 (lines 1-2 on page 12), Figure 6 (lines 14-21 on page 22 and lines 1-11 on page 23), Section 3.3 (lines 12-26 on page 23 and lines 1-2 on page 24), and Figure 9 (lines 1-10 on page 35).

Response to reviewer #2:

Reviewer*: The title of the manuscript is misleading. The paper does not explore the spatial variability of the soil moisture, it rather analyses how locally observed soil moisture values are related with both natural and human induced local factors.*

Authors: We have adjusted the title of the revised manuscript based on the collective suggestions from all the reviewers (please refer to the title section on page 1).

Reviewer: *The manuscript is too long, it provides several details that are not relevant for the key messages of the paper. Some data could be provided as supplementary material attached to paper.*

Authors: Following the reviewer's suggestion, we have checked through the manuscript carefully and removed/condensed some content that was less relevant to the key findings, such as Figure 2 (lines 1-2 on page 12), Figure 6 (lines 14-21 on page 22 and lines 1-11 on page 23), Section 3.3 (lines 12-26 on page 23 and lines 1-2 on page 24), and Figure 9 (lines 1-10 on page 35). Additionally, we provided the annual average rainfall distribution data, soil particle composition distribution data, and meteorological data as supplementary materials, which are attached to this manuscript (please refer to Section S1, S2, and S3 in the supplemental materials).

Reviewer: *Since the main scope of the paper is to assess the effect of the vegetation on soil moisture profile, a description of the root architecture of the different vegetation species in the examined sites would facilitate the analysis of the results. At lines 15-17, page 19, the authors state that "despite the deep root system of the apple orchard . . .the soil moisture in the apple orchard was higher than in native grasses". But how deep is the "effective" rooting system of the apple trees? Is it really deeper than native grasses? And what about the other species?*

Authors: We agree that a description of the root architecture of the different vegetation species can facilitate an analysis of the results. However, digging out the entire rooting systems of all the plants in the 151 sampling sites would be nearly impossible. Thus, root architecture information of the eight vegetation species in the study area has been obtained from other publications. We added the root architecture information of different vegetation types to the revised manuscript (see Table 1 on page 9).

Reviewer: *It is well known that the soil moisture profile in the inter-storm periods is influenced by the vertical distribution of the active roots. Previous studies (e.g. Laio et al., Geophysical Research Letters, 2006) showed that the vertical root distribution in water controlled ecosystems is the result on an equilibrium condition affected by the local climate and soil properties. The data provided in the paper do not prove an unbalance "between soil availability and water utilization by plants". The observed soil moisture profiles could be representative of a stationary equilibrium condition.*

Authors: We agree that the vertical distribution of the active roots can influence the soil moisture profile during inter-storm periods. However, EM50 dynamic monitoring data (shallow-root system native grasses and deep-root system *Caragana korshinskii*) indicated that no significant changes in deeper soil moisture (80-500 cm) occurred during the sampling period (July 10 - August 6). In contrast to surface soil moisture, which is greatly influenced by vegetation roots, the DSM is relatively stable over a short period (such as a month) and is probably determined by long-term moisture replenishment and consumption. We only explored stationary DSM data in this study; however, we can still demonstrate an imbalance between soil availability and water utilization by plants by comparing DSM under different vegetation types. For example, soil desiccation in introduced vegetation supported a long-term imbalance between rainfall infiltration and water consumption by plant root systems. We have added these EM50 dynamic monitoring data and clarified the influence of the roots on soil moisture in the revised manuscript (see section 3.1 on pages 14-15).

Reviewer: *Line 5-7 page 2 and Figure 2: it is not clear if the meteorological data collected during the sampling period have been exploited for the soil moisture data analyses. Apparently not. Therefore the sentence (lines 5-7) and Figure 2 can be removed. The authors should clarify to what extent the soil moisture observed in top layers could have been influenced by the rainfall events during the same sampling period.*

Authors: No, we did not analyze the meteorological data that were collected during the sampling period in terms of soil moisture data analyses; these data were used to illustrate the climate conditions of the sampling period (July 10 - August 6). In the revised manuscript, we have further exploited the meteorological data and moved Figure 2 and relevant content to the supplemental materials (see lines 16-18 on page 11, lines 1-2 on page 12, and section S3 in the supplemental materials). According to our EM50 dynamic monitoring data, the rainfall events during the sampling period influenced soil moisture no deeper than 80 cm; thus, we mainly analyzed the soil moisture at depths of 80-500 cm in the revised manuscript (see section 3.1 on pages 14-15).

Reviewer: *Equations 1 and 2 can be removed. They describe simple metrics (depth-average soil moisture values) but are quite confusing. The same symbol SMC is used with different subscripts to describe different metrics in a way that does not appear to be consistent. From Equation 2 and the corresponding description, is not clear that SMCs represents the average soil moisture within the same type of land management at a given layer depth.*

Authors: Following the reviewer’s suggestion, we have removed Equations 1 and 2 from the revised manuscript (see lines 6-13 on page 23).

Reviewer*: Table 2 provides details (such as Kurtosis, Skweness, K-S normality test) that are not commented in the manuscript.*

Authors: Following the reviewer’s suggestion, a detailed description of Table 2 (including the kurtosis, skewness, and K-S normality tests) has been added to the revised manuscript (see lines 16-20 on page 15).

Reviewer: *Lines 10-22, page 15. The classification of the different layers is rather subjective and not supported by experimental evidences. The first layer should be influenced by both evaporation and transpiration. Not clear while the second layer is a "rainfall infiltration layer": transpiration could be significant in this layer in case of deep-rooted vegetation.*

Authors: We agree that the classification of the different soil layers by only considering soil moisture variations in native grassland is subjective. In the revised manuscript, we have further adjusted the classification based on EM50 dynamic monitoring data and removed the 0-80-cm soil moisture layer because this layer is not relevant in terms of deep soil moisture. Additionally, we have included the transpiration of deep-rooted vegetation (see lines 6-22 on page 19 and lines 1-20 on page 20).

Reviewer: *Section 3.3 could be removed. It does not add information relevant for the main outcomes of the paper.*

Authors: As suggested, we have removed section 3.3 because it is not closely related to the main points of the manuscript (see lines 12-26 on page 23 and lines 1-2 on page 24).

Reviewer*: Line 15-18, page 20. It is not clear how the correlation of the soil moisture with the average annual rainfall has been computed. No data about rainfall height at the different sampling sites have been provided. The result is rather surprising. Since surface soil moisture is highly variable in time, due to evapotranspiration and rainfall events, what is the motivation of this "significant correlation"? Despite what is stated in the manuscript, Table 4 does not highlight the correlation value as "significant" (I do not see it in bold or underlined).*

Authors: Actually, no rainfall monitoring was conducted at any of the sampling sites. The average annual rainfall (2006-2013) was provided by 29 rain gauges in or around the Ansai watershed, and the Inverse Distance Weighted (IDW) interpolation method was performed by ArcGIS 10.0 to obtain the average annual rainfall at each sampling site (see lines 18-21 on page 11). We have added a distribution map of the average annual rainfall in the supplemental materials to further illustrate this approach (see Figure S1 in the supplemental materials). Additionally, we checked Table 4 and found that the bold style in this table was missing. We apologize for this oversight, and we have corrected this table in the revised manuscript (see Table 5 on page 28).

Reviewer: *From pages 9-10, it seems that soil properties (particle size distribution, bulk density, porosity) have been measured only from soils cores collected from the surface. Are these properties expected to be uniform along the soil profile? Soil moisture values are significantly influenced by soil texture and organic carbon content. Do the correlations presented in Tables 4-6 refer to surface soil properties?*

Authors: Yes, all the soil properties were measured only from soil cores that were collected from the surface (0-20 cm). The loess soil thickness in the Loess Plateau ranges from 30 to 80 m, and groundwater below this depth cannot influence deep soil moisture that is available for plant growth. Thus, the deep soil moisture in this region is mainly determined by land surface rainfall infiltration and evapotranspiration. Although soil properties may be different along the soil profile, surface soil properties (such as the particle size distribution, bulk density, porosity, and organic carbon content) usually have a greater influence on surface rainfall infiltration and evaporation compared to deep soil properties, and measuring the soil properties (especially bulk density) from the 0-500-cm layer at 151 sampling spots is nearly impossible. Thus, we mainly focused on analyzing the surface soil properties' influence on deep soil moisture. We have further explained the reason for this approach in the revised manuscript (see lines 10-13 on page 40).

Response to reviewer #3:

Reviewer: *The Fang et al. paper on the spatial variation of deep soil moisture in the Loess Plateau is in general well-written and it presented a very comprehensive dataset that was rarely available anywhere else.*

Authors: Thank you very much for your encouragement. Measuring deep soil moisture at depths of 0-500 cm is a very challenging but valuable task. We have carefully amended the manuscript based on your comments.

Reviewer: *The authors should clarify what they meant by "deep soil moisture" early in the introduction. How deep they investigated, and the temporal and spatial scale of their experiment.*

Authors: As suggested by the reviewer, we have defined “deep soil layer” clearly in the introduction section of the revised manuscript (see lines 15-26 on page 3 and lines 1-2 on page 4) and described the investigation depth and temporal and spatial scales of our experiment in detail (lines 5-9 on page 11).

Reviewer*: There are many very long paragraphs, please break them into two or more* *short sections. (page4, paragraph 2)*

Authors: As suggested by the reviewer, we have broken down long paragraphs into short sections (see lines 23-24 on page 5 and lines 2-3 on page 40).

Reviewer*: I was wondering how the soil moisture was measured, did they dig a 5-m hole for each profile, or use any technology that is able to reach up to 5 m without digging a hole? If they indeed dug hole for each site, how they did it? The paper did not make it clear in all these details. It would be very impressive to dig 151, 5-m soil profile holes for any study.*

Authors: Actually**,** the soil samples at depths of 0–500 cm were collected by a soil drill (5 cm in diameter) with 20-cm increments (see the following figure).

Collecting these data is indeed a challenging logistical task, so these data are quite valuable. We have clearly described the sampling details in the revised manuscript (see lines 5-9 on page 11).

Reviewer*: In page 3, line 7-9 only include a few representive references, this is too many.*

Authors: As suggested by the reviewer, we have further checked the references and only retained a few representative citations in the revised manuscript (see lines 12-15 on page 3).

***Reviewer**: In page4, line22. Should you simply use deep soil moisture (DSM) only? This is the term you used in your title.*

Authors: Yes, “deep soil moisture (DSM)” is more accurate than “deep soil moisture content (SMC)”; thus, we have replaced this term throughout the revised manuscript.

***Reviewer:** “whole” in page 5, line 4, “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).” in page 5, line27-29, and “The Ansai watershed is located on a warm forest steppe” in page 6, line 23 should be deleted.*

Authors: Following the reviewer’s suggestion, we have deleted these less relevant sentences in the revised manuscript (see line 20 on page 5, lines 15-19 on page 6, and lines 20-21 on page 7).

***Reviewer:** In page 7,line 4.You should include the boundary of Shanxi province since you mentioned it in your description.*

Authors: Following the reviewer’s suggestion, we have added the boundary of Shanxi province in Figure 1 in the revised manuscript (see Figure 1 on page 8).

***Reviewer**: In page 13, line 1. You don’t need to include the legends in the graphs since there is only one category.*

Authors: As suggested by the reviewer, we have deleted the unnecessary legend in the graphs in the revised manuscript (see lines 1-3 on page 17).

***Reviewer:** In page 24, line 8. I don’t think you need to count to two digits, simply 80%, 68% etc...*
Authors: As suggested by the reviewer, we have reported integer digits in the revised manuscript (see lines 3-6 on page 32).

Response to reviewer #4:

Reviewer: *The title is not representative of the results reported in the manuscript. The authors didn't show the spatial variation of soil moisture. The title should be more tailored on "influencing factors" rather than "spatial variation".*

Authors: Considering the collective suggestions from all four reviewers, we have revised the title of the revised manuscript (see the title section on page 1).

Reviewer: *The manuscript is too long with several repetition and some confusing sentences.*

Authors: Following the reviewer's suggestion, we have removed some content that was less relevant to the key findings, such as Figure 2 (lines 1-2 on page 12), Figure 6 (lines 14-21 on page 22 and lines 1-11 on page 23), Section 3.3 (lines 12-26 on page 23 and lines 1-2 on page 24), and Figure 9 (lines 1-10 on page 35). In addition, we have invited a native English speaker to revise the language of our manuscript to increase its readability.

Reviewer: *Equation 1 and 2 are not necessary.*

Authors: Following the reviewer's suggestion, we have deleted Equations 1 and 2 (see lines 6-13 on page 13).

Reviewer: *Citation should be always necessary. The need of some citation is not clear to me (i.e. at line 21 page 11). Do the authors say that tests on the distribution of data were performed by Shi et al. (2014)? In this case the authors should clearly state the origin of statistical results in table 2. Other- wise I think the citation to Shi et al. (2014) should be removed, because the need of normally distributed data to perform statistical analysis such as ANOVA was already known before Shi et al. (2014).*

Authors: We agree that some citations in this manuscript may be unnecessary; we have carefully checked all the citations in the manuscript to ensure their accuracy and removed unnecessary citations (see lines 12-15 on page 3 and line 20 on page 15).

Reviewer: *The authors state that data were normally distributed, and then they should probably explain why they choose a non-parametric correlation test (Spearman).*

Authors: The data were normally distributed; however, significant correlations existed in the soil moisture content at different soil depth ranges (see Figure 7 on page 24). Thus, we chose a non-parametric correlation test (Spearman), which we have further clarified in the revised manuscript (see lines 5-7 on page 27).

Reviewer: *The authors collected soil sample during summer 2014, but they say: "Most rain occurs in the form of thunderstorms during the summer months from July to September." (lines 20-21 page 6). How they took into account the effects of rainfall and actual evapotranspiration on soil moisture dataset? The duration of the sampling campaign is a key point. In the case the measurement campaign of a single soil moisture profile at each of the 151 sites took two months, the study is questionable, because the author considered fifteen parameters without taking into account the effects of water added from thunderstorms or removed by actual evapotranspiration. The authors should clarify this point.*

Authors: Actually, the duration of the sampling campaign was 28 days (from July 10 to August 6). According to field observation and EM50 dynamic monitoring data, the rainfall events and evapotranspiration influenced soil moisture no deeper than 80 cm, so we consider that deep soil moisture (80-500 cm) was seldom influenced by rainfall events and evapotranspiration during the sampling period. Additionally, the main objective of this manuscript is to examine variations in the deep soil moisture and its influencing factors, so we have removed our analysis of the 0-80-cm soil moisture data. We have further clarified this point in the revised manuscript, and EM50 dynamic monitoring data have been added to verify this point (see section 3.1 on pages 14-15).

Reviewer: *According to data presented in Table 1 the density of the solid phase of the soil varies from 2.37 to 2.47 Mg m^{-3}. How the authors measured this parameter? Why the authors decided to employ a variable density of the solid phase? A constant solid phase density would establish a linear relation between porosity and soil bulk density.*

Authors: Actually, "porosity" in Table 1 is "capillary porosity", not "soil total porosity". The capillary porosity was calculated from the solid phase density and bulk density. Undisturbed soil cores were collected in metal cylinders (diameter of 5 cm and length of 5 cm) at each sampling site, and then the capillary porosity was measured by the "cylinder soak method". We have changed "porosity" to "capillary porosity" in the revised manuscript to avoid confusion (see lines 9-12 on page 12).

Reviewer: *In some cases the authors drawn conclusions from results of statistical analysis, but in the discussion they didn't give any explanation on the hydrological processes that could have led to such results. Since any influence was observed in the upper layers, why soil moisture between 4 and 5 m depth below David peach should be influenced by grass biomass? Same question should be answered for the influence of litter biomass below apple orchard.*

Authors: As suggested by the reviewer, we have checked the results of the statistical analysis and provided explanations for the hydrological processes that could have led to such results in the revised manuscript (see lines 26-29 on page 38). The deep soil moisture below David peach trees and apple orchards had significantly positive relationships with the upper layer grass biomass and litter biomass, probably because thick litter and forest grasses can reduce surface runoff, which may help retain more rainfall for infiltration into deep soil layers. In addition, these factors can reduce soil evaporation, which may decrease DSM consumption.

***Reviewer**: the authors should change "buck density" to "bulk density" and "organic" to "organic matter". Pay attention to the use of "infiltration", sometimes was used instead of "storage".*

Authors: Following the reviewer's suggestion, we have checked the entire manuscript and changed all instances of "buck density" to "bulk density" and "organic" to "organic matter". We have also carefully checked the use of "infiltration"

~~Spatial v~~Variations of deep soil moisture under different vegetation types and influencing factors in a watershed of the Loess Plateau, China

X. N. Fang[1], W. W. Zhao[1], L. X. Wang [2], Q. Feng [3], J. Y. Ding [1], Y. X. Liu [1] and X. Zhang [1]

[1] State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Resource and Technology, Beijing Normal University, Beijing 100875, P. R. China

[2] Department of Earth Sciences, Indiana University-Purdue University, Indianapolis (IUPUI), Indianapolis, Indiana 46202, USA

[3] College of Forestry, Shanxi Agricultural University, Taigu, Shanxi 030801, P. R. China

Correspondence to: W. W. Zhao (Zhaoww@bnu.edu.cn) and L. X. Wang (lxwang@iupui.edu)

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 deep soil moisture ~~content~~ (DSM~~C~~) in (~~0~~80-500 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~~DSM 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~~DSM under native vegetation was much lower than that in human-managed vegetation and introduced vegetation. (2) The ~~deep SMC~~DSM 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. Among them, *Caragana korshinskii* and black locust caused most serious desiccation. (3) Taking the ~~SMC~~ DSM condition of native vegetation as a reference for local control, ~~soil could be divided into four layers:~~ DSM in this watershed could be divided into three layers: (Ⅰ) Rainfall transpiration layer (80-220cm). (Ⅱ) Transition layer (220-400cm). (Ⅲ) Stable layer (400-500 cm).~~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~~DSM at the watershed scale varied with ~~land~~

~~management types~~vegetation types. The main local controls of ~~SMC~~ DSM variation were soil particle composition and annual average rainfall; human agricultural management measures can alter soil ~~buck density~~bulk density, which contributes to higher DSM in farmland and apple orchard. In introduced vegetation, plant growth conditions, planting density, and litter water holding traits showed significant relationships with ~~deep SMC~~DSM. The results of this study are of practical significance for vegetation restoration strategies especially for the choice of vegetation types, planting zones, and proper human management measure.

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 (Cheema et al., 2011;Legates et al., 2010;Wang et al., 2012a;Zhao et al., 2013). ~~(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)~~ Soil moisture at different soil layers usually owns different hydrological processes and ecological function (Yang et al., 2012a). Surface or shallow layer soil moisture are usually greatly influenced by rainfall infiltration or evapotranspiration, and are regular water sources for vegetation growth, while moisture in deep soil layers works as a reservoir for soil. In rainy years DSM can be repleshed by rainfall infiltration, and in drought years it can also provide necessary water for plant growth. Thus, it is important for plant growth in dry seasons (Yang et al., 2012c;Jia and Shao, 2014). ~~at(Yang et al., 2012a)~~DSM~~(Yang et al., 2012c;Jia and Shao, 2014)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 (Yang et al., 2012c;Jia and Shao, 2014).~~ 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~~DSM even becomes the main constraining factor of plant productivity and ecosystem sustainability (Wang et al., 2010c;Wang et al., 2011a). In this study, we define deep soil layer as the layer whose soil moisture is not sensitive to daily evapotranspiration and regular rainfall event~~.~~

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., 2010b). 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 (Yang et al., 2014b). 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,~~DSM which is stored in unsaturated soil, becomes an important water resource for plant growth (Yang et al., 2012c). 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~~DSM, and a large range of soil desiccation has been reported (Wang et al., 2008b;Wang et al., 2010b;Wang et al., 2010c;Wang et al., 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., 2008a). 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~~DSM have gradually drawn attention from many scientists in recent years. For example, it was recently found that ~~deep soil moisture~~DSM 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., 2012c). It was also found that introduced vegetation diminished the spatial heterogeneity of ~~deep soil moisture~~DSM at the small catchment scale (Jia and Shao, 2014;Yang et al., 2014b). In recent years, several studies have been conducted on the variation and influencing factors of ~~deep soil moisture~~DSM in the Loess Plateau (Jia and Shao, 2014;Liu et al., 2010;Wang et al., 2013;Wang et al., 2012b;Yang et al., 2014a;Sun et al., 2014). Deep soil moisture is an indispensable water source for vegetation growth in the semi-arid Loess Plateau; understanding the variation and influencing factors of ~~deep soil moisture~~DSM 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)~~DSM is a result of long-term biophysical processes controlled by multiple factors (Vereecken et al., 2007). Several factors may impact ~~soil moisture~~DSM variation, such as vegetation traits, soil properties, topographical factors, climate factors, and human landscape management measures (Qiu et al., 2001;Zhu and Lin, 2011;Montenegro and Ragab, 2012;Vivoni et al., 2008;Lu et al., 2007;Lu et al., 2008). The dominant factors that affect ~~deep SMC~~DSM variation depend on the research scale (Entin et al., 2000). For instance, ~~deep SMC~~DSM variation was found to be mainly dominated by the 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~~DSM variation at the small catchment scale (1-100 km^2) (Yang et al., 2012a). Meanwhile, Wang et al. (2012b) reported that ~~deep SMC~~DSM 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~~DSM 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~~DSM 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~~DSM variation (Zhu et al., 2014a;BI et al., 2009;Zhu et al., 2014b;Gómez‐Plaza et al., 2000), 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~~DSM variation necessary for guiding local policies (Wang et al., 2010a;Wang et al., 2010d;Wang et al., 2012c). 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~~DSM variation mechanism. In particular, it is the scale at which people and nature mesh and interact most acutely (Zhao and Fang, 2014;Fang et al., 2015), and thus is a more operational scale for sustainable vegetation restoration policy making. Up to date, however, little particular research of ~~deep SMC~~ DSM variation has centered on such a moderate scale, and the variation mechanism of ~~deep SMC~~DSM at this kind of scale is still unclear.

In this study, we aimed to reveal the variation of ~~deep SMC~~DSM 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 (Yang et al., 2012c;Yang et al., 2014a;Jia et al., 2013;Jia and Shao, 2014).~~ This study included shallow root system vegetation and deep root system vegetation, covering eight specific vegetation types. We first identified the deep soil layer whose soil moisture is not sensitive to regular rainfall and daily evapotranspiration in Ansai watershed. Then we explored the overall variation of DSM in this area and compared the DSM of this two root system vegetation types as well as identify variations in their profiles. At last, the influence of various environmental factors on DSM under different vegetation types is discussed. ~~We first explored the overall variation of SMC DSM in this area and then compared the deep SMCDSM of this two root system vegetation types as well as identify variations in their profiles. Furthermore, the influence of various environmental factors on deep SMCDSM under different vegetation types is~~

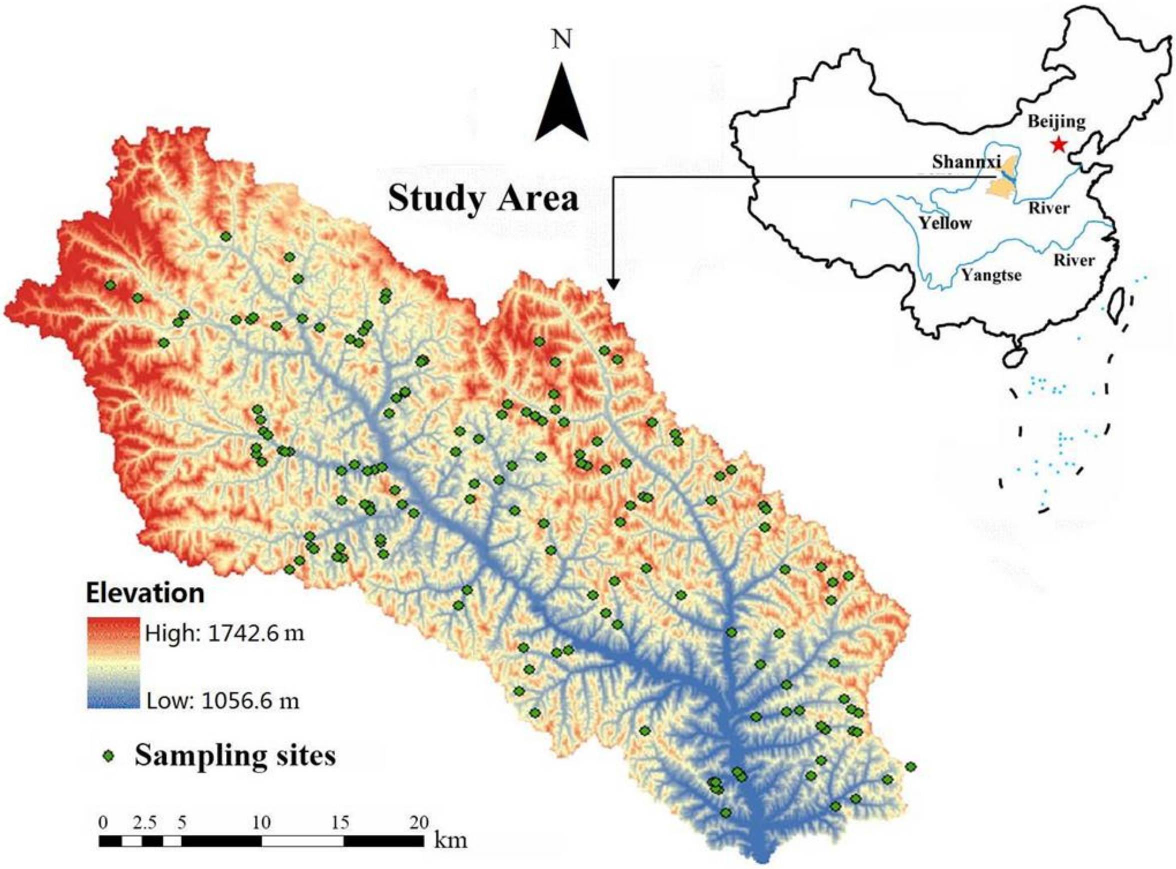
~~discussed.~~ The objectives of this study were to: (1) quantify the variation characteristics of ~~deep SMC~~DSM; (2) explore the mechanisms for controlling ~~deep SMC~~DSM variability among different vegetation types at the watershed scale; (3) develop recommendations for land use management and the 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~~ ranges from 375-546~~505~~ mm across the watershed (Fig. S1). Most rainfall occurs in the form of thunderstorms during the summer months from June to September. Soil types in this study area include mainly loess soil with low fertility and vulnerability to soil erosion (Zhao et al., 2012) Soil texture is different across the watershed with sand content ranging from 24%-57%,slit content ranging from 40%-65%, and clay content ranging from 6%-10% (Fig. S2).

~~he Ansai watershed is located on a warm forest steppe; the~~ The predominant land use types in Ansai watershed~~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 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.



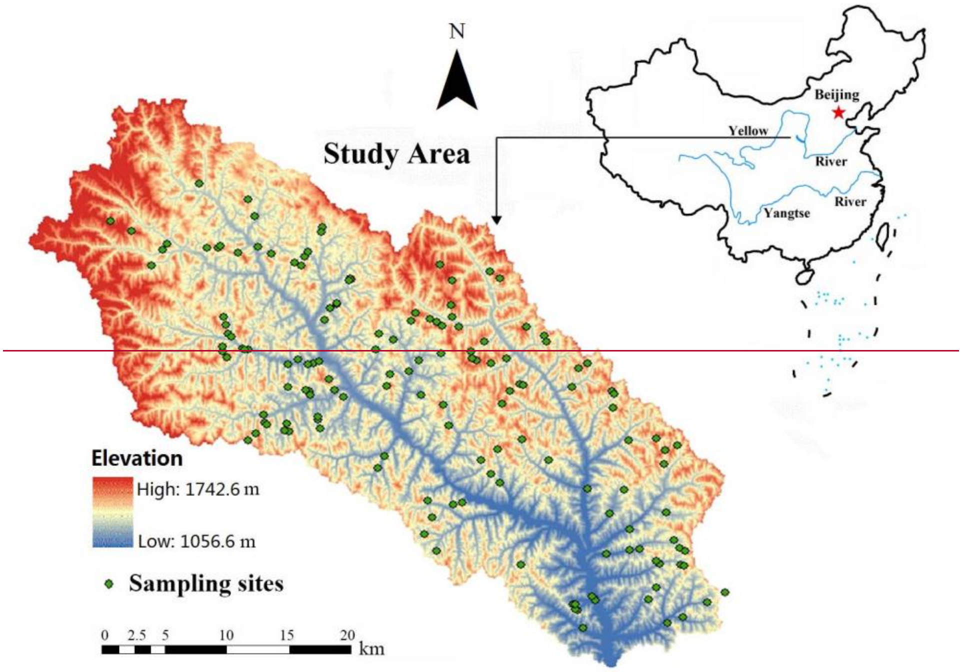


Figure 1. Location of the study area and sampling sites.

2.2 Sampling locations and description

In this study, two vegetation groups of different root system were selected (1) shallow root system vegetation: native grasses (NG), farmland (FL) with human agricultural measures; (2) deep root system vegetation: pasture grasses (PG), sea buckthorn (SB), *Caragana korshinskii* (CK), David peach (DP), black locust (BL) and apple orchard (AO) with human agricultural measures. The description of the root distribution of selected vegetation types are provided in Table 1.

~~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).~~

Table 1.The description of the root distribution of selected vegetation species.

Vegetation type	Root distribution traits	Source
NG	The roots of native grasses usually distribute in 0-50 cm depth ranges.	(Han et al., 2009)
PG	The fibrous roots of pasture grasses mainly distribute in 0-50cm depth ranges, while the taproot system can extend to 3m depth	(Wang et al., 2010d; Wei et al., 2006)
FL	the roots of farmland mainly distribute in 0-40 cm depth ranges	(Feng et al., 2007)
AO	The 90% roots of apple tree mainly distribute in 0-120cm depth ranges, and deep roots can reach to 160cm.	(Le et al.,2013; Hao et al., 1998)
CK	The fibrous roots of *Caragana korshinskii* mainly distribute in 0-100cm depth ranges, while the taproot system can extend to 6.4m depth.	(Wang et al., 2010d)
SB	The fibrous roots of sea buckthorn mainly distribute in 0-160cm soil depth, while and deep roots can reach to 200-300cm.	(Cong and Liang, 1990)
DP	The 90% roots of David peach mainly distribute within 100cm depth ,while deep roots can reach to 150cm	(Shi et al., 1989)
BL	The coarse roots mainly distributed within 260cm depth, while the fine roots can reach to 350 cm.	(Zhang and Xu, 2011)

To fully explore the influencing factors of deep soil moisture, we identified the following four types of factors: topography factors, surface 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~~organic matter (~~Or~~OM), ~~porosity~~capillary porosity (~~Po~~CP), soil bulk density (SBD), vegetation coverage (VC), grass biomass (GB), grass height (GH), planting density (PD), plant height (PH), diameter at breast height (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 2.

Table 2. Main characteristics and sampling numbers for different vegetation types.

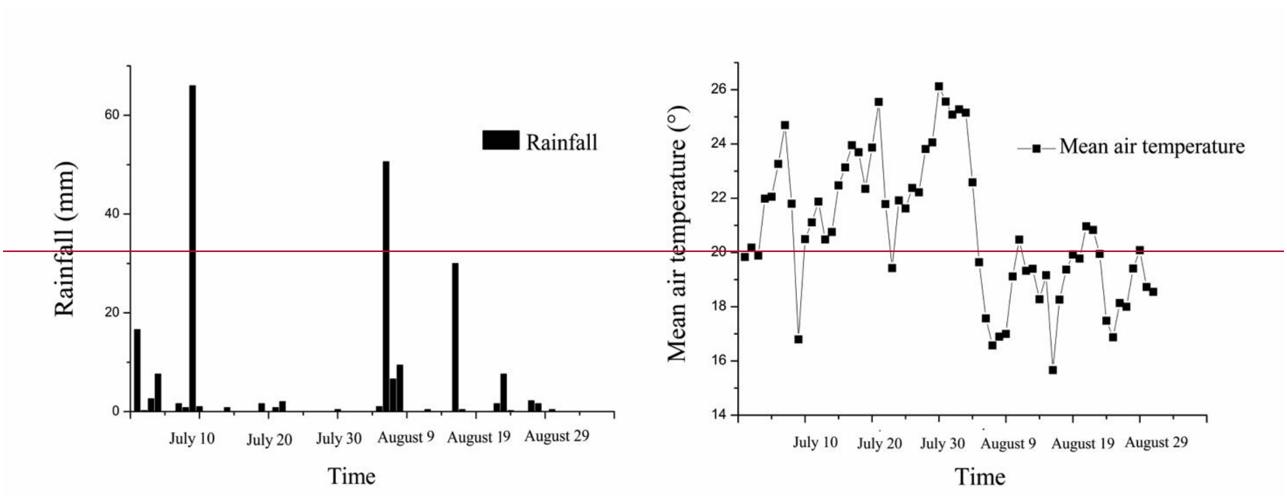
Vegetation conditions	Shallow root vegetation		Deep root vegetation					
	NG [a]	FL	AO	PG	CK	SB	DP	BL
Sampling number	25	22	10	11	18	15	12	38
Altitude (m)	1392.60	1380.1	1370.10	1401.00	1350.61	1435.67	1377.58	1326.54
Slope aspect (°)	170.67	200.6	173.5	195.43	161.75	195.77	128.09	156.36
Slope gradient (°)	16.72	6.3	19.9	13.10	17.56	16.40	24.17	27.24
Sand (%)	44.87	39.4	38.22	55.33	46.42	46.19	52.66	39.96
Silt (%)	47.08	52.6	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 matter (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
Capillary porosity~~Porosity~~ (%)	48	46	48	47	49	48	49	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

The soil samples at the depth of 0–500cm were taken by a soil drill (5 cm in diameter) with 20-cm increment within 28 days (from July 10 to August 6 in 2014).~~Each quadrat in the study area was covered by a single type of vegetation. Soil 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. Native grasses and *Caragana korshinskii* were selected as representatives of shallow root vegetation and deep root vegetation respectively. Soil moisture dynamic data (0-200cm) of this two vegetation types were monitored by EM50 (109°19′23″E, 36°51′26″N) from the same time period in 2015. ~~Meteorological data (Fig. 3) 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 Inverse Distance Weighted (IDW) interpolation method was performed by ArcGIS10.0 to obtain the average annual rainfall at each sampling site (Fig.S1).



~~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~~capillary porosity (Wang et al., 2008a). Bulk density was determined from the volume–mass relationship for each core sample and capillary was measured by “cylinder soak method”.~~Bulk density and porosity were determined from the volume mass relationship for each core sample~~. Soil samples 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):~~

~~$\mathrm{SMC}_d = \frac{1}{k}\sum_{i=1}^{k}\mathrm{SMC}_i$, (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):~~

~~$\mathrm{SMC}_s = \frac{1}{m}\sum_{j=1}^{m}\mathrm{SMC}_{ij}$ (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~~ DSM 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 variability of ~~soil moisture~~DSM 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~~DSM. Multiple comparisons were made using the least significant difference (LSD) method. To determine the contributing factors to ~~soil moisture~~DSM dynamics, spearman correlation analysis was first used to examine the relationships between ~~soil moisture~~DSM 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 Deep soil moisture identification

The soil moisture dynamic at 0-200cm during the sampling period are reported in Fig.2. As can be seen, the soil moisture in this two different root system vegetation fluctuates daily at 40 cm depth, while soil moisture at 80-200cm keeps constant with time going on. Thus, it can be concluded that the evapotranspiration during sampling period influences soil moisture no deeper than 80 cm in both shallow and deep root system vegetation. Combine Fig.2 and Fig.S3, the soil moisture in 40 cm does not change obviously with rainfall events which indicates the rainfall during monitoring time period influences soil moisture no deeper than 40cm.

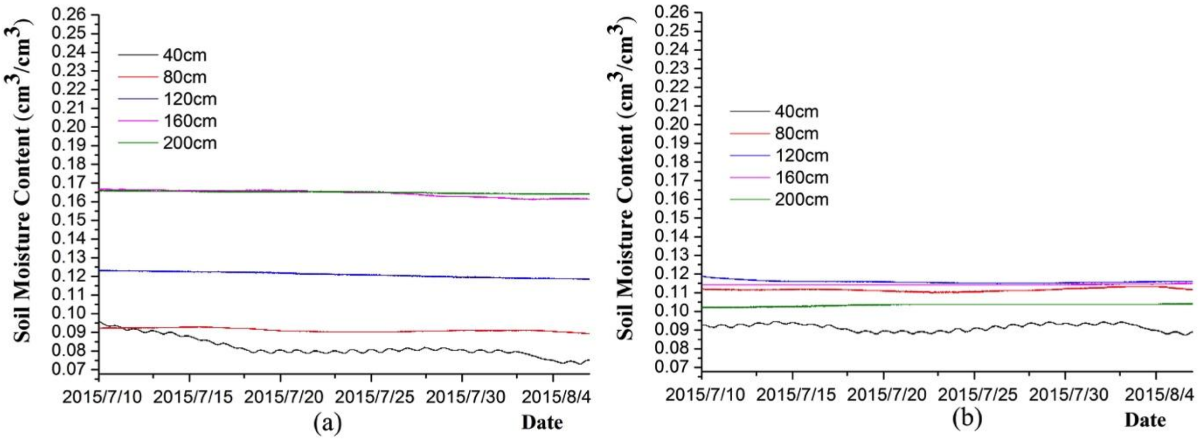


Figure 2. Soil moisture (0-200cm) dynamic monitoring during the sampling period. Note: (a) native grasses with shallow root system, (b) *Caragana korshinskii* with deep root system.

According to Fig.S3, the mean air temperature and rainfall of dynamic monitoring time period in 2015 is similar to that of sampling time period in 2014, thus, we consider rainfall and evapotranspiration during the sampling time period influence soil moisture no deeper than 80cm. And in this study, we consider soil moisture in 80-500cm as deep soil moisture.

3.2 Summary statistics of deep soil moisture

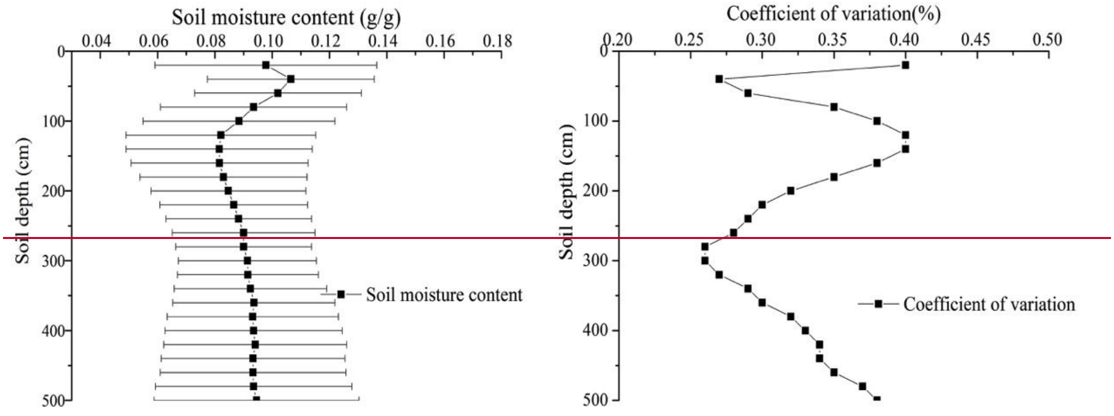
The summary statistics of ~~soil moisture~~DSM at various depths are given in Table 3. In general, the mean soil moisture, SD, and CV were highly dependent on depth. The profile distributions of mean ~~soil moisture conten~~DSM~~t~~, SD, and CV are given in Table 3 and Fig. ~~4~~3. The highest mean value (~~10.65~~9.45%) was observed at the ~~20~~400-~~40~~ 500cm depth, the lowest (8.15%) was at the 120-140 cm depth, and the mean ~~soil moisture~~DSM below 300 cm was almost constant. However, both SD and CV showed waving trends with increasing depth (Fig. ~~4~~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 3), which indicated that ~~soil moisture~~DSM at these depth ranges had relatively higher variability. Meanwhile, the lowest values occurred at ~~40-60 cm and~~ 260-300 cm, which indicated lower variability of ~~SMC~~ DSM at these depth ranges. Most of the Kurtosis (expect for 80-120 cm) and Skewness values are positive, and the highest values of both occurred at 200-240cm depth. The Kolmogorov–Smirnov test indicated that soil moisture data sets were normally distributed. Thus, statistical analysis could be performed without data transformation ~~(Shi et al., 2014)~~.

Table 3. Summary statistics of deep 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 0.05, Kolmogorov-Smirnov value is in parentheses).



(a) (b)

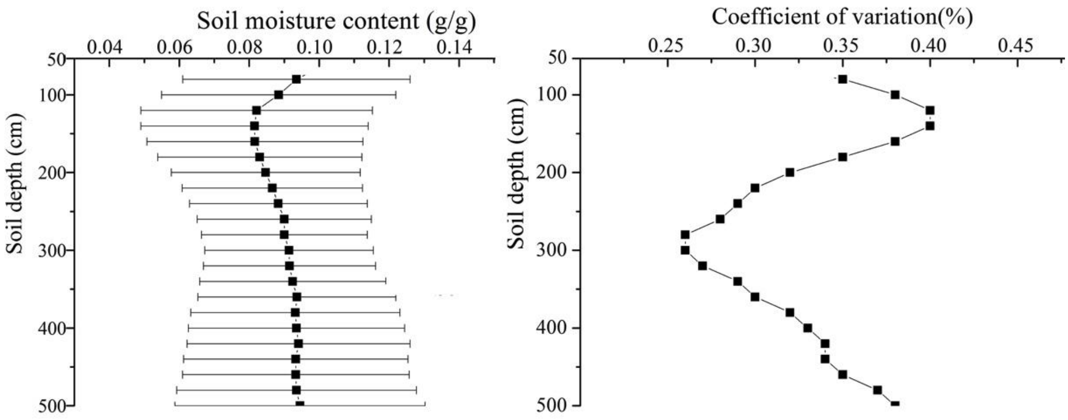
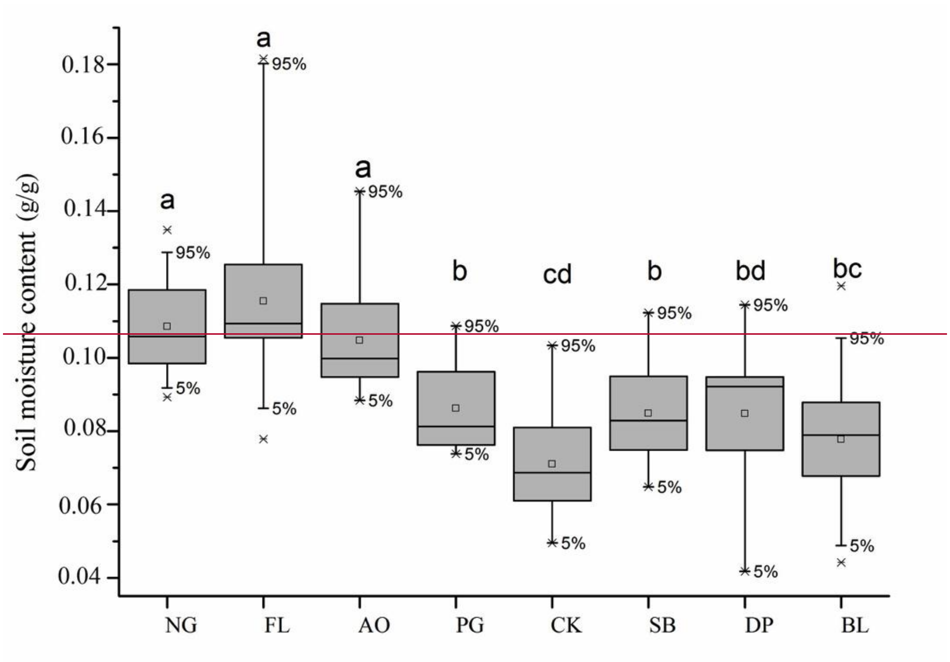


Figure ~~4~~3. The profile distribution of deep soil moisture content and coefficient of variation. Note: Error bar indicates standard deviation.

Moreover, different vegetation types greatly determined ~~deep soil moisture~~DSM variation; the ~~soil moisture~~ DSM statistics of various vegetation types under different vegetation types are reported in Fig.~~5~~4. The results showed that the depth-averaged ~~SMC~~ DSM of native grasses and human-managed vegetation (farmland and apple orchard) were significantly higher than that of introduced deep root vegetation. In general, the mean ~~soil moisture~~DSM of different vegetation covers was in the order: FL>NG>AO>DP>SB>PG>BL>CK. The highest ~~mean soil moisture~~DSM existed in farmland and the lowest in *Caragana korshinskii*. This result indicated that human agricultural management measures can significantly improve ~~soil moisture~~DSM conditions and that *Caragana korshinskii* was the most serious water consuming species among the selected introduced vegetation types.



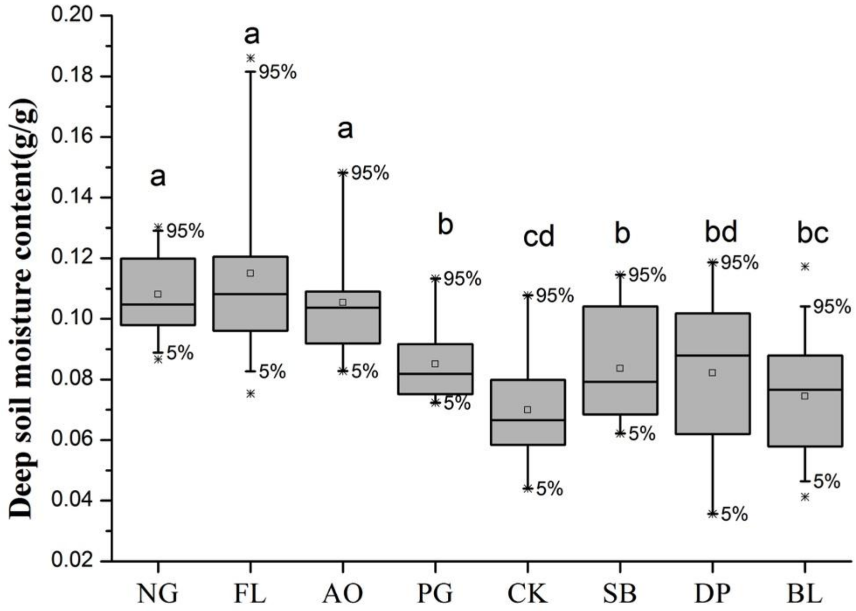


Figure ~~5~~4. Deep soil moisture statistics for different vegetation types. Means with the same letter above the box are not significantly different at the 0.05 significance level (LSD test); NG, FL, AO, PG, CK, SB, DP and BL refer to native grasses, farmland, apple orchard, pasture grasses, *Caragana korshinskii*, sea buckthorn, David peach and black locust, respectively.

3.3 Profile distribution of deep 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~~DSM varied by vegetation type (Fig. ~~6~~5).

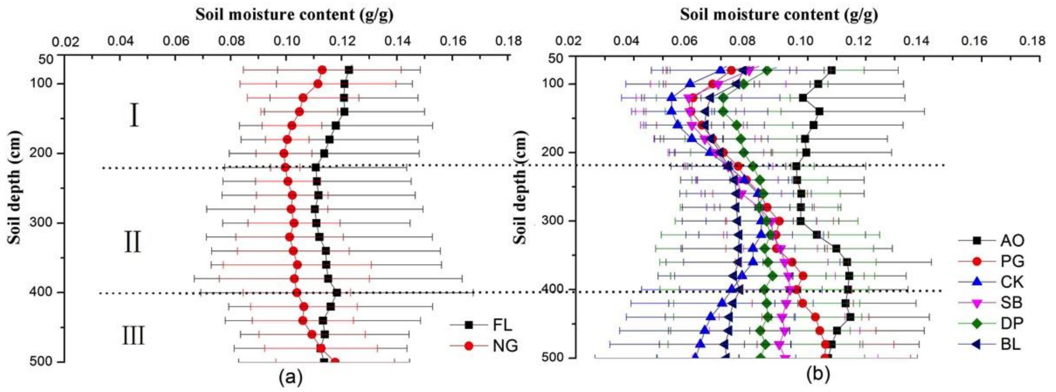
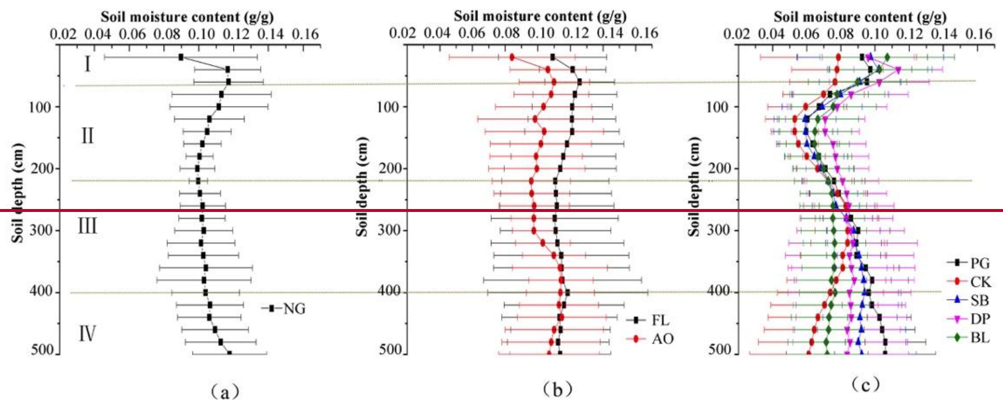


Figure ~~6~~5. Profile distribution of DSM for different vegetation types. Notes: (a) shallow root system vegetation (NG-native grass; FL-farmland), (b) deep root system vegetation (PG-pasture grasses; CK-*Caragana korshinskii*; SB-sea buckthorn; DP-David peach; BL-black locust; AO-apple orchard). Error bar indicates standard deviation. Ⅰ- Ⅲ: represent DSM at different soil layer depth ranges (Ⅰ: 80-220 cm, Ⅱ: 220-400 cm, and Ⅲ: 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., 2012c). Based on the inflection point of DSM and the trending change of SD, the 80-500cm soil moisture profile of native grasslands can be divided into 3 layers: (1) 80-220 cm, at this layer, both DSM and SD at 80-220cm 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. (2) 220-400 cm, DSM 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. (3) 400-500 cm, this is a relatively stable layer whose SD is constant as soil depth increases, despite increasing DSM with soil depth. At this layer, DSM is seldom influenced by rainfall infiltration. The profile distribution characteristics of farmland and apple orchards were similar to those of native grasslands, except for layer 300-500 cm. Perhaps this is because management measures increased the ranges of the rainfall infiltration layer. As for vegetation-introduced, DSM at 80-220cm depth of all vegetation types reached the lowest; at 220-500cm, the DSM of different introduced vegetation could be generally divided into three categories: (1) as soil depth increased, DSM increased (such as PG and SB); (2) as soil depth increased, DSM kept relative stable (such as DP and BL); (3) as soil depth increased, DSM increased first and then decreased (such as CK).

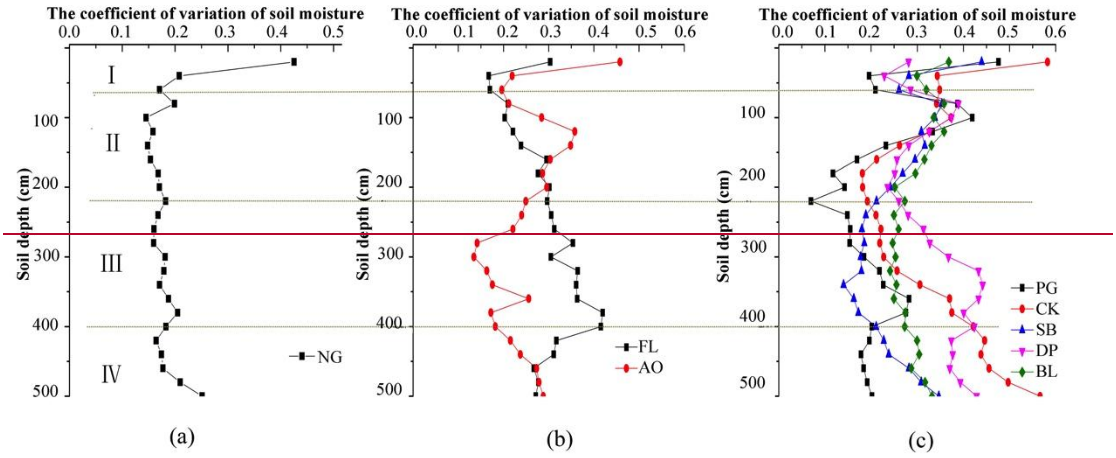
Based on the above analysis, we generally divided the DSM in this watershed into three layers: (Ⅰ) Rainfall transpiration layer (80-220cm). This layer is a main rainfall infiltration layer and can be greatly influenced by vegetation transpiration. (Ⅱ) Transition layer (220-400cm). This layer can be recharged by rainfall infiltration in rainy years, and can supply ordinary deep root vegetation with DSM in drought years (Ⅲ) Stable layer (400-500 cm). This is a relatively stable layer whose DSM is seldom influenced by rainfall infiltration in regular years, but can be influenced by extreme deep root vegetation such as CK and BL.



~~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., 2012c).Based on the inflection point of SMC and the trending change of SD in native grasslands, the 5 0-500cm soil moisture profile was can be divided into 4 layersfrom 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" (Hébrard et al., 2006;Cantón et al., 2004;Entin et al., 2000). (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., 2012c;Yang et al., 2012a;Yang et al., 2014a).~~

~~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.~~



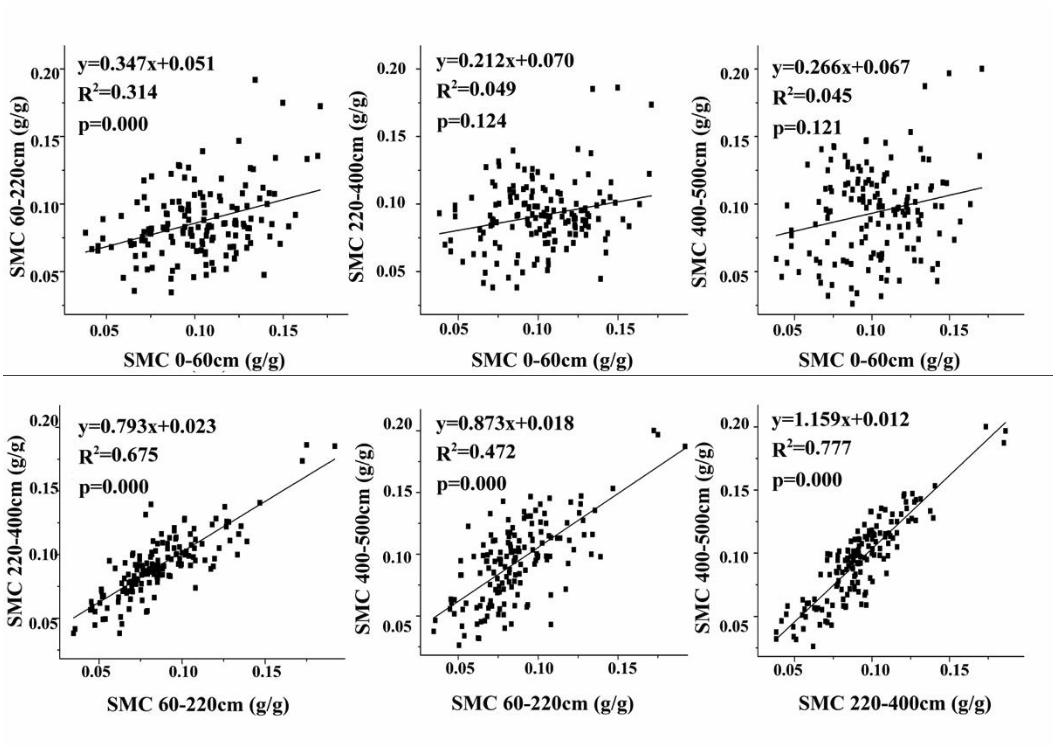
~~Figure 6. The coefficient of variation of soil moisture contents for different vegetation types. Notes: (a) native grassland (NG-native grass), (b) human-managed vegetation (FL-farmland, AO-apple orchard), (c) introduced vegetation (PG-pasture grass; CK-*Caragana korshinskii*; SB-sea buckthorn; DP-David 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).~~



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

3.4 Comparison of deep soil moisture content under different vegetation types

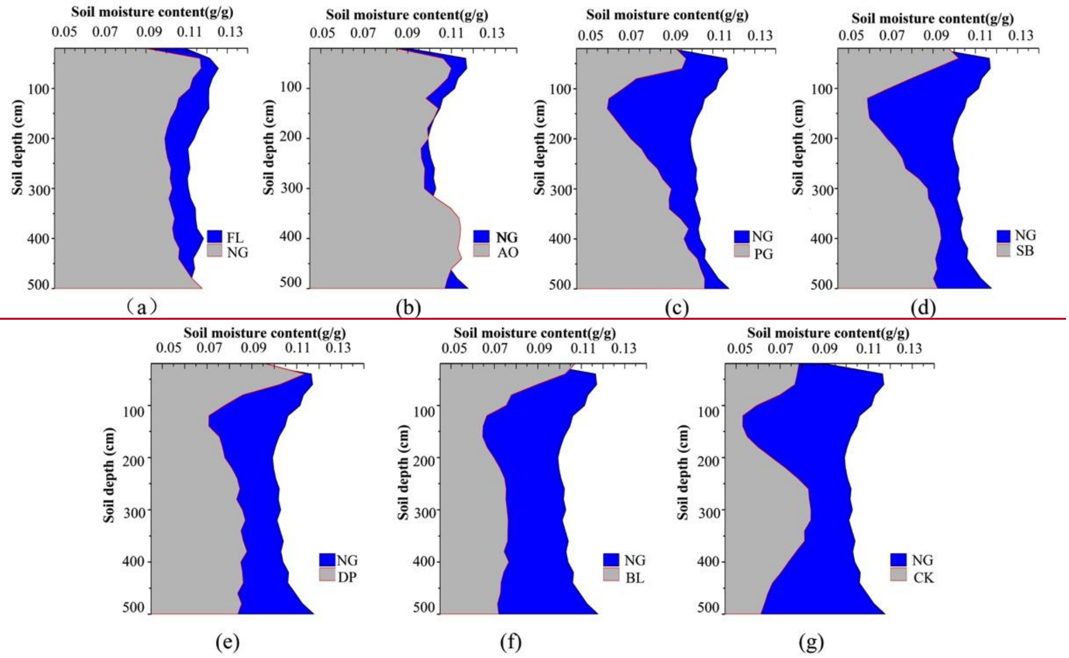
Generally, ~~soil moisture~~DSM at comparable soil depths was lower in introduced deep root vegetation (pasture grassland, shrub land and forestland) compared with native grassland and human-managed vegetation (farmland and orchard). Farmland (11.07-11.~~77~~79%) had the highest ~~SMC~~DSM, followed by native grasses (10.~~47~~52-11.19%). The LSD-test indicated that ~~soil moisture content~~DSM in native grasses and farmland was significantly higher than that in introduced vegetation (P<0.05, Table 4) at almost every soil depth. ~~Soil moisture~~DSM varied from ~~7~~6.~~56~~81% to 10.4% in pasture grassland, ~~7~~6.~~42~~85-9.75% in sea buckthorn, 6.~~49~~10-8.07% in *Caragana korshinskii*, 7.~~46~~19-7.66% in black locust, and ~~8~~7.~~10~~71-8.51% in David peach at layers of ~~60~~80-500 cm. The LSD-test indicated that there were significant differences in ~~soil moisture~~DSM 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 4).

Table 4. ~~Soil~~ Deep soil moisture of ~~0~~80-500 cm soil layers for different vegetation types.

Root types	Vegetation types	80-220 cm				220-400 cm				400-500 cm			
		Min %	Max %	Mean %	SD %	Min %	Max %	Mean %	SD %	Min %	Max %	Mean %	SD %
Shallow root vegetation	NG [a]	8.43	13.79	10.89a	1.46	8.35	12.84	10.52ab	1.62	8.17	14.72	11.19ab	2.03
	FL	7.25	17.90	11.79a	2.83	7.78	18.62	11.07a	3.20	7.53	20.01	11.77a	3.58
	AO	6.87	15.36	10.1ab	2.71	7.72	14.06	10.45abc	1.73	7.40	15.33	11.4ab	2.26
	PG	4.82	8.94	6.81c	1.33	7.69	13.14	8.97bcd	1.55	8.49	14.29	10.4abc	1.85
Deep root vegetation	SB	4.92	11.26	6.85c	1.79	7.11	12.09	8.93cd	1.62	5.12	14.67	9.75bc	2.64
	CK	4.24	8.76	6.10c	1.35	4.94	11.62	8.07d	2.11	2.63	12.50	6.49e	2.92
	BL	3.78	12.79	7.19c	2.11	4.16	10.94	7.66d	1.77	4.00	13.29	7.47de	2.47
	DP	3.16	10.68	7.71bc	2.14	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. ~~7~~6, the ~~SMC~~ DSM 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~~DSM in layer I ~~II~~ (~~60~~80-220 cm) was heavily consumed in almost all the introduced vegetation types. PG and SB consumed less ~~soil moisture~~DSM in layers II-III~~-IV~~ (220-500 cm) compared with the three other introduced vegetation types, while the ~~soil moisture~~DSM in layers II-III~~III-IV~~ (220-500 cm) of DP and BL consumed more consistently. Double layer soil desiccation occurred in CK, indicating that the ~~soil moisture~~DSM in layers I~~II~~ and III~~IV~~ of CK was heavily consumed, while the ~~soil moisture~~DSM in layer II~~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~~80-500 cm; even in the 320-450 cm layer, the ~~soil moisture~~DSM in the apple orchard was higher than in native grasses.



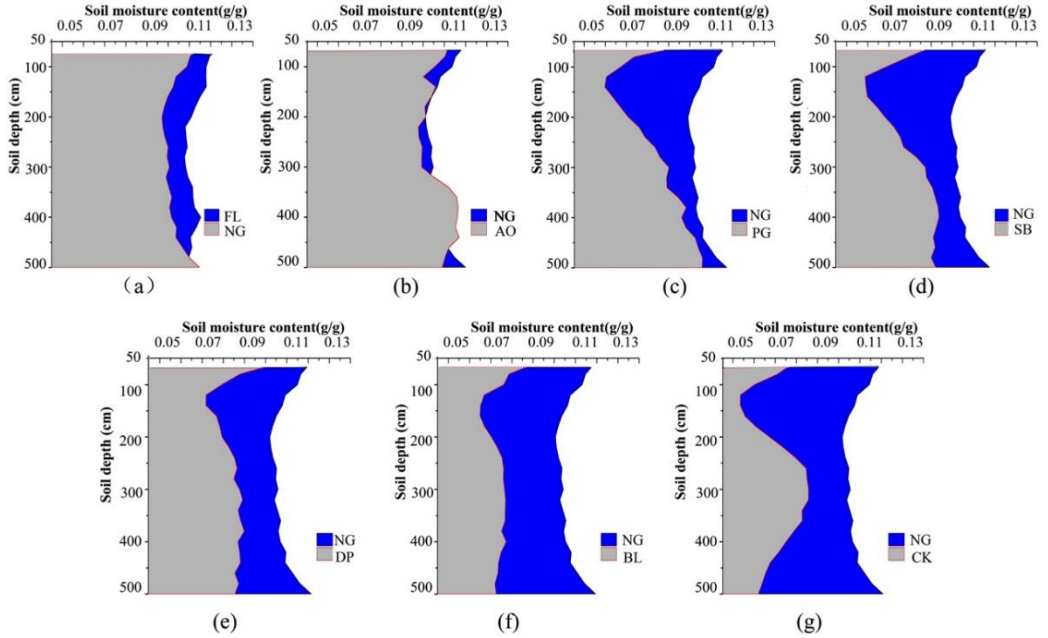


Figure ~~7~~6. The comparison of ~~soil moisture contents~~deep soil moisture between human-managed vegetation, introduced vegetation and native grasslands. Notes: (a) farmland (FL) and native grasslands (NG), (b) apple orchard (AO) and native grasslands (NG), (c) pasture grasslands (PG) and native grasslands (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~~deep soil moisture and selected environmental variables

Although the data of DSM were normally distributed; significant correlations exist in soil moisture content at different soil depth ranges. Thus, non-parametric correlation test (Spearman) ~~Spearman correlation coefficients~~were used to determine the strength of possible relationships between ~~soil moisture~~DSM and selected variables. The correlation analysis results are presented in Table 5, Table 6, and Table 7. The correlation between ~~soil moisture~~DSM 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~~ DSM ~~in the deep layer~~ showed significant correlations with altitude (~~60~~80-500 cm), slope gradient (220-500 cm), soil particle composition (~~60~~80-500 cm), and average annual rainfall (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~~DSM (~~60~~80-220 cm) ~~were~~was 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~~ DSM showed different correlations with vegetation growth traits. For instance, the ~~SMC~~ DSM of BL showed significant negative correlations with plant height (at ~~60~~80-220 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~~ DSM of SB showed a significant negative correlation with plant density (at ~~60~~80-500 cm depth). A significant correlation was found between aspect and ~~SMC~~ DSM in some introduced vegetation in PG (at 400-500 cm depth) and BL (at ~~60~~80-400 cm depth). Moreover, positive correlations existed between ~~deep SMC~~DSM and soil surface conditions; for instance, ~~SMC~~ DSM of DP showed significant correlations with grass biomass (at 400-500 cm depth), ~~SMC~~ DSM 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~~bulk density (at ~~60~~80-400 cm depth) and ~~porosity~~Capillary porosity (at ~~60~~80-220 cm depth) showed significant correlations with ~~SMC~~DSM.

Table 5. Spearman correlation coefficients between deep soil moisture (grassland, farmland and pasture grassland) and selected environmental variables.

	Native grasses			Farmland			Pasture grassland		
	80-220cm	220-400cm	400-500cm	80-220cm	220-400cm	400-500cm	80-220cm	220-400cm	400-500cm
Altitude	**-0.52**	**-0.56**	**-0.53**	-0.27	-0.30	-0.19	-0.14	-0.06	0.08
Slope position	0.13	-0.11	-0.07	0.25	0.28	0.41	-0.15	-0.32	0.02
Cos(Aspect)	-0.32	-0.35	-0.44	0.16	0.03	0.21	0.07	0.64	**0.86**
Tan(Slope)	0.46	**0.67**	**0.59**	-0.22	-0.07	0.21	-0.32	0.09	0.34
Clay	**0.62**	**0.56**	**0.43**	0.35	0.37	0.22	0.23	0.54	0.46
Slit	**0.59**	0.37	0.27	0.26	0.38	0.38	0.15	**0.66**	0.59
Sand	**-0.68**	**-0.42**	-0.32	-0.23	-0.35	-0.35	-0.16	-0.58	-0.47
Organic matter	-0.14	-0.30	-0.19	0.18	-0.13	-0.23	-0.07	-0.28	**-0.64**
Soil bulk density	-0.16	-0.07	-0.04	**0.55**	0.31	0.34	0.12	-0.01	-0.16
Capillary porosity	0.09	0.06	0.05	-0.34	-0.26	-0.20	-0.33	-0.26	-0.12
Annual average rainfall	-0.03	**0.46**	0.37	-0.15	-0.11	-0.23	-0.39	0.15	0.36
Vegetation coverage	-0.21	-0.08	-0.02	0.18	0.11	0.26	-0.30	0.37	0.11
Grass biomass	-0.11	0.20	0.08	-0.06	-0.06	-0.06	-0.02	0.28	-0.10
Grass height	0.30	0.01	0.00	0.04	0.06	0.15	-0.15	0.46	0.32

	~~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~~
~~OrganicOrganic matter~~	~~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~~
~~PorosityCapillary 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: Significant correlations (P<0.05) are shown in bold, and significant correlations (P<0.01) are shown in bold with underline.

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

	Caragana korshinskii Kom			Sea buckthorn		
	80-220cm	220-400cm	400-500cm	80-220cm	220-400cm	400-500cm
Altitude	-0.31	**-0.70**	**-0.59**	**-0.64**	**-0.56**	-0.33
Slope position	0.29	-0.08	-0.11	-0.22	-0.25	-0.35
Cos (Aspect)	0.32	0.34	0.32	0.23	0.34	0.07
Tan (Slope)	0.15	-0.10	-0.05	-0.45	-0.19	0.00
Clay	0.11	-0.24	-0.09	0.27	0.22	-0.02
Silt	0.16	0.32	**0.53**	**0.58**	**0.51**	0.41
Sand	-0.17	-0.23	-0.45	**-0.59**	-0.48	-0.37
Organic matter	0.08	**0.47**	**0.49**	0.25	0.28	-0.20
Soil bulk density	0.17	-0.23	-0.24	0.16	-0.28	-0.18
Capillary porosity	-0.02	0.13	0.14	-0.17	0.20	0.02
Annual average rainfall	**0.59**	0.23	0.19	0.17	0.22	0.18
Litter biomass	-0.14	-0.04	0.10	-0.29	-0.33	-0.39
Litter max water holding	0.32	**0.59**	**0.60**	-0.15	0.09	0.08
Vegetation coverage	-0.08	0.06	-0.03	-0.05	-0.14	-0.16
Grass biomass	0.27	0.42	0.45	0.35	0.26	0.31
Grass height	0.25	0.35	0.43	0.15	0.06	0.18
Plant height	0.26	0.24	0.23	-0.13	0.25	0.09
Crown width	0.27	0.24	0.30	-0.23	0.12	0.07
Basal diameter	-0.22	0.31	0.40	-0.25	0.06	-0.01
Plant density	-0.31	0.08	-0.09	**-0.66**	**-0.57**	**-0.56**

	~~*Caragana korshinskii Kom*~~				~~Sea buckthorn~~			
	~~I~~	~~II~~	~~III~~	~~IV~~	~~I~~	~~II~~	~~III~~	~~IV~~
~~Altitude~~	~~0.06~~	~~-0.34~~	~~**-0.70**~~	~~**-0.59**~~	~~-0.15~~	~~**-0.68**~~	~~**-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~~

~~OrganicOrganic matter~~	~~-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~~
~~PorosityCapillary 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**~~	~~**0.60**~~	~~-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~~	~~**-0.69**~~	~~**-0.57**~~	~~**-0.56**~~

Notes: Significant correlations (P<0.05) are shown in bold, and significant correlations (P<0.01) are shown in bold with underline.

Table 7. Spearman correlation coefficients between deep soil moisture (orchard land and forest) and selected environmental variables.

	Apple orchard			Black locust			David peach		
	80-220cm	220-400cm	400-500cm	80-220cm	220-400cm	400-500cm	80-220cm	220-400cm	400-500cm
Altitude	-0.58	-0.25	-0.16	-0.09	-0.07	0.20	-0.16	0.05	0.06
Slope position	0.13	0.34	0.14	-0.21	-0.22	-0.21	-0.32	-0.50	-0.55
Cos (Aspect)	0.04	-0.01	0.35	**0.44**	**0.34**	0.22	0.06	0.13	0.30
Tan (Slope)	-0.25	0.26	0.33	-0.17	-0.17	**-0.41**	-0.16	0.19	0.07
Clay	**0.88**	0.42	-0.25	0.20	0.13	-0.09	0.33	0.15	0.06
Silt	**0.85**	**0.67**	0.08	0.23	0.14	-0.15	0.42	0.42	0.27
Sand	**-0.83**	**-0.67**	-0.08	-0.25	-0.14	0.13	-0.46	-0.42	-0.27
Organic matter	**0.69**	0.38	0.13	0.01	0.02	-0.22	-0.13	-0.12	-0.35
Soil bulk density	**-0.64**	**-0.82**	-0.32	-0.23	-0.08	-0.06	-0.27	-0.43	-0.41
Capillary porosity	**0.89**	0.49	-0.06	0.21	0.14	0.00	0.35	0.52	0.30
Annual average rainfall	0.31	-0.07	-0.38	-0.12	0.26	-0.12	0.16	-0.11	-0.42
Litter biomass	0.24	0.47	**0.72**	-0.08	0.13	-0.03	0. 11	0.08	0.08
Litter max water holding	0.31	0.08	0.33	0.22	0.21	0.20	**0.35**	0.13	0.27
Vegetation coverage	-0.51	0.10	-0.01	-0.14	0.11	-0.03	-0.35	-0.47	-0.41
Grass biomass	-0.23	0.03	0.39	0.11	0.07	0.30	0.44	**0.80**	0.55
Grass height	-0.13	-0.17	-0.62	-0.05	0.02	0.08	-0.42	-0.01	-0.01
Plant height	0.23	-0.09	-0.49	**-0.42**	0.11	0.05	-0.32	-0.11	-0.01
Diameter at breast height	0.64	0.31	0.04	-0.23	-0.03	**-0.34**	-0.33	-0.24	-0.15
Crown width	0.43	0.29	0.15	-0.25	0.07	-0.07	**-0.56**	-0.36	-0.29
Basal diameter	0.51	0.22	0.07	-0.27	0.03	-0.25	**-0.43**	-0.20	-0.07
Plant density	-0.52	-0.20	-0.15	0.09	0.03	0.18	0.04	0.05	-0.08

	~~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~~
~~OrganicOrganic matter~~	~~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~~
~~PorosityCapillary 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: 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~~ DSM were retained for further analysis. There were 9 environmental variables for grassland and farmland (Group 1), ~~9~~ 7 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 8. 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 (Shi et al., 2014;Mandal et al., 2008). 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 7~~4.54~~5% 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~~DSM 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~~bulk 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 organic matters ~~one variable from each~~ had a high factor loading~~: litter max water holding and organicorganic matter, 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~~Capillary 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~~bulk 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.

Table 8. 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~~					

	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 #1	PC #2	PC #3	PC #4	PC #5
Eigenvalue	3.58	1.45	1.13	1.05	2.20	1.88	1.01	4.51	2.62	1.80	1.17	1.08
% of variance	39.75	16.07	12.50	11.71	31.47	26.91	14.48	30.09	17.49	11.97	7.78	7.23
Cumulative %	39.75	55.82	68.32	80.04	31.47	58.38	72.85	30.09	47.57	59.54	67.32	74.54
Factor loading/eigenvector												
Annual average rainfall	0.21	-0.50	**0.71**	0.06	-0.39	-0.59	-0.39					
Altitude	-0.46	0.23	0.53	0.51	0.24	**0.83**	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				0.64	-0.44	**-0.50**	-0.03	-0.04
Silt	**0.93**	0.27	0.05	0.09	**-0.94**	0.16	0.27	0.68	-0.44	**-0.45**	0.28	0.08
Sand	**-0.94**	-0.27	-0.02	-0.11	**0.95**	-0.16	-0.24	**-0.77**	0.39	0.37	-0.23	-0.17
Organic matter	-0.48	-0.03	-0.50	0.49	0.15	-0.53	**0.70**	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
Capillary 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					0.42	-0.27	0.45	-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								**0.75**	0.37	0.26	0.18	0.07
Plant density					0.10	**0.77**	0.22					

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.

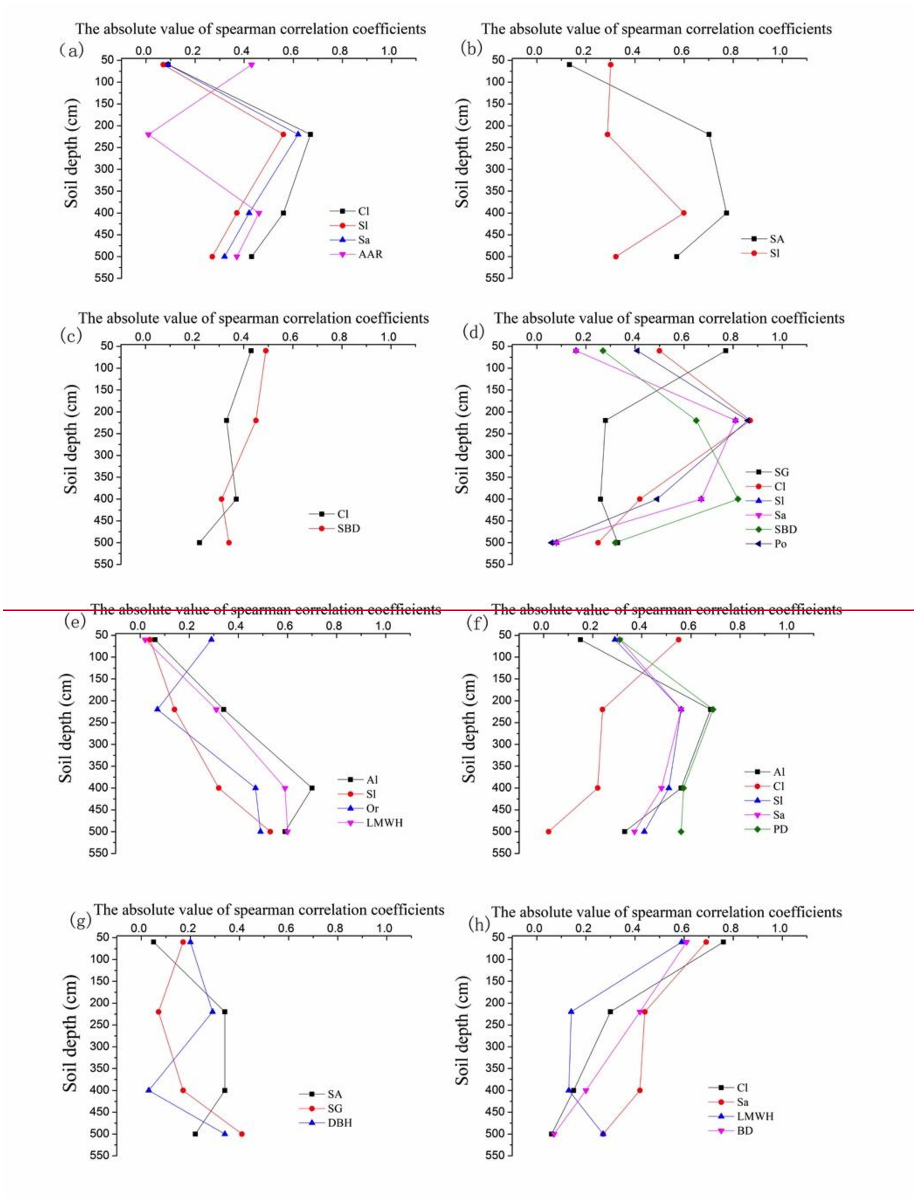
In total, 6 out of 9 environmental variables for grassland and farmland (group 1),

~~7~~ 5 out ~~9~~ 7 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 9). It can be concluded that, at the watershed scale, the main influencing factors of ~~SMC~~ DSM 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~~bulk density. For introduced vegetation types, the main influencing factors were more complex; apart from soil texture and physical characteristics, topographical factors and vegetation traits also strongly affected ~~SMC~~ DSM 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~~80-220 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 9. 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~~CP
Pasture grasses	SA, Sl
Sea buckthorn	Al, Sl, Sa, ~~Cl,~~ PD
Caragana korshinskii	Al, Sl, ~~Or~~OM~~, LMWH~~
Black locust	SA, SG, DBH
David peach	Cl, Sa, BD, LMWH

Note: [a] Cl, SA, SG, Sl, Sa, ~~Or~~OM, ~~Po~~CP, SBD, DBH, BD, LMWH refer to clay, slope aspect, slope gradient, silt, sand, ~~organic~~organic matter, ~~porosity~~capillary 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 Variation characteristics of deep soil moisture at the watershed scale

The variation of ~~deep soil moisture~~DSM at the watershed scale varied with soil depth (Fig. ~~4~~ 3 and Fig. ~~6~~5). ~~The shallow layer (0-60 80 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~~80-220 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~~ DSM storage layer (Fig. ~~6~~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~~ DSM distribution rules, resulting in more complex variation (Fig. ~~4~~3). The highest variation of ~~SMC~~ DSM 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 (Hébrard et al., 2006;Cantón et al., 2004;Entin et al., 2000).~~ However, the ~~SMC~~ DSM was the lowest in the 120-140 cm layer, with high variation. This result is inconsistent with previous studies, which reported that high variations usually appear in higher ~~SMC~~ DSM and decrease when ~~SMC~~ DSM 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. ~~7~~6), 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 (Wang et al., 2009;Chen et al., 2008b).

~~Soil moisture content~~DSM 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~~DSM 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~~DSM 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 variation of ~~SMC~~DSM. In farmland, the ~~SMC~~ DSM and its variation were higher than that in native grassland, indicating that human agricultural measures can greatly increase ~~SMC~~ DSM and its variation. For introduced vegetation, the ~~SMC~~ DSM 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. ~~7~~6). This result is different from that of a previous study (Yang et al., 2012c), 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. ~~5.~~4); this partly disagrees with most previous studies (Yang et al., 2012c;Wang et al., 2009;Wang et al., 2010c;Wang et al., 2011b), which reported that forest consumes more ~~soil moisture~~ DSM 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~~80-220 cm and 400-500 cm (Table 4, Fig. ~~7.~~6); this contributed to the higher ~~-~~variation of ~~SMC~~ DSM at these two layers (Fig. ~~4~~3).

4.2 Mechanisms of deep soil moisture variability

The variation of ~~deep SMC~~DSM 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~~DSM variation. The effect of vegetation on ~~soil moisture~~DSM is shown in many aspects. First, due to the existence of a root system, ~~soil moisture~~DSM 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~~DSM consumption traits for various vegetation types (Fig. ~~7~~6). ~~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 (Yang et al., 2014b;Wang et al., 2010c). Thus, i~~Introduced vegetation with a deep root system consumes more and deeper ~~soil moisture~~DSM than farmland and native grasses (Table 4). Individual vegetation growth conditions and planting density can also influence ~~deep SMC~~DSM variation. For example, ~~deep soil moisture~~DSM in BL showed negative correlations with plant height and diameter at breast height, while SB showed negative correlations with plant density (Table 6 and Table 7). This phenomenon indicates that, in the deeper root system, forest individual growth conditions mainly explain ~~SMC~~ DSM consumption, while planting density mainly accounts for ~~SMC~~ DSM consumption in the less deep root system of shrubs. In addition to ~~SMC~~ DSM consumption, the canopy interception system and surface coverage system can also have positive influences on ~~soil moisture~~DSM (Martínez-Fernández and Ceballos, 2003;Starks et al., 2006). In this study, litter biomass, water holding capacity, and forest grasses all showed different degrees of significant positive correlations with ~~deep soil moisture~~DSM for different vegetation types (Table 5, Table 6, and Table 7). This is probably because thick litter, humus layer and forest grasses can reduce surface runoff which may help retain more rainfall for infiltrating into deep soil layers; besides, they can also reduce soil evaporation which may decrease DSM consumption (Vivoni et al., 2008).

Climate factors that affect ~~soil moisture~~DSM are mainly determined by differences in rainfall infiltration and solar radiation (Savva et al., 2013). According to previous studies, ~~deep soil moisture~~DSM is relatively stable compared with the shallow layer, especially at depths below 200 cm. For example, Chen et al. (2008b) 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, the ~~SMC~~ DSM ~~in the deep soil layer~~ (~~60~~80-220 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~~DSM 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~~DSM (Zhu et al., 2014b;Qiu et al., 2001). 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 (Zhu et al., 2014a;He et al., 2003), while slope gradient usually shows a negative correlation with soil moisture content , indicating that a steep slope usually has a lower soil moisture content 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., 2012b), resulting in different rates of soil moisture evaporation. Thus, soil moisture content 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~~DSM; slope gradient showed significant positive correlations with ~~SMC~~ DSM 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~~ DSM variation; this was also verified by Yang et al. (2012b), who found that introduced vegetation can lead to homogeneity of the ~~deep SMC~~DSM. This was true for slope aspect, which only showed positive correlations with ~~SMC~~ DSM in pasture grasses (400-500 cm) and black locust (~~60~~80-400 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~~capillary 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 loess Plateau, the DSM is mainly determined by land surface rainfall infiltration and evapotranspiration. Surface soil properties are usually more important in influencing surface rainfall infiltration and evaporation than deep soil properties, thus in this study we mainly analyzed surface soil properties influence on DSM. The result indicated soil particle composition was an important influencing factor of ~~deep SMC~~DSM variation at the watershed scale. Both clay and silt content showed significant positive correlations with ~~soil moisture~~DSM, and sand content showed negative correlations with ~~deep SMC~~DSM for most vegetation types. However, soil bulk density and ~~porosity~~capillary porosity only showed significant correlations with ~~deep SMC~~DSM in farmland (~~0~~80-220 cm) and apple orchard (~~60~~80-400 cm). This result reflects that human agricultural management measures, or other factors that result in lower soil ~~buck density~~bulk density and higher ~~porosity~~capillary porosity conditions, can significantly improve infiltration capacity, thus increasing ~~deep soil moisture content~~DSM.

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., 2015). 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. ~~7~~6). 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.~~5 –~~ 4 and Fig. ~~7~~6); 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 good soil moisture conditions with suitable planting density and human management measures.

Furthermore, proper planting location should also be considered based on ~~deep SMC~~DSM conditions. Annual average rainfall spatial variations can significantly influence ~~deep SMC~~ DSM conditions (Table 5 and Table 6). 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~~DSM is not evenly distributed: lower altitudes (such as a gully bottom or lower slope) usually had higher ~~deep SMC~~DSM (Table 5 and Table 6), while the ~~deep SMC~~DSM of native grasslands at steeper slopes was higher than that at gentle slopes (Table 5). Thus, shrubs or trees with high water consumption capacity can be arranged at these locations. At higher altitudes or upper slopes, where ~~deep SMC~~DSM 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~~DSM conditions. The ~~SMC~~ DSM of farmland was highest among the selected vegetation types (Fig. ~~5~~4); even though introduced vegetation has deep root systems, no soil desiccation was found in apple orchards (Fig. ~~7~~6). 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~~ DSM in these vegetation zones. Moreover, in this study, forest grasses, litter biomass, and litter max water holding showed significant correlations with ~~SMC~~DSM (Table 6 and Table 7). 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~~DSM recharge. Likewise, considering that plant density has significant negative correlations with ~~SMC~~DSM, vegetation control (when artificial forest and shrub are mature, the density should be reduced according to deep soil water conditions) may be an effective measure for helping reduce soil desiccation.

5 Conclusions

Based on the analysis of mean, SD, and CV of ~~deep SMC~~DSM at the watershed scale, the results indicate that the ~~spatial~~ variation of ~~deep SMC~~DSM varies with soil depth and vegetation types. In the vertical direction, the higher ~~spatial~~ variation of ~~soil moisture~~DSM occurred at ~~three~~ two 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~~ DSM profile distribution and its variation characteristics, the ~~SMC~~ DSM profile of local control natural grassland can be divided into ~~four~~ three layers: (Ⅰ) Rainfall transpiration layer (80-220cm). (Ⅱ) Transition layer (220-400cm). (Ⅲ) Stable layer (400-500 cm). ~~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~~DSM. 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, ~~t~~rainfall transpiration layer Ⅰ ~~he main rainfall infiltration layer Ⅱ~~ had the most serious desiccation layer. The high ~~SMC~~ DSM in farmland and apple orchard indicates that human management measures can greatly improve ~~deep soil moisture~~DSM, 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~~DSM in this area is actually the combined result of climate, vegetation, topography, soil, and human management measures. The ~~SMC~~ DSM in native grassland, which can reflect local ~~native soil moisture~~DSM 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~~ DSM. In farmland and orchards, human management measures greatly increased the influence of soil traits on ~~deep SMC~~DSM, which increased rainfall infiltration and improved ~~deep SMC~~DSM. 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~~ DSM 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~~ DSM 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.

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