SOIL MOISTURE VARIATIONS WITH LAND USE ALONG THE PRECIPITATION GRADIENT IN THE NORTH–SOUTH TRANSECT OF THE LOESS PLATEAU

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ABSTRACT

Knowledge of soil moisture spatial variation with land use along the precipitation gradient is necessary to improve land management and guide restoration practice in the water-limited Chinese Loess Plateau. This study selected 45 sampling points at 11 sites across the north–south transect of the Loess Plateau based on the precipitation gradient and land use. Results showed that the vertical profiles of soil moisture revealed large variations with the precipitation gradient changing, especially in the surface layer (0–100 cm). Significant linear correlation existed between the average soil moisture of the profile and the mean annual precipitation (MAP) for each land use type ($p < 0.05$). Hereinto, the soil moisture under the grassland was affected more greatly by precipitation. The soil moisture under each land use commonly revealed the trend as farmland > grassland > shrubland > woodland, while it might be higher under the woodland than the shrubland in the surface layer in regions with MAP < 500 mm. The soil moisture of woodland or shrubland at the selected points was below or approximate to the permanent wilting point in regions with MAP < 520 mm. Covariance analysis confirmed the effects of land use and MAP on the soil moisture in depth of 100–300 cm, and it showed land use did not pose significant effects in the surface layer. In addition, our study indicated that it is necessary to reconsider and re-evaluate the current vegetation restoration strategy in the perspective of vegetation sustainability and soil water availability, in which woodland and shrubland were selected on a large scale in the arid and semi-arid regions. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: soil moisture; land use type; precipitation gradient; restoration strategy; north–south transect

INTRODUCTION

Anthropogenic activities have induced land degradation processes, which further affect the atmosphere, water resources, biota and soils (Berendse *et al.*, 2015; Bochet, 2015; Gao *et al.*, 2015; Muñoz-Rojas *et al.*, 2015; Parras-Alcántara *et al.*, 2015; Qadir *et al.*, 2013). These impacts would affect the hydrological cycle and lead to distinct spatio-temporal variability of the hydrological regimes, especially in water-limited regions (Cohen *et al.*, 2014; Gao *et al.*, 2015; Milly *et al.*, 2005). Soil moisture is an integrative state variable that plays key roles in many terrestrial ecosystem processes especially in arid and semi-arid environments (Legates *et al.*, 2011; Porporato *et al.*, 2002; Yang *et al.*, 2014a). The spatio-temporal variability of soil moisture regulates many hydrological processes (Famiglietti *et al.*, 1998). Characterizing soil moisture variations across a range of spatial and temporal scales is fundamental to understand and model eco-hydrological processes because of the complex and nonlinear relationships among various biophysical processes and soil moisture (Famiglietti *et al.*, 1998; Yang *et al.*, 2015). Exploring the soil moisture variation at

regional scale is a key issue for the eco-hydrology research in water-limited regions such as the Loess Plateau in China.

The Loess Plateau is located in the middle reaches of the Yellow River basin in China with a total area of 0.64 million km² (Feng *et al.*, 2012). The natural vegetation cover in the Loess Plateau is generally low, and the cultivated croplands are the main land use type due to the long history of human settlement (Feng *et al.*, 2012). The loose loess soils, steep slopes, high rainfall intensity and poor vegetation conditions have made the Loess Plateau one of the most severely eroded areas in the world (Gao *et al.*, 2015; Li *et al.*, 2009). Several efforts including afforestation, pasture reestablishment, terraces and check dams have been made to control soil erosion and restore ecological functions (Liang *et al.*, 2015). The Grain for Green project aiming to convert steep cropland to forest and pasture lands have been implemented at the end of the 1990s (Feng *et al.*, 2012).

The land use has changed dramatically with the implementation of Grain for Green project in the Loess Plateau, which altered the hydrological cycle. For example, the soil water repellency would be affected by land use change, which further triggers soil and water loss (Keesstra *et al.*, 2016). The soil moisture variation research has drawn considerable attentions in this region. The soil moisture patterns of different vegetation types in the catchments of the Loess Plateau have been well studied in recent studies (Wang *et al.*, 2013a). The soil moisture

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difference between different land use/vegetation has been compared in many catchments in the Loess Plateau (e.g. Chen *et al.*, 2004; Qiu *et al.*, 2001), and such studies indicated that soil moisture in bare soils were usually higher than that in vegetated soils, and soil moisture in annual crops and grasses was higher than that in forests (Wang *et al.*, 2013a). The water balance in the soil–vegetation–atmosphere system was also studied in the catchments, indicating that the vegetation type would be a major influencing factor (Wang *et al.*, 2011a).

There are limited regional-scale studies on the soil moisture spatio-temporal variability in the Loess Plateau. Entin *et al.* (2000) found that the soil moisture variance at small scale was controlled by soil, topography, vegetation and root structure, and at large scale it was controlled by the atmosphere. Vinnikov *et al.* (1996) indicated that the spatial variability in the red noise component of soil moisture reflects the statistical properties of the monthly averaged precipitation field at the scale of about 500 km. Wang & Franz (2015) examined the effect of soil hydraulic parameters on soil moisture spatial variability and found that the mean relative difference of soil moisture was mainly controlled by soil hydraulic properties instead of the climatic factors. The dominant factors of soil moisture spatial variability at regional scale still need further analysis in the Loess Plateau. In addition, soil properties and hydrological processes revealed corresponding variations along the environmental gradient (altitudinal gradient, climatological gradient and recuperation gradient), while the variations might also be linked to many factors such as land use (Campos *et al.*, 2014; Cerdà, 1998a; Cerdà, 1998b; Choudhury *et al.*, 2015; Hedo *et al.*, 2015; Vasconcellos *et al.*, 2016). The precipitation gradient factor would affect the role played by the soil surface component in regulating soil hydrological processes (Ruiz Sinoga *et al.*, 2010). In the Loess Plateau, precipitation gradient exists ranging from 750 mm in the southeast to 200 mm in the northeast, which provides excellent opportunities to study the soil moisture variation in the whole matrix and incorporates variation caused by land use. Thus, it is necessary to study the soil moisture variation with land use along the precipitation gradient in the Loess Plateau.

In this study, we characterized the soil moisture variations with the environmental gradient in the north–south transect of the Loess Plateau. Specifically, the objectives are (i) to characterize soil moisture variations with the land use type and precipitation gradient across the north–south transect of the Loess Plateau and (ii) to explore the effects of land use and precipitation on the soil moisture at different layers.

MATERIAL AND METHODS

Study Areas and Sites

The Loess Plateau is located between 102–114°E and 35–41°N (Figure 1). Following the precipitation gradient, the vegetation distribution pattern varies from forests in the south to grasslands in the north (Feng *et al.*, 2012).

The north–south transect of the Loess Plateau was selected based on the precipitation gradient. The transect included all the main regional climate conditions and vegetation types. A total of 11 sites were chosen to characterize the spatial variation of soil moisture (Table I). The landform at these sites is typical loess and hilly, and the mean annual precipitation (MAP) increases from 406 mm at the northern site to 624 mm at the southern site.

Soil Sampling and Measurement Method

In July and August of 2014, a total of 45 sampling points were chosen at the 11 sites based on land use type (Table I). The land use types selected in this study are woodland, shrubland, grassland and farmland. It is noted that the farmlands selected had undergone similar cultivation practices (i.e. no irrigation and normal fertilization levels). No precipitation occurred during the sampling periods at each site or a week before sampling. Soil samples in depth of 0–300 cm were taken by an auger (5 cm in diameter) with 20 cm interval. The soil samples were kept immediately in airtight aluminium boxes after they were taken out. The gravimetrically soil moisture content was measured using the oven-dry method (24 h at 105 °C) in the laboratory. The volumetric soil moisture content was calculated by multiplying the gravimetric water content and the bulk density and dropping the units. In the majority of the sampling points, soils were collected along a vertical profile over 300 cm except for a few exceptions at the northern site. The latitude, longitude and elevation were determined for each sampling point by a handheld global positioning system device Magellan 500. The slope gradient and aspects were determined by a compass in field investigations. The undisturbed soil cores were collected at each sampling point to obtain the soil bulk density with metal cylinders (5 cm in diameter and 5 cm in length) and to determine field capacity and permanent wilting point by the capillary suction method.

Data and Statistical Analysis

The K value was introduced to describe the variation trend of soil moisture vertical profiles, which is the linear regression coefficient between soil moisture and soil depth (Wang *et al.*, 2014). A positive K value means the soil moisture would increase with soil depth and vice versa. Paired sample t -test was used to examine the effect of topography factors (slope position, slope gradient and slope aspect) on soil moisture variation at regional scale. In this study, the sampling points were divided into three groups to analyse the soil moisture variation under the effects of terrain factors. To elucidate the role of slope aspect on the soil moisture, several pairs of points were selected to compare soil moisture affected by slope aspect. It is noted that each pair of sites under the same land use type selected in this group was on similar slope position, similar slope gradient and similar precipitation conditions, but varied by slope aspects. The other two

Figure 1. Location of sampling sites in the catchments across the Loess Plateau. [Colour figure can be viewed at wileyonlinelibrary.com]

groups of sampling points were also selected to analyse the role of slope position and slope gradient on the soil moisture according to the criteria earlier (Table S1). Covariance analysis was used to explore the effects of precipitation and land use on the soil moisture at regional scale.

RESULTS

General Features of Profile Distribution of the Soil Moisture

The vertical profiles (0–300 cm) of soil moisture at 45 sampling points were shown in Figure 2. The soil moisture of the vertical profiles reveals great variability in the 0- to

100-cm soil layer. The range of soil moisture of vertical profiles varied greatly with the precipitation. Generally, the soil moisture under woodland and shrubland was lower than that in the farmland and grassland, especially in the deep layers, despite the environmental gradient differences across the transect. The vertical profiles of soil moisture variations at these sites revealed different trends, for example, the soil moisture in sampling points (30, 31, 32, 33 and 34) in Yangjuangou catchment revealed a consistent increasing trend, while the soil moisture in sampling points (20, 21, 22, 23 and 24) in Maliantan catchment revealed a consistent decreasing trend. The K values along the vertical soil profiles in these points ranged from -0.00036 to 0.00037 (Figure 3 a). The points with K values lower than -0.0015 showed an obvious decreasing trend, and these points belong to woodland/shrubland located in regions where MAP ranges from 475 to 575 mm. The points with K values larger than 0.0015 showed an obvious increasing trend, and these points mostly belong to farmland/grassland located in regions where $\text{MAP} > 550$ or < 450 mm. The average soil moisture of the vertical profiles (0–300 cm) under different land use types was shown in Figure 3b. Results showed the order of average soil moisture under the four land use types was farmland (15.23%) > grassland (12.34%) > shrubland (10.43%) > woodland (10.41%), and the woodland revealed greatest variability, while the farmland revealed smallest variability.

The Soil Moisture Variations with Environmental Gradient

The relationships between the soil moisture and MAP under each land use type were shown in Figure 4. There was a significant linear correlation between the soil moisture and MAP for each land use in different layers, except for the farmland in 0- to 100-cm and 100- to 200-cm layer ($p > 0.05$). Results showed that the correlation coefficient in different layers varied from 0.56 to 0.87, which was highest for grassland in 100–200 cm and lowest for farmland in 0–100 cm. The linear correlation between soil moisture and MAP indicated that the soil moisture under each land

Table I. General information of 45 sampling points across the north–south transect in the Loess Plateau

Category		Sampling points
Land use type	Woodland ($n = 18$)	1, 7, 8, 9, 13, 16, 20, 21, 23, 25, 27, 29, 30, 37, 38, 40, 42, 43
	Shrubland ($n = 10$)	4, 10, 14, 17, 22, 26, 28, 34, 35, 39
	Grassland ($n = 10$)	2, 5, 11, 12, 15, 18, 31, 32, 36, 45
	Farmland ($n = 7$)	3, 6, 19, 24, 33, 41, 44
Site	Zhuanyagou catchment ($n = 4$), MAP = 406 mm	1, 2, 3, 4
	Jiuyangou catchment ($n = 4$), MAP = 415 mm	5, 6, 7, 8
	Liudaogou catchment ($n = 5$), MAP = 430 mm	9, 10, 11, 12, 13
	Pingqiaozhen ($n = 3$), MAP = 436 mm	14, 15, 16
	Wangjiagou catchment ($n = 3$), MAP = 460 mm	17, 18, 19
	Maliantan ($n = 5$), MAP = 488 mm	20, 21, 22, 23, 24
	Yangou catchment ($n = 5$), MAP = 520 mm	25, 26, 27, 28, 29
	Yangjuangou catchment ($n = 5$), MAP = 535 mm	30, 31, 32, 33, 34
	Zhifanggou catchment ($n = 3$), MAP = 550 mm	35, 36, 37
	Renjiatai ($n = 4$), MAP = 560 mm	38, 39, 40, 41
	Zhaojiayuan ($n = 4$), MAP = 624 mm	42, 43, 44, 45

MAP, mean annual precipitation.

Figure 2. Vertical profiles of soil moisture at 45 sampling points (black points represent the woodland, red points represent the shrubland, green points represent the grassland and blue points represent the farmland). MAP, mean annual precipitation. [Colour figure can be viewed at wileyonlinelibrary.com]

use type varied with the MAP gradient. The slope of regression equation between soil moisture and MAP indicated how the soil moisture varied with the precipitation gradient. The soil moisture under shrubland in 0–100 cm increased most with MAP increasing, and the grassland increased most with MAP increasing in 100–200 and 200–300 cm compared with other land use types. In addition, the average soil moisture also revealed significant linear correlation with MAP for each land use type ($p < 0.01$ for woodland and grassland; $p < 0.05$ for shrubland and grassland).

The comparisons among soil moisture at each site were shown in Figure 5. Results showed that the soil moisture in the surface layer (0–100 cm) under each land use types along the precipitation gradient did not reveal a consistent trend. In the middle layer (100–200 cm) and deep layer (200–300 cm), the soil moisture under each land use type basically revealed the common trend as farmland > grassland > shrubland > woodland. The soil field capacity and permanent wilting point were compared with the soil moisture at the sites along the precipitation (Figure 5).

Figure 3. Statistical parameters of soil moisture content at 45 sampling points in the catchments across the Loess Plateau. [Colour figure can be viewed at wileyonlinelibrary.com]

Results showed that the soil moisture monitored in this study mostly ranged from the permanent wilting point to field capacity across the transect, while some exceeded this range. In the surface layer (0–100 cm), the soil moisture of shrubland and woodland was approximate to or below the permanent wilting point at the sites with MAP <480 mm. In the middle layer (100–200 cm) and deep layer (200–300 cm), the soil moisture of shrubland and woodland was approximate to or below the permanent wilting point at the sites with MAP <520 mm.

Effects of Land Use and Precipitation on Soil Moisture Content

In order to illuminate the effects of land use and precipitation on the soil moisture across the transect, the effects of terrain factors were first examined. The sampling points were divided into three groups to examine the effects of slope aspect, slope degree and slope positions on the soil moisture, respectively (Table S1). The paired sample *t*-test results showed there were no significant differences in soil moisture in each layer between shady and sunny lands, between steep and gentle slopes, and between higher and lower slope positions, respectively. These results indicated the slope aspect, slope degree and slope positions did not play a significant role on the soil moisture at selected sites across the transect.

Thus, the effects of land use and precipitation were examined through analysis of covariance (Table II). Results revealed that in the surface layer (0–100 cm) the MAP had significant effects on the soil moisture ($p < 0.01$), while land use did not reveal significant effects, which might be explained that various factors affect the surface soil moisture and they revealed large spatio-temporal variability. In the middle layer (100–200 cm) and deep layer (200–300 cm), both the MAP and land use had significant effects on the soil moisture ($p < 0.01$).

DISCUSSION

Vertical Features of Soil Moisture along the Transect

In this study, the vertical profiles of soil moisture variations in Yangjuangou catchment (MAP=535 mm) revealed a consistent increasing trend, while those in Maliantan catchment (MAP=488 mm) revealed a consistent decreasing trend, despite the order of soil moisture under each land use type remains consistent. The soil moisture under *Caragana korshinskii* was also found to decrease with the soil depth in the 470- to 500-mm precipitation zone (Liu *et al.*, 2016). This could be explained that some other factors might play important roles, although the land use still affects the vertical profiles of soil moisture. Previous studies have indicated that the vertical profiles of soil moisture might decrease with the vegetation growth (Wang, 2010). The growth age of the introduced vegetation in Yangjuangou catchment was no more than 15 years, which is shorter than that in Maliantan catchment (about 20–30 years). In addition, it might also be related to the rooting depth and distribution in the two sites. Wang *et al.* (2010b) found that significant correlation relationships between root indices and soil moisture within the profiles, and the root indices varied with vegetation type and ages of vegetation. The soil moisture profiles in the surface layer revealed greater variations compared with deep layers, which was also consistent with recent study on the spatial variations of soil moisture under *C. korshinskii* (Liu *et al.*, 2016). A number of factors could contribute to the large variability in the profile of soil moisture in the surface layer, including surface evaporation, transpiration from shallow-rooted vegetation and the precipitation recharge. Soil evaporation from soil is generally constrained to the surface soil layer (Suleiman & Ritchie, 2003) and is affected by canopy cover and soil temperature differences because of the vegetation cover changing. Another key effect of vegetation on surface soil moisture is transpiration from the soil profile (Western *et al.*, 1999), as the fine root systems of introduced vegetation in the Loess Plateau were mainly distributed in shallow layers (Yang *et al.*, 2014b), while the root system distribution pattern in the surface layer varied with the vegetation types. Land cover changes would also affect the water recharge to soil and surface water (Wang *et al.*, 2011a). These mentioned factors contribute to the large variability of the soil moisture profiles in the surface layer. The smaller variations in deep layer soil moisture might be more affected by the land use. Dynamic monitoring and soil sampling in the

Figure 4. The soil moisture variation with the precipitation gradient at different depths under each land use type. [Colour figure can be viewed at wileyonlinelibrary.com]

catchments have proved that the soil moisture in the layer below 100 cm was not affected by the frequent light rains in the Loess Plateau (Yang *et al.*, 2012). The underground water also did not affect the soil moisture because of the deep loess soil. The soil moisture is temporally stable in the deep layer, and the variations in the deep soil layer were mainly caused by the land cover types changing with different water consumptions. The introduced vegetation has deep roots, for example, the roots of *C. korshinskii*, which could reach 640 cm (Wang *et al.*, 2010b), while the rain infiltration depth was found to be 200 cm in the drought year and 300 cm in the rainy year (Chen *et al.*, 2008). Thus, effects of precipitation on the deep layer soil moisture were secondary compared with the land use, especially in the lowest layer (2–3 m). The K value was introduced to reflect the vertical variations of the soil moisture in each sampling points; the results showed that the grassland or farmland located in the relatively humid and arid regions would probably reveal increasing trends, while the woodland or shrubland located in transition zones between these regions mentioned earlier would probably reveal decreasing trends. The grassland and farmland mainly consume the soil moisture in the surface layer because of their root systems, even in the relatively arid regions. It is reasonable that woodland and shrubland would probably reveal decreasing trends because of their deep root systems. Why the woodland or shrubland did not reveal obvious decreasing trends in the relatively arid regions? In the relatively arid regions, the soil moisture

content from surface to deep layers was low and has limited water for vegetation absorption. Meanwhile, the soil evaporation in the arid areas posed obvious effects on the surface soil moisture. Thus, the deep soil moisture might be higher than the surface soil moisture. In addition, the root distribution would also influence the soil moisture trend in the profile, as significant correlation relationships exist between root indices and soil moisture within the profiles (Wang *et al.*, 2010b).

Controls of Land Use and Precipitation on Soil Moisture at Regional Scale

Significant linear correlation existed between soil moisture of the profile and the MAP for each land use type, which indicated that the soil moisture under different land use types varied with the precipitation gradient in varying degrees. Analysis of covariance confirmed the significant effects of land use and MAP on the soil moisture across the transect, while the land use did not pose significant effects on the soil moisture in the surface layer. Soil moisture in the surface layer was affected by various factors, including rainfall infiltration, evapotranspiration, land cover, topographic features and soil properties (Ferreira *et al.*, 2007; Qiu *et al.*, 2001; Western *et al.*, 1999). In addition, these factors revealed large spatio-temporal variability across the transect in the Loess Plateau. The effects of these factors on the soil moisture would decrease with the soil profile, while the soil

Figure 5. Comparisons of soil moisture under each land use type at each site along the precipitation gradient. [Colour figure can be viewed at wileyonlinelibrary.com]

moisture in the deep layer was more affected by land use because of the root systems. Thus, the effects of land use on the surface soil moisture were not significant compared with the deep layer. On the other hand, the unsaturated soil layer is deep and groundwater is located at a depth of 50–200 m below the soil surface in the Loess Plateau (Chen *et al.*, 2008). Rainfall infiltration is the only source of water for the soil in the Loess Plateau, and the recharge depth by the precipitation was in the 0- to 100-cm depth (Yang *et al.*, 2014a). The precipitation varied greatly across the transect in the Loess Plateau at large scale; it is reasonable that the effects of precipitation on the surface soil moisture were dominant. It is noted that the precipitation effects on surface

soil moisture were dominant at large scale, while land use effects were still dominant at small scale. The effects of land use on the soil moisture in the deep layers have been proved in previous studies in small catchments on the Loess Plateau (Zeng *et al.*, 2011; Zhang *et al.*, 2012). Land use also had a direct effect on the hydrological processes despite the strong influences of climate (Campos *et al.*, 2014; Cerdà, 1998a; Cerdà, 1998b; Choudhury *et al.*, 2015; Vasconcellos *et al.*, 2016). Root water uptake was as an important process controlling soil moisture dynamic in the Loess Plateau (Yang *et al.*, 2014a). The woodland and shrubland sampling points selected in this study were mainly covered by introduced vegetation with root systems mainly distributed in shallow layers; however, all types of introduced vegetation have deep root systems below the precipitation infiltration depth and could consume more deep soil moisture than farmland and grassland (Chen *et al.*, 2010; Yang *et al.*, 2014b). The root system of maize crop in the farmland could only reach approximately 100 cm, which is shallower than that in grassland and woodland (Wang & Jiao, 2011). Wang *et al.* (2010b) found that the roots of soybean and *Stipa bubeana* were mainly distributed in the 0–100 cm and the roots of *C. korshinskii* could extend to 640 cm. Wang *et al.* (2011b) found that the formation depth of dried soil layer under the *Robinia pseudoscacia* was at 100 cm below the soil surface and its thickness was 491 cm, and the formation depth of

Table II. Summary of analysis of covariance results for the soil moisture in each layer in relation to MAP and land use type

Source of variations	Soil moisture (0–100 cm)	Soil moisture (100–200 cm)	Soil moisture (200–300 cm)
MAP	<0.001	<0.001	<0.001
Land use	0.86	<0.001	<0.001
MAP × land use	0.924	0.43	0.691

MAP, mean annual precipitation.

dried soil layer under the *C. korshinskii* was at 162 cm below the soil surface and its thickness was 294 cm, which also indicted a larger impacts at deeper layer exerted by the introduced vegetation. The excessive depletion of soil water by the deep root system without sufficient precipitation infiltration results in the lower level of deep soil moisture under the woodland and shrubland (Yang *et al.*, 2014a). The amount of precipitation infiltrating is distinct under different land use types because of the crown interception; the amount of precipitation infiltrating woodland is lower than the amount infiltrating shrubland, artificial grassland (Yu *et al.*, 2015). In addition, the difference in leaf area index in different land use types would also cause the difference in soil water consumption (Wang *et al.*, 2013b). The precipitation and land use affect the source and consumption of the soil moisture, which further affect the soil moisture variability.

Implications for the Restoration Strategy

The large-scale vegetation restoration projects were implemented in the Loess Plateau to control soil and water loss, while their dire challenges remain to be confronted. No guidance for plant species selection for the restoration purpose virtually existed (Chen *et al.*, 2010). Our results showed that the middle and deep layer soil moisture of shrubland/woodland was approximate to or below the permanent wilting point at the sites with MAP <520 mm, which further indicated that the restoration approaches might exacerbate soil moisture deficits and result in serious soil desiccation, and a reduction in vegetation carrying capacity (Wang *et al.*, 2010b). Although the soil moisture could be replenished by rainfall during rainy season, the effective influence depth of light rainfalls on soil moisture did not exceed 60 cm (Li *et al.*, 2006), the soil moisture below 100 cm has been proved fairly stable in case of no heavy or continuous rains (Li *et al.*, 2006; Wang *et al.*, 2010a) and the soil moisture below 200 cm might be unchanged for many years in the Loess Plateau (Wang *et al.*, 2009; Yao *et al.*, 2012). Then, we might speculate that the soil moisture below 200 cm could hardly be replenished by rainfall during rainy seasons in the Loess Plateau. Thus, we could conclude that the soil moisture of deep layer (200–300 cm) under woodland/shrubland below or approximate to the permanent wilting point is non-sustainable with regard to soil water availability, and it is necessary to reconsider the selection of restoration vegetation cover type in the restoration project. In the perspective of vegetation sustainability and soil water availability, our results indicate that the large-scale woodland/shrubland might not be the optimal solution to the vegetation restoration in the regions with MAP <520 mm in the Loess Plateau, and drastic measures should be taken to monitor and retain soil moisture. The precipitation gradient played significant roles in the eco-geomorphological processes (Ruiz Sinoga *et al.*, 2010), and vegetation cover and type are associated with the precipitation gradient. Through soil–vegetation interaction, vegetation affects the infiltration rates and water holding

capacity (Ruiz Sinoga *et al.*, 2010); thus, soil moisture under different vegetation types would reveal great variations along the profile. In this study, the incidence of the precipitation gradient threshold was detected at MAP = 520 mm for woodland/shrubland. Related studies found that dwarfed trees have occurred throughout the reforestation regions with MAP <400 mm in the Loess Plateau (Cao *et al.*, 2011; McVicar *et al.*, 2010), which also confirmed the negative effects in the large-scale afforestation. Vegetation restoration is a complex issue, relating to many aspects, especially in the Loess Plateau. Actually, many studies have focused on the unintended environmental, ecological and socio-economic consequences in the current vegetation restoration (Cao *et al.*, 2011; Hu & Shao, 2002), and our results at least lead to the reflection on the current vegetation restoration. The policy should convert from forest–shrub-based approach to evidence-based approach (Cao *et al.*, 2011). Further study should focus on the influence of spatial patterns of land use types and long-term vegetation restoration on soil moisture dynamics.

CONCLUSIONS

The vertical profiles of soil moisture across the transect revealed large variations, especially in the surface layer (0–100 cm). There was significant linear correlation between the soil moisture and MAP for each land use type, and the soil moisture under the grassland was affected more greatly by the precipitation compared with other land use types. The soil moisture under each land use type generally revealed the common trend as farmland > grassland > shrubland > woodland, while the soil moisture in the surface layer did not reveal this consistent trend. In addition, the soil moisture of shrubland and woodland at the selected sites was approximate to or below the permanent wilting point in regions with MAP <520 mm. The effects of MAP and land use on the soil moisture across the transect were confirmed by the analysis of covariance ($p < 0.01$), while the land use posed no significant effects on the soil moisture in the surface layer. The results provided new information and held implications for the restoration that the woodland/shrubland is non-sustainable with regard to soil water availability and might not be the optimal solution to the current vegetation restoration in the arid and semi-arid regions in the Loess Plateau. Understanding the soil moisture variation characteristics under different land use types along the precipitation gradient in individual layers would help with the sustainable land use and water management in the Loess Plateau.

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