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Vertical variations of soil moisture in response to vegetation restoration on the Loess Plateau of China

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Abstract

Soil moisture is essential for vegetation restoration in arid and semi-arid regions. Ascertaining the vertical distribution and transportation of soil moisture under different vegetation restoration types has a profound impact on the ecological construction. In this study, the soil moisture at a depth of 500 cm for four typical vegetation types, including *R. pseudoacacia* (forestland), *C. korshinskii* (shrubland), *S. bungeana* (abandoned land), and corn (cropland) were investigated and compared in the Zhifanggou watershed of Loess plateau, China. Additionally, hydrogen and oxygen stable isotopes were detected to identify and reflect the characteristics of soil water. The results showed vertical distribution and transportation of soil moisture have different variations under different vegetation types. Depth-averaged soil moisture under *S. bungeana* and corn increased along the profile as a whole, while *C. korshinskii* and *R. pseudoacacia* showing a trend of weakly increasing and relatively stable state after an obvious decreasing trend (0–40 cm). The mean soil moisture under *R. pseudoacacia* is lower than other types, especially in deeper layers. In addition, it was observed that the longer vegetation age, the lower mean soil moisture, while this phenomenon was unobvious in *S. bungeana*. Planting arbor species such as *R. pseudoacacia* intensified the decline of soil moisture in the Loess Plateau, this limited the growth of arbor species in turn. The capacity of evaporation fractionation of soil moisture followed the sequence: corn > *S. bungeana* > *R. pseudoacacia* > *C. korshinskii*. Profiles of δ^{18}O values of soil moisture under different vegetation types are quite different. On the whole, the δ^{18}O values varied greatly in upper soil layers and tend to be consistent with the increase of soil depth. We estimate that piston flow is the main mode of precipitation infiltration, and the occurrence of preferential flow is related to vegetation types. These results are expected to help improve the understanding of the response of deep soil moisture to vegetation restoration and inform practices for sustainable water management.

Keywords: soil moisture, vegetation restoration, hydrogen and oxygen isotopes, Loess Plateau

1. INTRODUCTION

The Loess Plateau is considered the most severely eroded area in the world, where severe water loss and soil erosion have intensified the fragility of ecology system (*Shi & Shao, 2000; Wang et al., 2015; Yang et al., 2015*). To mitigate the soil erosion and improve the ecological environment, trees and shrubs have been planted on the slope lands since the 1950s (*Jia, Shao, Zhu, & Luo, 2017*). A series of large-scale artificial afforestation campaigns were carried out by the Chinese government at the end of the 1990s to reconvert croplands to forests, shrubs and grass (*Cao, Chen, & Yu, 2009*). Afforestation has increased the vegetation coverage on the Loess Plateau by 28% from 1999 to 2013 (*Chen et al., 2015*). *Wang et al. (2015)* observed that 26% decline in water discharge and 21% decline in sediment concentration which attributed to the massive afforestation in the region. However, the soil desiccation appeared to different degrees after the extensive afforestation implemented in the Loess Plateau region (*Huang & Gallichand, 2006; Jia et al., 2017; Wang, Shao, & Shao, 2010*). On the other hand, the efficiency of vegetation restoration was not as satisfactory as expected due to the water shortage (*Chen, Huang, Gong, Fu, & Huang, 2007*). Hence, the establishment of the balance between soil moisture supply and plant water consumption is essential to the health and sustainability of an ecosystem (*Issa et al., 2011*), especially in the Loess Plateau.

Soil moisture can be affected by various factors, including climate (e.g., precipitation, temperature, etc.), topography (e.g., elevation, slope, aspect, etc.), soil properties (e.g., soil texture, porosity, aggregation, bulk density, etc.), land use, vegetation types and ages (*Gwak & Kim, 2017; Zheng, Gao, Teng, Feng, & Tian, 2015*). In small scale (watershed, slope), topography and land use are the main factors affecting soil water heterogeneity (*Wendroth et al., 1999; Western & Blschl, 1999;*

Yao et al., 2012). Under similar climatic, topographical and soil conditions, the vegetation types and age play a leading role in soil moisture (*Chen, Huang, et al., 2007; Chen, Wei, Fu, & Lu, 2007*). In arid and semi-arid regions, soil moisture is a crucial factor affecting plant growth that may determine the distribution of vegetation (*Engelbrecht et al., 2007*); meanwhile, plants affect soil moisture by forming a pathway for soil water transport to the atmosphere using root systems (*Wang et al., 2010*). In the past 50 years, climate warming and rainfall reduction may be the direct causes of the formation of soil dry layer in the Loess Plateau, improper selection of vegetation types, excessive community density and high productivity aggravated the drying process of deep soil (*Chen, Shao, & Wang, 2005; Yang & Tian, 2004*). Therefore, studying effect of revegetation on soil moisture dynamic helps to understand the soil hydrological effect of different vegetation restoration types, but also provides valuable reference for the scientific allocation of vegetation by Grain for Green Policy.

Recent studies have documented the effects of afforestation on soil moisture (*Jia et al., 2017; Jia & Shao, 2014; Jian, Zhao, Fang, & Yu, 2015; Liu et al., 2018*), they investigated the impact of different vegetation types and focused on the spatio-temporal heterogeneity in soil moisture. However, the heterogeneity in the hydrogen and oxygen isotope composition of soil water was seldom studied, although it can reveal processes of water cycling within soil (*Oerter & Bowen, 2019*). Tracing water movement has been advanced by the use of natural variations in the stable isotopes of hydrogen and oxygen (^{2}H and ^{18}O) in the water molecule (*Barnes & Allison, 1983; Kendall & Mcdonnell, 1998; Sprenger, Leistert, Gimbel, & Weiler, 2016; Zimmermann, Muennich, & Roether, 2013*). The hydrogen and oxygen stable isotope systems have become increasingly useful in ecohydrologic studies, which can efficaciously identify and reflect the characteristics of different water bodies. Studies have suggested that the isotopic composition of precipitation is greatly affected by evaporation, and evaporation fractionation is obvious in the hilly and gully regions of the Loess Plateau (*Ma et al., 2012*). In addition, there is a lag effect in the recharge of groundwater by precipitation in the region (*Wang, Li, Ma, Ma, & Zhang, 2016; Xu, Zhao, & Zhang, 2013*). In terms of infiltration mode, the piston flow and the priority flow coexisted in the process of precipitation infiltration in the Loess Plateau, but there was a certain relationship between the occurrence of the priority inflow and the land-use patterns (*Cheng, Liu, Li, & Chen, 2013*). These results greatly promoted the study of soil water transport characteristics in the Loess Plateau.

However, deep soil moisture evaluations based on ground-truth observations remain fundamentally lacking, and the spatial-temporal variations of soil moisture with vegetation age is still poorly understood. Moreover, studies about combination of the soil moisture and stable isotopes were less. Thus the specific objectives of this study were: (1) to investigate the vertical distribution of soil moisture under different vegetation restoration types in the hilly and gully regions of the Loess Plateau, (2) to determine the impact of Grain for Green on soil moisture at different depths in the past 40 years, and (3) to analyze the process and mechanism of soil water movement under different vegetation restoration types. An understanding of this information about soil moisture under different vegetation types is critical to the sustainable management of water resources in the hilly and gully regions of the Loess Plateau.

2. MATERIALS AND METHODS

2.1 Study site description

The study was conducted in the Zhifanggou watershed (109°13′46″E–109°16′3″E, 36°42′42″N–36°46′28″N) at Ansai County, Shaanxi Province, China (*Fig. 1*). The total watershed area is approximately 8.27 km^2 and the altitude is between 1041.50 m and 1425.71 m. The region located in semi-arid regions, belong to the typical continental climate with an annual precipitation of 549.1 mm, of which about 61.1% falls during July to September. The mean annual air temperature is 8.8°C, and the annual accumulated temperature above 10°C is 3113.9°C with 159 frost-free days. The entire watershed is covered by a thick, silt-loam loess soil. With the special geological conditions and long-term soil erosion, many complicated ravines and a large number of loess slopes were shaped, and the coverage of surface vegetation is low. The watershed has experienced the periods of serious vegetation destruction (1938–1958), continuous destruction (1959–1973), instability (1974–1983), stable recovery and improvement (1984–1990) and preliminary stage of benign ecology (1991 until now), and the land-use patterns has changed vastly. The predominant land use types are forest land, shrub land, grassland, cropland, orchard, nursery and abandoned land, etc. Trees (*Robinia Pseudoacacia, Populus simonii, and Armeniaca sibirica*), shrubs (*Caragana korshinskii and Hippophae rhamnoides*) and herbs (*Astragalus adsurgens, Artemisia gmelinii and Stipa bungeana*) are the dominant vegetation in the study area. Water shortage severely limited economic, social and ecological sustainable development in the region.

[Insert Figure 1]

2.2 Experimental design

For this study, a regional, short-term field experiment was conducted in May 2019. We adopted a method of space-for-time (SFT) substitution to reveal the interactions between vegetation restoration and soil moisture. We selected eight representative plots with four vegetation types that had been established for various numbers of years: *Robinia pseudoacacia* (15, 20 and 40 years), *Caragana korshinskii* (20 and 40 years), *Stipa bungeana* (15 and 20 years) and corn (0 year). Among these, cornfield was used as a control plot, which had more than 40 years history of tillage. In each plot, three points were selected at equal intervals from the mid-slope positions, and were considered as replicates. The sampling depth ranged from 0 to 500 cm. A total of 24 samples were collected at each point by using a soil auger (10 cm intervals from 0 to 100 cm, 20 cm intervals from 100 cm to 300 cm, 50 cm intervals from 300 cm to 500 cm). All selected plots with similar slope, aspect and elevation to exclude the effects of topography on soil moisture. In this way, we analyzed that the effect of growth age on soil moisture under *R. pseudoacacia*, *C. korshinskii* and *S. bungeana*. The vegetation age was determined by consulting local forest bureaus. The longitude, latitude and elevation of each plot were obtained using an RTK-GPS receiver, while slope and aspect were measured with a compass. For subsequent laboratory measurement, samples of each layer soil were divided into two parts. Part of samples were used for measuring soil moisture which were placed in aluminum boxes, and the remaining was used for measuring hydrogen and oxygen isotopes which were stored in a polyethylene bottle (250 ml) and sealed with parafilm sealing film. To avoid impact of evaporation on isotopes measurement, we put the samples into a freezer (□20 °C) in time. The first sampling activity for soil moisture and stable isotopes was finished within three days (from May 24, 2019 to May 26, 2019), when no rainfall had occurred for at least a week prior to it. The second sampling activity for stable isotopes was finished on the third day (June 8, 2019) after rainfall.

2.3 Methodology

All samples were measured for gravimetric moisture content (unit: g/g or %) using the oven-dry method (24 h at 105 °C). The depth-averaged soil moisture for each sampling plots (θ_{ij}) were calculated by Eq. (2):

$$\theta_{ij} = \frac{1}{i}\sum_{i=1}^{i}\theta_{i} \tag{1}$$

where i is the number of measurement layers at plot j, and θ_i is the mean soil moisture in layer i calculated by three sampling points.

The depth-averaged soil moisture for each vegetation type (θ_m) was calculated by Eq. (3):

$$\theta_{m} = \frac{1}{k}\sum_{k=1}^{k}\theta_{ij} \tag{2}$$

where k is the number of sampling plots for each vegetation type.

The soil water was extracted in the laboratory of Northwest Agriculture and Forest University in Xi'an using L I-2000 vacuum condensation extraction equipment (LICA, China), with an extracting rate of more than 98%. Extracted water samples were measured for δD and δ^{18}O values using a DLI-100 liquid water isotope analyzer

(Los Gatos Research Inc., USA). Based on the results from standard waters (Vienna Standard Mean Ocean Water-VSMOW) analyzed concurrently, analytical precision for these liquid water analyses is ± 0.5% for δD and ± 0.3% for δ^{18}O. Isotope values are reported in δ notation:

$$\delta = \left(R_{Sample} / R_{Standard} - 1 \right) \qquad (3)$$

where R_{sample} and $R_{standard}$ are the $^{2}H/^{1}H$ or $^{18}O/^{16}O$ ratios for the sample and standard, respectively, and values are reported in per mille (‰) by multiplying by 1000, and referenced to the VSMOW standard.

Basic soil moisture statistics, including maximum (Max), minimum (Min), mean values (Mean) and standard deviations (SD) were reported for different vegetation types in the study area. One-way ANOVA was used to test the statistical significance of the effects of vegetation types and depth on the soil moisture. Multiple comparisons were made using the Bonferroni method. Grey theory analysis was used to evaluate the associated degree of soil moisture in different vegetation types and layers. All the statistical analyses in this work were performed with Matlab 2018a and IBM SPSS 20.0, and Origin 2017 was used to create figures.

3. RESULTS

3.1 Characteristics of soil moisture under different vegetation types

Soil moisture was clearly affected by vegetation types (*Table 1*). The average soil moisture under *R.pseudoacacia* (7.43 g/g) was significantly lower than *C.korshinskii* (9.98 g/g), *S. bungeana* (10.98 g/g) and corn (11.03 g/g). However, the statistical test detected there are no significant differences between different vegetation types except *R.pseudoacacia*. Soil moisture ranged from 5.91 to 13.55 g/g, and the minimum value was near to the wilting humidity 5 g/g (*Li, Wang, Shao, Zhao, & Li, 2008*). The variation amplitudes of soil moisture are relative greater for *S. bungeana* and corn and smaller for *R.pseudoacacia* and *C.korshinskii* in term of SD.

[Insert Table 1]

Fig. 2 shows the soil moisture content distribution in different land use type and soil layer. The whole soil profile were divided into five layers at 100 cm intervals to quantify and compare the effect of soil depth under different vegetation types. In the 0–100 cm soil layers, the soil moisture from high to low in order was *S. bungeana*, corn, *C. korshinskii* and *R. pseudoacacia*. Furthermore, the statistical analysis showed significant differences between *R. pseudoacacia* and *S. bungeana* and corn, respectively. In contrast with first layer, the soil moisture of the rest four layers from high to low in order was cron, *S. bungeana*, *C. korshinskii* and *R. pseudoacacia*. Moreover, the statistical analysis showed that soil moisture in *R. pseudoacacia* was significantly lower than that in other three vegetation types.

[Insert Figure 2]

It is suitable to make use of gray relational theory for comprehensive evaluation of soil moisture among different layers (*Zhang, Xu, Liu, & Du, 2008*). As shown in *Table 2*, the first, second, third, and fourth layers were defined as the reference sequence successively, and R_{12}, R_{13}…, R_{45} indicate the relational grade of different soil layers. Both of the soil moisture under *R. pseudoacacia* and *C. korshinskii* have similar rules_that the second layer (100–200 cm) and the third layer (200–300 cm) were closely related, with the correlation degree of 0.6539 and 0.9176, respectively. In contrast, *S. bungeana* and corn have the highest relational grade in the third layer (200–300 cm) and the fourth layer (300–400 cm), which were 0.7994 and 0.7201, respectively. Moreover, the highest relational grade under different vegetation types appeared in the adjacent soil layers.

[Insert Table 2]

3.2 Vertical distribution of soil moisture with vegetation types and ages

The soil moisture in the soil profiles of the different vegetation types and ages are displayed in *Fig. 3*. Overall, the soil moisture in the upper 0–40 cm had larger change range, which was sensitive to rainfall, root water uptake, and soil evaporation. With the increase of soil depth, the soil moisture under *R. pseudoacacia* decreased sharply from 0 to 40 cm and then remained relatively stable. Compared with *R. pseudoacacia*, soil moisture under *C. korshinskii* decreased firstly from 0 to 40 cm and then increased slightly. For *S. bungeana*, however, the soil moisture gradually increased with the increasing soil depth, which was similar to the trend of corn. Meanwhile, soil moisture varied with vegetation age. Every layer of soil moisture under *C. korshinskii* showed significant decreases with the increase of vegetation age. However, this rule is not applicable to all the soil layers of *R. pseudoacacia* and corn, such as *R. pseudoacacia* in the 0–150 cm and corn in the 100–500 cm. Furthermore, the soil moisture variation under *R. pseudoacacia* in the same soil layer are relative smaller in term of SD.

[Insert Figure 3]

To determine the age-related variations of the soil moisture under different vegetation types, a map of the distribution of soil moisture change rate was plotted (*Fig. 4*). In the past 40 years, compared with corn (cropland), the soil moisture under *R. pseudoacacia* at the 0–30 cm depth had been restored somewhat. However, the planting in *R. pseudoacacia* significantly decreased the soil moisture below 30 cm, and the change rate was ranked as 40 yr (32.98%) > 20 yr (28.22%) > 15 yr (24.31%) (*Fig. 4A*). On the contrary, the annual change rate of the soil moisture was ranked as 15 yr (1.62%·yr^{-1}) > 20 yr (1.41%·yr^{-1}) > 40 yr (0.82%·yr^{-1}) (*Fig. 4B*). Similar to *R. pseudoacacia*, the change rate of the soil moisture under *C. korshinskii* increased 8.86% and 22.84% in the middle stage (20 yr) and later stage (40 yr), respectively (*Fig. 4C*), and the annual change rate was ranked as 20 yr (0.43%·yr^{-1}) < 40 yr (0.57%·yr^{-1}) (*Fig. 4D*). Athough the change rate of the soil moisture under *S. bungeana* showed an increasing trend with ages as well (incrased from − 7.32% to

0.12%), the soil moisture is overall higher than that of corn (*Fig. 4E*). Regardless of the vegetation age (15 yr and 20 yr), the annual change rate of *S. bungeana* is near zero (*Fig. 4F*). Moreover, it is noteworthy that the degree of soil moisture reduction with age was far higher than other two types, though the annual change rate of soil moisture under *R. pseudoacacia* decreased distinctly.

[Insert Figure 4]

3.3 Composition characteristics in hydrogen and oxygen stable isotopes

To further explore the influence of vegetation types on soil moisture transport, we analyzed the composition characteristics in hydrogen and oxygen stable isotopes for soil water. As shown in *Fig. 5*, the slope and intercept of the local meteoric water line (LMWL) were all smaller than those of the global meteoric water line (GMWL). This reflects the climate characteristics of Zhifanggou watershed, the low air humidity and high evaporation (*Xu et al., 2013*). The relationship between δD and δ^{18}O in soil water showed that the values are distributed around the LMWL, indicating that the soil water originated from atmospheric precipitation. In the absence of the interference, the source of the soil water supply was relatively stable, so δD and δ^{18}O values should be stable. However, the data deviated from the LMWL to some degree during the observation period, and most of them were below the LMWL. The evaporation line (EL) could be determined by fitting the relationship between δD and δ^{18}O in soil water. Each one of these ELs had smaller slope and intercept than the LMWL, which indicated that the rainfall was evaporating and fractionating in the process of precipitation recharge, resulting in heavy isotopes enriched obviously. Furthermore, the EL of *C. korshinskii* in which slope and intercept were the largest, followed by *R. pseudoacacia* and *S. bungeana*, the corn were the minimum. Composition characteristics of hydrogen and oxygen stable isotopes in soil water under different vegetation types shown in *Table 3*. Comparative analysis of the average values of δD and δ^{18}O showed that *S. bungeana* (− 69.33‰ ± 9.70‰) > corn

(− 70.45‰ ± 6.60‰) > *R. pseudoacacia* (− 71.93‰ ± 8.12‰) > *C. korshinskii* (− 74.12‰ ± 9.37‰) and *R. pseudoacacia* (− 9.39‰ ± 1.27‰) > *S. bungeana* (− 9.44‰ ± 1.69‰) > corn (− 9.45‰ ± 1.28‰) > *C. korshinskii* (− 10.17‰ ± 1.46‰), respectively.

[Insert Figure 5]

[Insert Table 3]

3.4 Vertical distribution of hydrogen and oxygen stable isotopes

A good linear relationship meet between δD and δ^{18}O, so we selected only δ^{18}O to analyze the vertical distribution of hydrogen and oxygen isotopes in soil water under different vegetation types. *Fig. 6* compares depth-averaged δ^{18}O values under different vegetation types in various soil layers. In the 0–100 cm depth, the δ^{18}O values is relatively high than other layers. Under the same vegetation type, the δ^{18}O values in various soil layers have no remarkable difference. For a certain soil layer, the δ^{18}O value of *C. korshinskii* is significantly lower than *S. bungeana* and corn in 200–300 cm, and corn is significantly lower than *S. bungeana* in 300–400 cm, the rest are non-significant ($p < 0.05$).

[Insert Figure 6]

Vertical changes of the δ^{18}O values under different vegetation types are presented in *Fig. 7*. On the whole, the δ^{18}O values varied greatly in the upper soil layer and tend to be consistent with the increase of soil depth. After rainfall, the δ^{18}O values under *R. pseudoacacia*, *C. korshinskii* and corn, increased firstly (0–20 cm) and then decreased (20–50 cm). We also found abrupt changes in isotope depth profiles. For example, peaks of a depleted δ^{18}O signal appeared in corn. Due to the limited depth of evaporation, the variation of deep soil water isotope can only by mixing, that is, the precipitation supplement infiltrating into the deep soil in the form of preferential flow (*Beven & Germann, 1982; Germann, Edwards, & Owens, 1984*).

It should be noted that, above 100 cm depth, the $\delta^{18}O$ values under corn fluctuates greatly, which is probably due to the fact that the cultivated layer is mainly distributed at surface layer. The disturbance of artificial cultivation could affect physical characteristics of soil such as porosity and bulk density, subsequently affect rainfall infiltration. When the error of $\delta^{18}O$ value in soil water at a certain depth is less than twice the SD, it can be regarded as a relatively stable critical depth (*Geldern & Barth, 2016*). The accuracy of $\delta^{18}O$ measured in this experiment is 0.3‰, so the critical error change for relatively stable $\delta^{18}O$ value is 0.6‰. Under *R. pseudoacacia*, *C. korshinskii* and *S. bungeana*, the SD of $\delta^{18}O$ values is less than 0.6‰ below 220, 200 and 230 cm, respectively. Therefore, it can be predicted that the hydrogen and oxygen isotopic values in soil water in *R. pseudoacacia*, *C. korshinskii* and *S. bungeana* are relatively stable below 220, 200 and 230 cm soil depth, respectively.

[Insert Figure 7]

4. DISCUSSION

4.1 Effects of vegetation types on soil moisture

In the past few decades, the Grain for Green Program and the Soil and Water Conservation Project were launched to prevent soil erosion and improve soil quality in China (*Chen, Wang, Wei, Fu, & Wu, 2010*). Afforestation and the introduction of new shrubs and grasses have become one of the important ways of vegetation restoration in the region (*Yang, Wei, Chen, Chen, & Wang, 2014*). Consequently, the newly introduced vegetation has become the dominant vegetation type (*Liu, Li, Ouyang, Tam, & Chen, 2008*). However, with the increase of forest and grass coverage rate, the original land use structure and type changed, which literally altered the redistribution and migration process of soil moisture. Unsuitable artificial forest species and overly high planting density can result in severe water depletion (*Deng, Yan, Zhang, & Shangguan, 2016*). When dried soil layers form, deep soil water can only be fully replenished on rare occasions (*Chen, Shao, & Li, 2008*), leading to weakened function of "soil water reservoir" (*Shao, Jia, Wang, & Zhu, 2016; Zhu, 2006*). Water resources in deep soil layers thus play an important role in ensuring a well-established cover of vegetation in semiarid regions (*Jia & Shao, 2014*). It is an urgent problem to achieve the stability of soil moisture conditions and the sustainability of vegetation restoration (*Dijk & Keenan, 2007; Yang et al., 2014*). In this study, the soil moisture under *R. pseudoacacia* was lower than other three vegetation types, especially below 100 cm, since the extensive root systems and huge amounts of root water uptake (*Wang et al., 2010; Zhang, Chen, & Jiang, 2014; Zhang, Niu, Liang, Shi, & Guo, 2014*). Nevertheless, the soil moisture under *R. pseudoacacia* in topsoil (over 40 cm) was obviously greater than that under corn. This is reflected early in the former theoretical and empirical research. As discussed by (*Robichaud & Hungerford, 2000*) that the trees can increase the hydraulic conductivity of the surface soil layer through the buffering and interception of leaves. In addition, the litter layer of trees can retard runoff, increase infiltration and inhibit soil water evaporation. Since the surface of cropland with low vegetation coverage, we hypothesize that this that this contributes to the severely water loss in soil. The lower SD of soil moisture under *R. pseudoacacia* indicated little moisture replenishment by rainfall. This is probably due to more plant interception and higher plant uptake by the introduced vegetation such as *R. pseudoacacia* in the near-surface soil layer, thus reducing deep soil moisture recharge (*Daniel et al., 2010*). Likewise, the soil moisture between *S. bungeana* and corn are different from various soil layers. For instance, when the depth is less than 100 cm, *S. bungeana* is higher than corn, but when more than 100 cm, corn is higher. Besides extremely low vegetation coverage mentioned above, causes for this result might be owed to the cropland was newly ploughed before sampling which leads intense evaporation at surface. However, water uptake by *S. bungeana* root system resulted in relatively low soil mosture. Moreover, the relational grade in different layers shows that *S. bungeana* have a greater effect on the regulation of deep soil moisture than *R. pseudoacacia* and *C. korshinskii*. (*Wang, Shao, & Zhang, 2008*) have shown that the artificial *R.*

pseudoacacia belongs to high water consumption tree species. With the increase of years, the water consumption will gradually increase, and even form dried soil layer. Not only artificial *R. pseudoacacia*, the soil water deficit in the artificial *P. tabulaeformis* and *C. korshinskii* presented an enhanced trend with the progress of ecological restoration and increase in soil depth (*Jia et al., 2017*). These previous studies are in line with our own independent analyses and show that the soil moisture under *R. pseudoacacia* and *C. korshinskii* decreased in the 100–500 cm layer with the increase of vegetation ages, particularly *R. pseudoacacia*. This observation was also an indication that the precipitation in the region has little effect on the deep soil layer (*Yang et al., 2014*). However, under *S. bungeana*, only over 80 cm showed a significant trend that the longer vegetation ages and lower soil moisture. Therefore, compared with afforestation, natural restoration is more conducive to increase soil water holding capacity and stabilization. Generally, soil moisture might be severely affected by plant roots in 100–200 cm soil layer (*February & Higgins, 2010*), resulting in soil desiccation. In this regard, the 40-year-old *R. pseudoacacia* has the obvious characteristic which severe soil water deficiency appeared at around 200 cm (*Fig. 3*). Water deficit in turn affects the normal growth of plants and form a vicious circle which threatens the ecosystem and water resource security. Due to water depletion continues after afforestation in general, especially for artificial *R.pseudoacacia*, some 20–30 years plantations only grow to approximately 20% of their normal height (*Jia et al., 2017; Jin, Fu, Liu, & Wang, 2011; Wang, Shao, Zhu, & Liu, 2011*). *Jia et al. (2017)* concluded that the height of artificial *R.pseudoacacia* even showed a negative growth during 26–40 years in the Fuxian district. However, because the sample size of this study is small, and the study area is different, the distinct negative growth phenomenon was not observed. Previous research found that the soil moisture under artificial *R. pseudoacacia* has recovered to some extent after 20 years of growth (*Jia et al., 2017*). Our comparison of the soil moisture under *R. pseudoacacia* of different ages does not support the findings, which may be mainly determined by growth status of trees. Still, high consumption of soil moisture by artificial forest leads to soil desiccation, particularly at deep soil layers, in contrast, abandoned land has relatively better effect on soil moisture recovery and conservation.

4.2 Effects of vegetation types on hydrogen and oxygen isotopes

In the transportation process of soil water, the original soil water isotope concentration will change due to exchange and mixture after precipitation with different isotopic content infiltrates into the soil. Soil isotopic composition depends on the frequency and efficiency of the mixing process, which depends on the soil water migration mechanism (*Gehrels, Peeters, Vries, & Dekkers, 1998; Marc, Didon-Lescot, & Michael, 2001*). In addition, precipitation entering the soil may become partly evaporated, and the water remaining in the soil will thus get enriched in heavy isotopes by evaporation fractionation (*Sprenger et al., 2016*). Evaporation is the most important hydrological process that causes isotopic fractionation of soil water (*Ren, Yao, & Xie, 2016*) and there is no evidence that root water uptake can produce isotope fractionation effect (*Hsieh, Chadwick, Kelly, & Savin, 1998*). According to the slope and intercept of the fitting curve of soil water isotopic characteristics, the degree of soil water evaporation fractionation followed the sequence: corn > *S. bungeana* > *R. pseudoacacia* > *C. korshinskii*. The results shown here are basically in accordance with the preceding analysis. In the area with low precipitation and comparatively high evaporation capacity annually, *Liu, Phillips, Hoines, & Campbell (1995)* reported that stable isotopes of hydrogen and oxygen in soil water were strongly enriched, and an obvious peak appeared in the root zone of soil surface layer. The observations reported here are in broad agreement with previous work. We found that the $\delta^{18}O$ values in soil water enriched sharply at 20 cm depth and then decreased, which indicates that the evaporation surface of soil water occurs above 20 cm. In addition, it is also essential to understand the mechanism of precipitation infiltration for the study of groundwater recharge. *Gazis & Feng (2004)* suggested that the precipitation penetrates down in the form of piston flow, while some rainwater can reach the deep soil quickly in the form of preferential flow. Different precipitation infiltration mechanisms lead to different soil water stable isotopes in various layers. Deep soil moisture receives limited precipitation compensation, and precipitation is evenly mixed with soil water. This suggests that the isotopic composition should be changed slightly. However, abrupt changes of isotopics appeared at both shallow and deep layers actually. Accordingly, we hypothesized that the precipitation may supply soil water directly through some large pores of soil. Recent work by (*Ke et al., 2017*) has pointed out that forestland can significantly extend the path of preferential flow. For *R. pseudoacacia*, however, preferential flow is difficult to form at deep layers due to the presence of dried soil layer. Even if preferential flow has formed, it will be quickly absorbed by dry soil owing to water potential gradient (*Cheng & Liu, 2012*). Therefore, piston flow is likely to dominate the movement of soil water under *R. pseudoacacia*. For *C. korshinskii* and corn, profiles of δ^{18}O values in soil water are similar before and after the rain, respectively. This conform to general characteristics of piston flow. *Mathieu & Bariac (1996)* concluded that water moves through the soil profile by two means: (1) slow infiltration through the soil matrix and mixing with mobile soil water; (2) fast direct recharge by flow through conducting fissured zones. These two proposed mechanisms are compatible with the observations of our study. Overall, profiles of δ^{18}O values in soil water under different vegetation types are quite different, which is probably caused by the continuous evaporation of soil moisture and the inconsistency of preferential flow. The conceptual visualization in *Fig. 8* provides an overview of the general hydrological processes that occur within the context of the vadose zone. However, due to lack of stable isotope data for precipitation in the same period, it is difficult to accurately distinguish the movement mode of soil water in this study. Furthermore, there is an interplay of various processes that alter the soil water isotopic composition (*Sprenger et al., 2016*). Therefore, a multidisciplinary approach is required, where the interactions of the soil with the precipitation, groundwater and vegetation are considered to understand the isotopic composition of the vadose zones.

[Insert Figure 8]

4.3 Implications for soil moisture and vegetation management

It is important to note the limitations of this study mainly due to lack of long-term continuous soil moisture and isotopic data. Previous studies have shown that large-scale conversion of agricultural lands to forest lands in the Loess Plateau is considered a land use activity which may cause negative effects through transpiration, infiltration and interception (*Dijk & Keenan, 2007*), such as a “dried soil layer” (*Wang et al., 2011*). Conversely, the decline in soil moisture induced soil drought that caused a serious impact on plant growth and development, even resulting in degeneration of vegetation, for instance, “small old trees” forms in dry areas (*Jia et al., 2017; Y. Wang et al., 2011*). Moreover, the introduction of exotic tree species and high planting density further intensified consumption of soil water in this region (*Deng et al., 2016; Jin et al., 2011; Wang, Liu, Gang, & Zhang, 2009*). Therefore, vegetation restoration should not only consider preventing soil erosion, but also should play a relatively positive role in rational utilization of soil water resources. (*Liu & Shao, 2016*) indicated that the natural fallow was the best vegetation type for achieving sustainable utilization of soil water and preventing soil desiccation. In our work, the soil moisture under corn is considered the initial soil moisture condition serving as the baseline soil moisture level in order to develop a better plan for vegetation recovery. Result shows that the deep soil moisture under *S. bungeana* remains relatively stable. Thus, planting shallow root herbs and natural restoration are the better choice for vegetation restoration and ecological construction in the Loess Plateau. In the future ecological restoration, some measures to alleviate the depletion of water resources in the Loess Plateau should be taken, such as selecting suitable vegetation type and reasonable vegetation density (*Huang & Gallichand, 2006; Shao et al., 2016*). In addition to considering land use and plant species, soil properties in deep soil such as textures should be taken seriously (*Mendham et al., 2011; Oliveira et al., 2005*).

We also should respect the law of vegetation succession in order to ensure the sustainable, healthy and harmonious development of forest and grass ecological construction.

5. CONCLUSIONS

Spatial changes in soil moisture due to vegetation restoration in the semi-arid Loess Plateau were investigated and compared. Results indicated that vertical distribution of soil moisture was varied somewhat under different vegetation restoration types. Compared with corn, *R. pseudoacacia* and *C. korshinskii* reduced soil moisture in 500 cm soil profile, while soil moisture was not obviously affected by *S. bungeana*. Within limits, the longer the vegetation age is, the lower the soil moisture, especially in *R. pseudoacacia* and *C. korshinskii*. By contrast, *S. bungeana* has relatively better effect on soil water conservation and stabilization, which indicates that planting shallow-rooted herbs is a more reasonable way of vegetation restoration in the region. In addition, different vegetation types also changed the water infiltration mode and further affected the vertical variability of soil moisture. In the loess hilly gully region, precipitation infiltration has the characteristics of top-down piston infiltration, and part of precipitation may reach the deep soil through some "fast passage" in the way of preferential flow. This largely depends on the vegetation types. Overall, vegetation types have profound effects on the distribution and transportation of soil moisture. Thus, selection of appropriate vegetation types and planting density according to local soil moisture conditions is important when maintaining a sustainable soil water resource balance at all depths, especially when water is scarce.

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TABLES

Table 1 Soil moisture in the 0–500 cm layers by vegetation types.

Land use	Vegetation types	Soil moisture			
		Max (g/g)	Min (g/g)	Mean (g/g)	SD
Forestland	*R. pseudoacacia*	13.42	8.38	7.43 b	1.05
Shrubland	*C. korshinskii*	12.66	8.31	9.98 a	0.79
Abandoned land	*S. bungeana*	13.55	5.91	10.98 a	1.46
Cropland	Corn	13.60	8.90	11.03 a	1.35

Means with the same letter in the same column are not significantly different at the 0.05 level (Bonferroni method).

Table 2 Grey relational grade of soil moisture in different layers.

Grey relational grade	Vegetation types			
	R. pseudoacacia	*C. korshinskii*	*S. bungeana*	Corn
R_{12}	0.3895	0.6109	0.4952	0.4722
R_{13}	0.4186	0.6335	0.4061	0.3437
R_{14}	0.3447	0.7500	0.4427	0.3889
R_{15}	0.3701	0.3396	0.3546	0.6405
R_{23}	**0.6539**	**0.9176**	0.5689	0.4074
R_{24}	0.3701	0.5787	0.4566	0.6429
R_{25}	0.6240	0.4226	0.4250	0.5166
R_{34}	0.4429	0.6149	**0.7994**	**0.7201**
R_{35}	0.5501	0.4051	0.4664	0.3421
R_{45}	0.5139	0.3854	0.4988	0.3666

Table 3 Composition characteristics of δD and δ^{18}O in soil water under different vegetation types.

Vegetation types	δD (‰)				δ^{18}O (‰)				EL
	Max	Min	Mean	SD	Max	Min	Mean	SD	
R. pseudoacacia	−26.53	−82.25	−71.93	8.12	−1.86	−10.90	−9.39	1.27	$\delta D = 6.29\delta^{18}O - 12.90$ ($R^2 = 0.98$)
C. korshinskii	−32.29	−93.14	−74.12	9.37	−4.25	−12.85	−10.17	1.46	$\delta D = 6.68\delta^{18}O - 6.11$ ($R^2 = 0.98$)
S. bungeana	−23.65	−87.43	−69.33	9.7	−2.03	−12.19	−9.44	1.69	$\delta D = 5.90\delta^{18}O - 13.65$ ($R^2 = 0.99$)
Corn	−	−	−	6.6	−	−	−	1.2	$\delta D = 5.13\delta^{18}O - 21.95$ ($R^2 =$

	36.69	86.33	70.45		4.00	11.54	9.45	8	0.90)