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Comparison of deep soil moisture in two re-vegetation watersheds in semi-arid regions

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SUMMARY

Soil moisture stored below rainfall infiltration depth is a reliable water resource for plant growth in semi-arid ecosystems. Along with the large-scale ecological restoration in Chinese Loess Plateau, identifying the ecohydrological response to human-introduced vegetation restoration has become an important issue in current research. In this study, soil moisture data in depth of 0–5 m was obtained by field observation and geostatistical method in two neighboring re-vegetation watersheds. Profile characteristics and spatial pattern of soil moisture was compared between different land use types, transects, and watersheds. The results showed that: (1) Introduced vegetation drastically decreased deep soil moisture when compared with farmland and native grassland. No significant differences in deep soil moisture were found between different introduced vegetation types. (2) An analysis of differences in soil moisture for different land use patterns indicated that land use had significant influence on deep soil moisture spatial variability. Land use structure determined the soil moisture condition and its spatial variation. (3) Vegetation restoration with introduced plants diminished the spatial heterogeneity of deep soil moisture on watershed scale. The improvement of land use management was suggested to improve the water management and maintain the sustainability of vegetation restoration.

1. Introduction

Soil moisture is one of the primary limiting factors for plant growth in semi-arid regions. It also plays critical roles in many terrestrial ecosystem processes (Legates et al., 2011; Porporato et al., 2002). Soil moisture exhibits a tremendous heterogeneity in space and time even in small watersheds (Gómez-Plaza et al., 2001; Western et al., 2004). Characterizing soil moisture variations across a range of spatial and temporal scales is important for both theoretical and practical applications on runoff, soil erosion, agriculture, and ecological restoration.

Scientific literatures indicated that soil moisture on watershed scale was affected by dozens of environmental factors, such as land use/vegetation, topographic factors, soil properties, and others (Brocca et al., 2007; Cantón et al., 2004; Gómez-Plaza et al., 2000). Among these factors, soil properties and topography can be considered relatively constant in short term, while land use and climate are the dominant variables (Montenegro and Ragab, 2012; Wei et al., 2009). In fact, land use can disrupt the surface water balance and the partitioning of precipitation into evapotranspiration, runoff, and groundwater flow (Foley et al., 2005; Sun et al., 2006; Vose et al., 2011; Shi et al., 2013). Land use/vegetation controls the soil moisture distribution pattern in many ecosystems (Ferreira et al., 2007; Vivoni et al., 2008). On the other hand, soil moisture in different depth may have different response to influencing factors (Meerveld and McDonnell, 2006; Venkatesh et al., 2011).

Soil moisture stored in deep layers (below annual rainfall infiltration depth, usually below 1–2 m) is a reliable water resource for plant growth in semi-arid regions (Ferreira et al., 2007). Specifically, because of the thick loess soil (nearly 100 m in thickness) and loose soil structure (Mu et al., 2003), nearly little groundwater in Chinese Loess Plateau can be used by plants. Because of this reason, deep soil moisture has become an important water source for this region (Yang et al., 2012). Due to the large-scale implementation of "Grain to Green Program" initiated by central government since 1999, introduced vegetation has become the main vegetation type for the purpose of decreasing serious soil erosion in this region (Chen et al., 2010). However, introduced vegetation usually consumes more soil moisture than native plants and cannot obtain sufficient water for its growth due to limited rainfall amount. These plants are forced to develop deep root system to utilize deep soil moisture (Chen et al., 2008a). Recent studies have found that introduced vegetation in this area affect lots of hydrological processes

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and ecosystem services (Chen et al., 2008b; Liu et al., 2008), such as decreasing deep soil moisture, changing the spatial pattern of deep soil moisture, decreasing the potential water yield production.

The correlations between land use and surface soil moisture variability have been identified by previous studies in loess regions (Fu et al., 2003; Qiu et al., 2001). Since the functions of deep soil moisture on local ecosystems in Loess Plateau were realized in last decades, the influence of land use/land cover change on deep soil moisture was highlighted in recent studies. For example, Wang et al. (2011b) found that land use have significant influence on deep soil desiccation on regional scale. However, the relationships between land use structure and deep soil moisture are poorly documented in literatures. Thus, it is urgent to evaluate the influence of vegetation restoration on deep soil moisture variability in this area. The objectives of this study are: (1) to compare the soil moisture content in different soil layers between different land use patterns; (2) to find the relation between land use structure and soil moisture variability; (3) to elucidate the response of spatial variation in soil moisture to human-introduced vegetation restoration.

2. Material and methods

2.1. Study area

Two neighboring small watersheds, Lijiawan and Jianzicha (35°43′–35°44′N, 104°28′–104°29′E), which are located in the western Loess Plateau, covers an area of 0.94 km^2 and 0.30 km^2 (Fig. 1), respectively. The altitude of the two watersheds range from 1937 m to 2151 m, with a highly fragmented landscape. They belong to typical semi-arid loess hilly region, with mean annual temperature of approximately 6.8 °C and mean annual precipitation of 386 mm. Most rainfall occurs in the form of thunderstorms during the summer months from July to September. The potential annual evaporation (pan evaporation) is about 1649 mm. These annual averages were derived from data provided by a meteorological station which is located 0.6 km from the watersheds and represent 45-year averages (1961–2006). The rainfall pattern had a uniform spatial distribution in two watersheds based on five spatially distributed auto-recording rain gauges in or near the two watersheds during 2008–2013 periods. Soil types in the study area are mainly composed of loess soil with low fertility and are vulnerable to soil erosion. Soil thickness varies from 40 to 60 m. The basic properties of this soil are a loose structure, high silt content (ca. 81%), soil moisture field capacity (0.180–0.240 g/g), and low organic matter content (ca. 0.2–2.9%). The wilting point in study area is 0.054 g/g (Chen et al., 2010). The predominant land use types are rain-fed farmland, pasture grassland, shrubland, forestland, and native grassland. Land use structures of the two watersheds were shown in Table 1. The introduced vegetation types are alfalfa (*Medicago Sativa*), korshinsk peashrub (*Caranana korshinskii*), Siberian apricot (*Armeniaca sibirica* (L.) Lam.), and other varieties. In this semi-arid area, water shortages threaten economic development, sustainable human livelihoods, and environmental quality.

2.2. Observation and analysis

2.2.1. Experimental site designs

The native grassland, farmland (including farmland and abandoned farmland), re-vegetation lands (including pasture grassland, shurbland, and forestland) were selected in this study. Native grassland is the dominant community of native species in this region. The main species are native grasses and herbs with low water demands, including bunge needlegrass, common leymus, altai heterpappus, and others. The soil moisture profile in native grassland was used as the reference to present no human impact in study area. The farmland was planted with annual crops in a potato-corn rotation system. Crops were sown in April and harvested manually at the end of September or beginning of October. Because all the pasture grasses, shrubs, and trees were initially planted on farmland. The soil moisture in farmland can be considered as the reference value representing soil moisture conditions before vegetation restoration. Abandoned farmland has been fallowed since 2002, and has plant species of native grasses and herbs with low water demands. The re-vegetation lands were converted from farmland and planted with introduced vegetation types. In study area, pasture grassland was planted with alfalfa in 2002 after the initiation of the "Grain-for-Green Program". Alfalfa is cut only once in rainfall-deficit year or cut twice in rainfall-rich years. The shrubland was planted with korshinsk peashrubs in 1984 with a planting density of 2.2×10^5 plants/km^2. The forestland was planted with Chinese arborvitae trees in Lijiawan watershed with a density of 1.9×10^5 plants/km^2 in 1985, and Siberian apricot trees in Jianzicha watershed with a density of 1.9×10^5 plants/km^2 in 1982.

Eight typical transects in Lijiawan watershed and seven typical transects in Jianzicha watershed were selected to investigate soil moisture variations. 3–5 experimental sites were located on each transect from hillslope top to bottom according to land use type and hillslope length. Experimental sites on each transect have similar slope gradient and slope aspect with a distance of 30–100 m between each other (Fig. 1). The soil properties are generally homogeneous in the two small watersheds. 32 experimental sites and 26 experimental sites in total were selected in Lijiawan watershed and Jianzicha watershed, respectively. The latitude, longitude and elevation were determined for each experimental site using a Garmin GPS60.

2.2.2. Soil moisture data collection

In August 2013, soil moisture content in 0–5 m layers was measured at each experimental site. At each experimental site, three sampling profiles were randomly chosen to obtain the average soil moisture content. Soil samples in depth of 0–5 m were taken by a drill (5 cm in diameter) with 20-cm increment. A total of 25 soil samples were collected from each sampling profile. When the soil samples were taken out, the soil samples were sealed immediately in airtight aluminum cylinders and brought to the laboratory for determination of gravimetrically soil moisture content (unit: g/g). The soil moisture content was determined using the oven-dry method (24 h at 105 °C). All the field sampling and laboratory work were completed in 5 days.

Soil moisture content was interpolated by the inverse distance weighted approach (IDW) to produce the spatial distribution map in different layers in two watersheds. The ArcGIS®10.2 (ESRI Inc., USA) was used to perform IDW analyses and to produce soil moisture distribution maps. Basic statistics on interpolated soil moisture content based on IDW method were conducted by spatial analyst tools in ArcGIS.

2.3. Statistical methods

The soil moisture content and profile distribution of each watershed were calculated by taking the mean value of all experimental sites in each soil layer. The depth-averaged soil moisture content for each experimental site (θ_{ij}) was calculated by Eq. (1)

$$\theta_{ij} = \frac{1}{i}\sum_{i=1}^{i}\theta_i \quad (1)$$

where i is the number of measurement layers at site j, and θ_i is the mean soil moisture content in layer i calculated by three random sampling profiles. In the following section, the soil moisture content was calculated for every meter, and the j = 5.

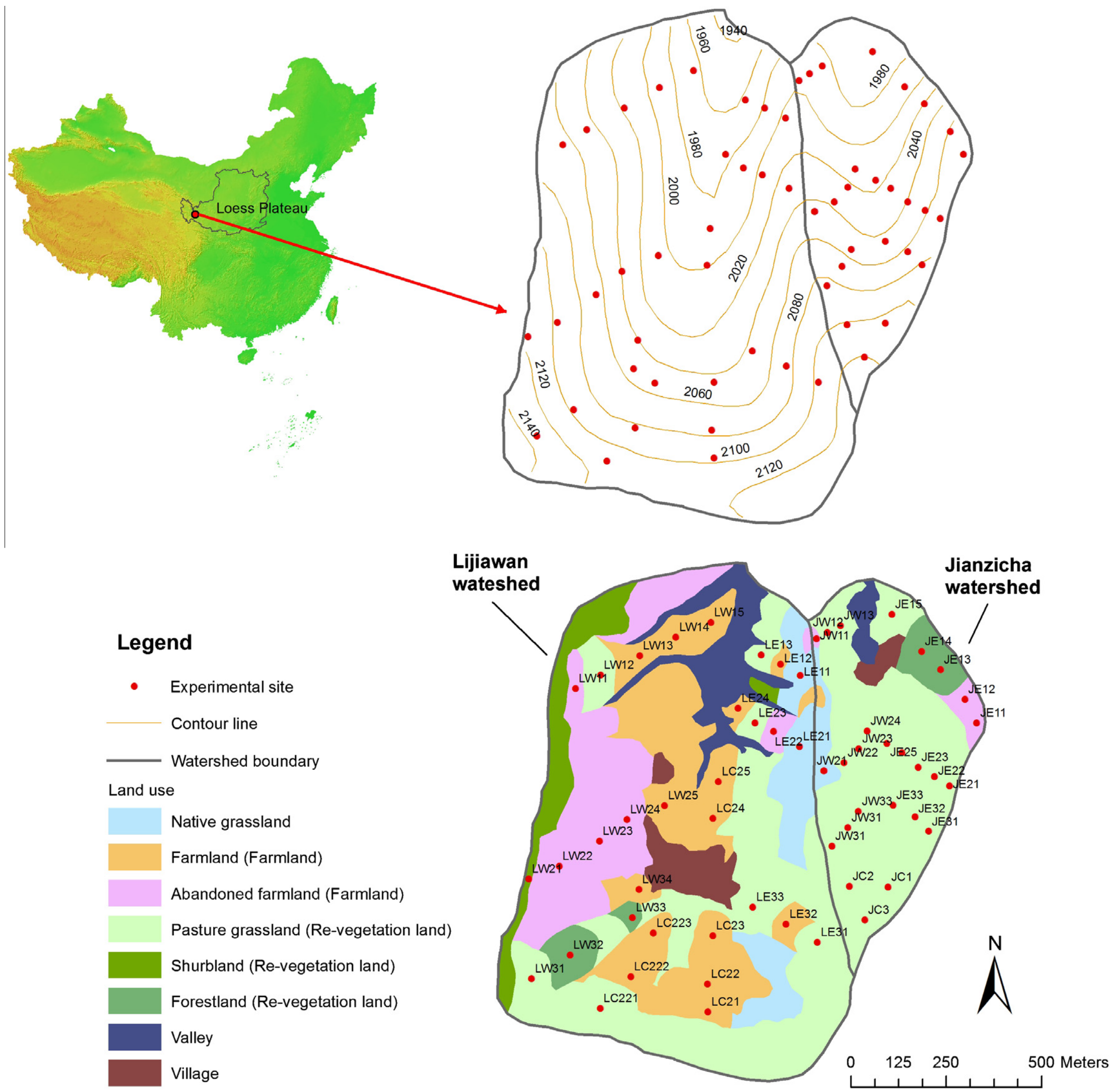

Fig. 1. Location of the study area and experimental sites in two watersheds.

Table 1
Land use structures of the two watersheds.

Land use	Sub-land use	Lijiawan watershed		Jianzicha watershed	
		Area (ha)	Percentage	Area (ha)	Percentage
Native grassland	Native grassland	7.5	8.0	1.3	4.2
Farmland	Farmland	22.8	24.3	0.1	0.4
	Abandoned farmland	16.4	17.5	1.2	3.9
Re-vegetation land	Pasture grassland	29.0	29.0	23.3	77.5
	Shrubland	5.9	6.3	N/A	N/A
	Forestland	2.1	2.2	2.2	7.5
Valley	Valley	6.7	7.1	1.2	3.9
Village	Village	3.5	3.7	0.8	2.8
	Total area	93.9		30.0	

The depth-averaged soil moisture content (θ_m) for each land use type was calculated by Eq. (2)

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

where k is the number of experimental sites for each land use type.

Basic population statistics data, such as mean values (mean), standard deviations (std), and coefficient of variation (cv) were reported for each measurement. One-way ANOVA was used to assess the contribution of different land use types to the overall variation in the soil moisture variables. Multiple comparisons were made using the least significant difference (LSD) method. The SPSS® (Version 18.0) was used for all of the statistical analyses.

3. Results

3.1. Profile distribution of soil moisture in two watersheds

Obvious difference in soil moisture content below 1.0 m between the two watersheds can be found in Fig. 2. The depth-averaged soil moisture content in Lijiawan watershed was 0.087 g/g in layers of 2–5 m, while the value in Jianzicha watershed was 0.064 g/g. Compared with Jianzicha, depth-averaged soil moisture content in Lijiawan was approximately 36% higher than that of Jianzicha in layers below 2 m. Standard deviation of soil moisture can reflect the degree of spatial variability of soil moisture in different layers. The standard deviation indicated that soil moisture in Lijiawan watershed had relatively higher spatial variability than Jianzicha watershed (Fig. 2).

3.2. Soil moisture in different land use types

Generally, soil moisture at comparable soil depths was lower in re-vegetation lands (pasture grassland, shrub land and forestland) as compared with native grassland, and farmland (farmland, and abandoned farmland) in both watersheds (Fig. 3 and Table 2). The farmland (0.099–0.120 g/g) had the highest soil moisture content in Lijiawan watershed. The LSD-test indicated that soil moisture content in farmland was significant higher than that in other land use types ($P < 0.05$, Table 2). Soil moisture in abandoned farmland had a relatively higher value than re-vegetation lands but lower than farmland in the entire 0–5 m soil profiles in two watersheds. Soil moisture varied from 0.058 g/g to 0.067 g/g in pasture grassland, and 0.060–0.074 g/g in shrubland and 0.054–0.069 g/g in forestland in layers of 2–5 m in two watersheds. The LSD-test indicated that soil moisture content in re-vegetation lands was significant lower than that in native grassland, farmland, and abandoned farmland in depth below 2 m. Furthermore, no significant differences in deep soil moisture (soil moisture below 2 m) were found between different re-vegetation lands ($P < 0.05$, Table 2).

3.3. Comparison of soil moisture between different transects

In this present study, we focused on deep soil moisture in depth below 2 m. Fig. 4 shows the changes in depth-averaged soil moisture content (2–5 m) for different land use structures. As has been discussed by previous studies (Yang et al., 2012), deep soil moisture presented a stable decreasing trend from the top to bottom of hillslope on single land use structure (Fig. 4a). This was because introduced vegetation on hillslope bottom usually had relatively higher biomass and consumed more deep soil moisture than upper

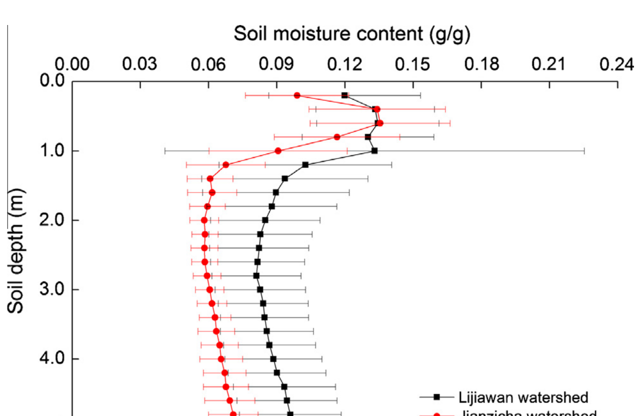

Fig. 2. Profile distribution of mean soil moisture content in two watersheds. *Note:* error bar indicates standard deviation.

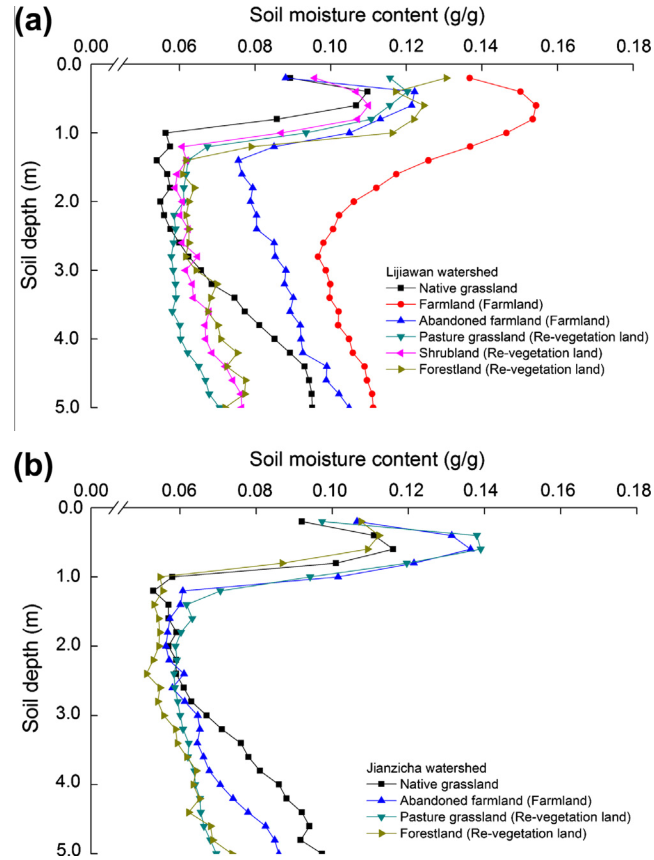

Fig. 3. Soil moisture in different land use types in two watersheds (a) Lijiawan watershed and (b) Jianzicha watershed.

hillslopes (Yang et al., 2012). Because re-vegetation lands usually had significantly ($P < 0.05$) lower soil moisture than farmland and abandoned farmland, the experimental sites covered with introduced vegetation usually have relatively lower values. The relatively higher values on each transect appeared on experimental sites covered with farmland or abandoned farmland. This indicated that the land use determined the deep soil moisture pattern on hillslope scale. For example, pasture grassland in LW1 and LC2 transects induced an obviously low value (0.064 g/g in LW1, and 0.065 g/g in LC2) in Fig. 4b, while the mean soil moisture content on each transect was 0.094 g/g and 0.091 g/g, respectively. In the land use structure of native grassland/pasture grassland–farmland–pasture grassland (LE1 and LE3 transect), peak value of soil moisture content (0.111 g/g and 0.126 g/g) appeared on middle position which covered with farmland (Fig. 4c).

3.4. Spatial distribution of soil moisture in different layers

The spatial distribution of soil moisture in five different layers was shown in Fig. 5, and the basic statistics were shown in Table 3. The spatial distribution of soil moisture was closely related to land use pattern, in that high soil moisture content usually corresponded to farmland and abandoned farmland. Furthermore, relatively lower soil moisture content was closely related to pasture grassland, shrubland, and forestland in depth below 1 m (Fig. 5b–e). It was clear that soil moisture spatial distribution characteristic was similar with each soil layer across the land use types.

Compared with Lijiawan watershed, soil moisture in Jianzicha watershed had obviously lower values in different soil layers based on IDW. This was corresponding to field observation (Fig. 2). On the other hand, the standard deviation and coefficient variation in soil moisture content indicated that after the implementation of "Grain

Table 2
Soil moisture of 0–5 m soil layers in different land use types.

Land use	Soil depth (m)	Native grassland		Farmland				Re-vegetation lands					
		Native grassland g/g	std	Farmland g/g	std	Abandoned farmland g/g	std	Pasture grassland g/g	std	Shrubland g/g	Forestland g/g	std
Lijiawan watershed	0–1	0.090a*	0.007	0.148b	0.022	0.110c	0.022	0.111c	0.023	0.101ac	0.122c	0.013
	1–2	0.056ac	0.001	0.120b	0.023	0.079d	0.011	0.063c	0.007	0.060c	0.066cd	0.002
	2–3	0.060a	0.001	0.099b	0.012	0.084c	0.015	0.058a	0.005	0.061a	0.063a	0.002
	3–4	0.077a	0.002	0.102b	0.011	0.090e	0.016	0.059c	0.003	0.066cd	0.069ad	0.001
	4–5	0.093a	0.002	0.109b	0.015	0.099a	0.019	0.067c	0.005	0.074c	0.075c	0.002
Jianzicha watershed	0–1	0.096ac				0.119ac	0.011	0.118bc	0.029		0.094a	0.019
	1–2	0.057ac				0.058ac	0.002	0.063bc	0.011		0.055a	0.002
	2–3	0.062a				0.060a	0.006	0.059a	0.006		0.054b	0.001
	3–4	0.078c				0.067a	0.008	0.063bd	0.007		0.062ad	0.002
	4–5	0.093c				0.081a	0.010	0.067b	0.009		0.068b	0.001

* Means with the same letter in the same row are not significantly different at the 0.05 level (LSD rest, 0.05); std represents standard deviation.

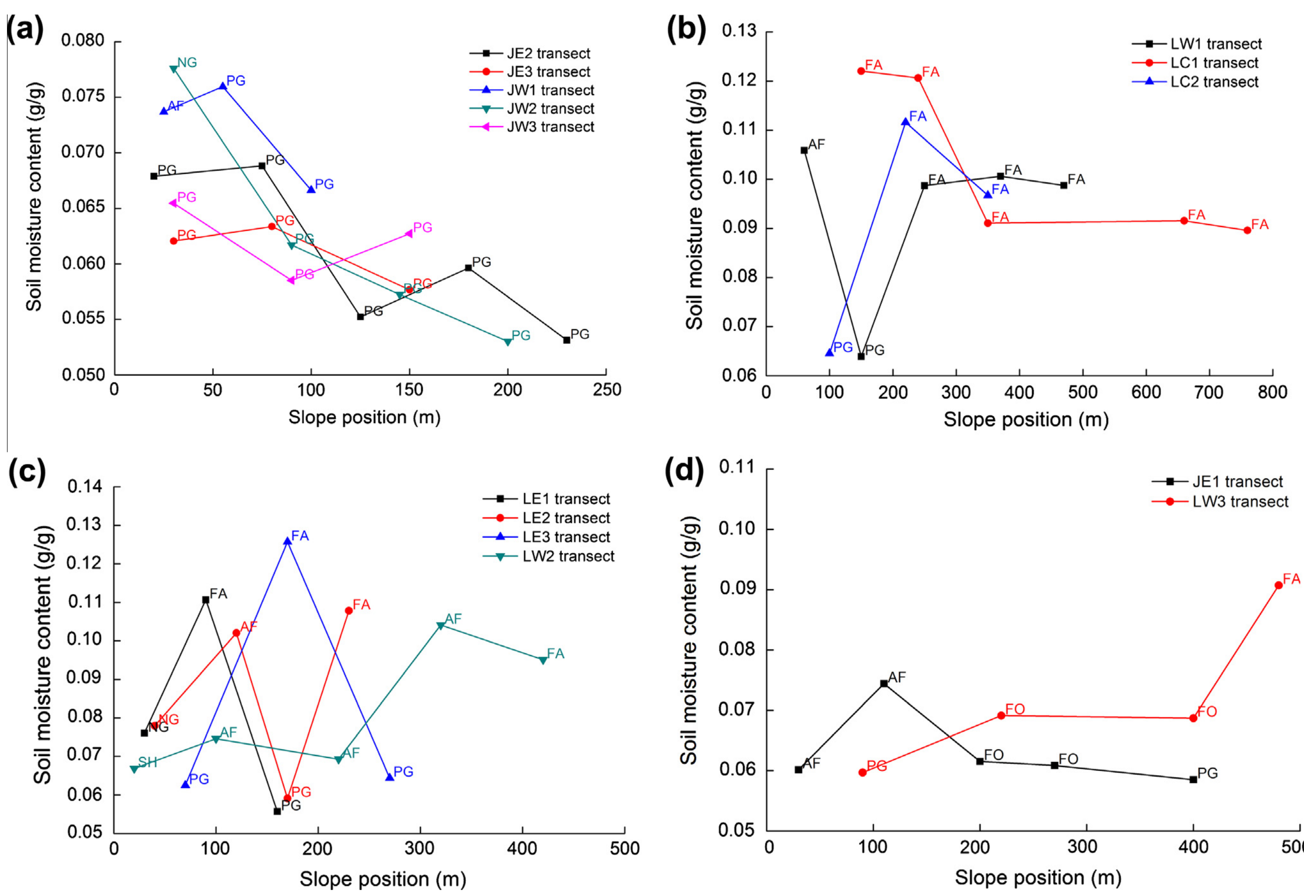

Fig. 4. The distribution of depth-averaged soil moisture content (2–5 m) on different land use structures. *Note:* NG represents native grassland, FA represents farmland, AF represents abandoned farmland, PG represents pasture grassland, SH represent shrubland, and FO represents forestland.

for Green Program", the soil moisture content in Jianzicha watershed had relatively lower spatial heterogeneity than that in Lijiawan watershed (Table 3). This was especially true in deeper soil layers. The coefficient of variation of soil moisture in depth below 2–5 m was 6.8–9.4% in Jianzicha watershed, while the values ranged from 11.8% to 14.6% in Lijiawan watershed.

4. Discussion

4.1. Vertical distribution characteristics of soil moisture in the Loess Plateau

The experimental sites selected in this study were near to each other, which were affected by unique spatial distributed precipitation. In semi-arid areas, soil moisture varies seasonally and inter-annually in shallow layers depending on precipitation. Compared with topsoil, temporal dynamics in deeper soil layers were diminished due to less rainfall infiltration and root water uptake (Rosenbaum et al., 2012). Due to the thickness of loess covered on the Loess Plateau, vertical distribution and temporal variations of deep soil moisture differ from shallow soil moisture (Chen et al., 2008b; Wang et al., 2009; Yang et al., 2012). The soil moisture content below rainfall infiltration depth was relatively stable than shallow layers in re-vegetation lands in loess regions. For example, Wang et al. (2009) found that no significant difference in deep soil moisture (below 2 m) occurred based 6 years of observation in the Loess Plateau. In fact, annual rainfall infiltration depth in re-vegetation lands can hardly reach 1 m in the study area and soil

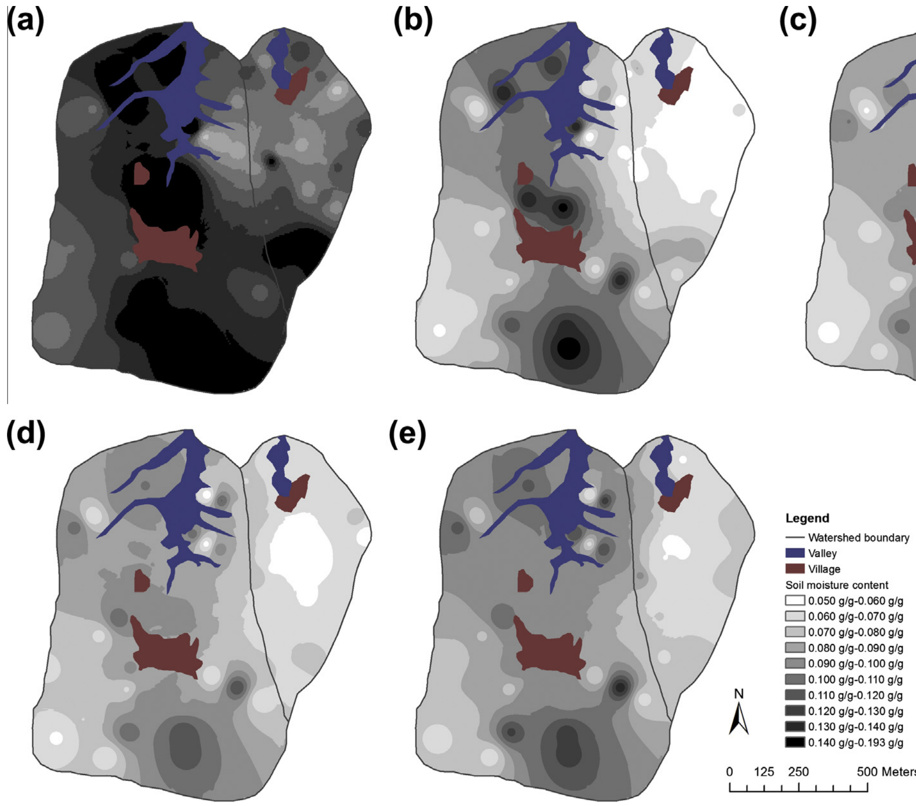

Fig. 5. Soil moisture content interpolated by the IDW method in different soil depth. (a) 0–1 m, (b) 1–2 m, (c) 2–3 m, (d) 3–4 m, and (e) 4–5 m.

Table 3
Basic statistics on soil moisture content in two watersheds based on IDW.

Soil depth (m)	Lijiawan watershed					Jianzicha watershed				
	Min g/g	Max g/g	Mean g/g	std	cv (%)	Min g/g	Max g/g	Mean g/g	std	cv (%)
0–1	0.077	0.179	0.131	0.014	10.7	0.076	0.193	0.114	0.018	15.8
1–2	0.052	0.152	0.093	0.018	19.4	0.050	0.088	0.062	0.008	12.9
2–3	0.052	0.124	0.082	0.012	14.6	0.050	0.073	0.059	0.004	6.8
3–4	0.055	0.120	0.086	0.011	12.8	0.051	0.078	0.064	0.005	7.5
4–5	0.060	0.136	0.093	0.011	11.8	0.056	0.093	0.070	0.007	9.4

Note: std represents standard deviation; cv represents coefficient of variation.

moisture content below this depth was temporal stable, according to long-term field soil moisture observations (Yang et al., 2014).

The introduced vegetation in study area have been planted for more than 10 years and the re-vegetation lands become mature community. Deep soil moisture in mature pasture grassland, shrubland and forestland is generally temporal stable (Chen et al., 2008a, 2010). This study was focused on the deep soil moisture conditions, which can be used to reflect the stable soil moisture conditions in deep soil profiles, can be considered as a relatively stable result of introduced vegetation restoration. On the other hand, further studies based on located and long-term monitoring are still required to provide more convincing evidence on temporal variation in deep soil moisture. Root water uptake is an important process determining soil moisture dynamics in semi-arid areas. The root systems of the introduced vegetation (alfalfa, peashrub, Siberian apricot, and Chinese arborvitae) selected in this study are mainly distributed in shallow layers, however, all types of introduced vegetation have deep root systems below rainfall infiltration depth and consume more deep soil moisture than farmland and native grassland (Chen et al., 2008a, 2010; Yang et al., 2014). The excessive depletion of deep soil moisture by deep root system of introduced vegetation and long-term insufficient rainfall infiltration, may lead the deep soil moisture in re-vegetation lands have significantly lower values than farmland and native grassland (Table 2 and Fig. 3). Result of this study showed that the deep soil moisture had no significant difference between different re-vegetation lands (Table 2). There was a possible reason that only annual precipitation can be used by introduced plants after years' growth. However, this should also be explored in further studies.

4.2. Mechanism for controls on deep soil moisture variability

Because precipitation is the only water source for soil moisture in the semi-arid regions, precipitation and evapotranspiration jointly control soil moisture (Wang et al., 2012). Fu et al. (2003) and Huang et al. (2013) found that land use can give rise to differences in evapotranspiration and rainfall recharge that influence the soil moisture in loess regions. The fact that land use/vegetation have significant influence on deep soil moisture content has been well studied in previous studies (Chen et al., 2008b; Ferreira et al., 2007; Wang et al., 2011a,b). Our results demonstrated that deep soil moisture differed in various land use types (Fig. 3 and Table 2) and land use structures (Fig. 4). The re-vegetation land had significant lower soil moisture content. This may be due to relatively higher potential evapotranspiration than that in the farmland, abandoned farmland, and native grassland. Furthermore, the planting densities of pasture grasses, shrubs, and trees were relatively higher than recommended values in the study area (Yang et al., 2014), soil moisture in this area was insufficient for plants with a high planting density. Thus, low soil moisture content was found in introduced vegetation types.

In Lijiawan watershed, most of farmlands were located on bottom of hillslopes, while, most of shrubs were planted on top positions. Abandoned farmlands in Lijiawan and Jianzicha watershed usually distributed on top-middle positions of hillslope which were far from villages. Native grasslands in two watersheds were located on top positions and the trees were planted on middle positions. The pasture grassland uniformly distributed in Jianzicha watershed and most of pasture grassland distributed on top and middle positions in Lijiawan watershed. The relatively higher values of soil moisture usually appeared on sites covered with farmland and abandoned farmland on each transect, while the lower values appeared on lands planted with introduced vegetation (Fig. 4). Multiple land uses can disturb topographical factors' influence on soil moisture distribution (Fu et al., 2003). In this study, experimental sites have similar slope gradient and slope aspect on each transect. For these reasons, the spatial distribution of soil moisture on each transect was more prone to relate land use. Because no significant differences in deep soil moisture between different types of introduced vegetation and farmland/abandoned farmland had relatively higher soil moisture (Fig. 3 and Table 2), deep soil moisture pattern on each transect was determined by land use and its spatial location. The areal extent of soil moisture from top to bottom hillslope can be found in Fig. 5. Generally, the spatial distribution of soil moisture was closely related to land use pattern. The areal extent of high or low values of soil moisture content on each hillslope was mainly determined by land use. Comparison of depth-average soil moisture content on transects with different land use structures indicated that the land use structure played an important role in determining deep soil moisture pattern on hillslope scale.

Understanding watershed responses to losses of native species or additions of non-native species was one of key issues in ecohydrolgical research (Vose et al., 2011). In this study, the standard deviation of soil moisture was used to reflect the degree of spatial variation in soil moisture. Higher values of standard deviation in soil moisture content represented relatively higher spatial variation. The high values of standard deviation in Lijiawan watershed indicated that soil moisture had higher spatial variability than that in Jianzicha watershed (Fig. 2 and Table 3). Most of Jianzicha is covered with introduced vegetation and have a simple land use structure on watershed scale, while Lijiawan watershed has a more complex land use structure and spatial pattern (Table 1 and Fig. 1). The difference of spatial variation in deep soil moisture indicated that complex land use structure had relatively higher spatial heterogeneity of deep soil moisture (Table 3 and Fig. 5). Different with spatial distribution characteristics of deep soil moisture in Lijiawan watershed, deep soil moisture in Jianzicha watershed had higher spatial homogeneity. The results demonstrated that vegetation restoration with simple land use pattern diminished the spatial heterogeneity of deep soil moisture. Different with the surface soil moisture pattern studied by Qiu et al. (2001) and Fu et al. (2003), results of this study indicated the homogeneity appeared in deep soil moisture after human-introduced ecological restoration. This also indicated that vegetation restoration with introduced plants may diminish the spatial heterogeneity of deep soil moisture.

4.3. Implications for land use management

Because soil moisture profiles in native grassland and farmland were used as the references to present soil moisture conditions with no human impact and before vegetation restoration, respectively. The difference in soil moisture between native grassland and re-vegetation lands indicated the degree of soil moisture deficit relative to the initial soil moisture condition. The difference in soil moisture between farmland and re-vegetation lands was used to reflect the response of soil moisture to vegetation restoration. Results of this study showed that re-vegetation lands have significant lower deep soil moisture than farmland, abandoned farmland, and native grassland (Fig. 3 and Table 2). As an important water source for introduced vegetation, deep soil moisture was hardly recharged by rainfall (Chen et al., 2008a; Wang et al., 2010). Field observation showed that mean soil moisture content (2–5 m) in Jianzicha watershed was only 0.064 g/g. The low deep soil moisture content may provide little available water source for these high water consumption plants. Shortage of soil moisture would seriously restrict land productivity in semi-arid environments. Land use management in these areas should balance the soil moisture conditions and sustainable vegetation restoration. Because the land use structure determines the soil moisture conditions and their spatial patterns, more attention should be paid to the selection and arrangement of land use on hillslope and watershed scale based on the interactions between soil moisture and vegetation. The improvement of land use management was suggested to improve the water management and maintain the sustainability of vegetation restoration.

5. Conclusion

Variation in spatial and profile changes of soil moisture in relation to land use and land use structure at a depth of 0–5 m was compared and analyzed in two neighboring re-vegetation watersheds. Comparison of soil moisture between re-vegetation lands and farmland and native grassland showed that introduced vegetation can drastically decrease deep soil moisture. Land use determines the deep soil moisture content. The analysis of soil moisture for different land use patterns indicated that land use structure determined the deep soil moisture conditions and their spatial variability. Complex land use structure had relatively higher spatial heterogeneity of deep soil moisture, while simple land use structure was related to higher homogeneity. The ecological restoration with planting introduced plants diminished the spatial heterogeneity of deep soil moisture on watershed scale.

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