Effects of micro-topography and vegetation type on soil moisture in a large gully on the Loess Plateau of China

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ABSTRACT

Large gullies occur globally and can be classified into four main micro-topographic types: ridges, plane surfaces, pipes and cliffs. Afforestation is an effective method of controlling land degradation worldwide. However, the combined effects of afforestation and micro-topography on the variability of soil moisture remain poorly understood. The primary objectives of this study were to determine whether afforestation affects the spatial pattern of the root-zone (0–100 cm) soil moisture and whether soil moisture dynamics differ among the micro-topographic types in gully areas of the Chinese Loess Plateau. The results showed that in the woodland regions, the spatial mean moisture values decreased by an average of 6.2% and the spatial variability increased, as indicated by the standard deviation (17.1%) and the coefficient of variation (22.2%). In general, different micro-topographic types exerted different influences on soil moisture behavior. The plane surface presented the largest average soil moisture values and the smallest spatial variability. The lowest soil moisture values were observed in the ridge, mainly due to the rapid drainage of these areas. Although pipe woodland region can concentrate surface runoff during and after rainfall, the larger trees growing in these areas can lead to increased soil moisture evapotranspiration.

Key words | afforestation, gully, Loess Plateau, micro-topography, soil moisture

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INTRODUCTION

Soil moisture plays a significant role in land-surface ecosystems (Rodriguez-Iturbe *et al.* 1999) and usually exhibits highly variable patterns that are jointly affected by precipitation, vegetation, topography, and soil properties (Vereecken *et al.* 2007). Large gullies, which often occur in areas with loess soils, represent an important form of severe land degradation (Melliger & Niemann 2010) and can reduce the agricultural potential and grazing value of a given region (Avni 2005). Moreover, gully erosion may represent the dominant soil erosion process in a watershed (Smith & Dragovich 2008; Bouchnak *et al.* 2009; Wilkinson *et al.* 2013). Soil loss rates by gully erosion represent from minimal 10% up to 94% of total sediment yield caused by water erosion (Poesen *et al.* 2003). The afforestation of degraded land is an effective method of alleviating water loss and soil erosion (Nunez-Mir *et al.* 2015), controlling land desertification, and conserving biodiversity (Chirino *et al.* 2006; Porto *et al.* 2009). However, afforestation greatly influences soil moisture balance (Rodriguez-Iturbe *et al.* 2001) through a series of complex and interacting ecological and hydrological processes (Porporato *et al.* 2002). Gómez-Plaza *et al.* (2001) showed that vegetation plays a vital role in establishing soil moisture variability within a vegetated zone. Planted trees can also affect soil moisture content via the interception of rainfall by leaves, the uptake of soil moisture by roots, buffering of the litter layer, and changes

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in the soil water-retention capacity (Jin *et al.* 2011). For example, Chirino *et al.* (2006) discovered that 23–35% of the total annual rainfall is intercepted by Aleppo pine (*Pinus halepensis*) canopies in the Ventós-Agost catchment of Spain. Wang *et al.* (2012) reported that black locust (*Robinia pseudoacacia*) stands within the Loess Plateau of China greatly decrease soil moisture. Therefore, characterizing the effects of afforestation in large gullies on the spatial behavior of soil moisture is critical for providing a better understanding of the hydrological and ecological processes in gullied environments.

Within the past two decades, the spatial-temporal variability of soil moisture has been extensively investigated at different scales by a series of ecologists and hydrologists (Famiglietti *et al.* 1998; Qiu *et al.* 2001; Cosh *et al.* 2004; Penna *et al.* 2009; Brocca *et al.* 2010; Gao *et al.* 2011; Hu *et al.* 2011; Rosenbaum *et al.* 2012; Biswas *et al.* 2014). However, relatively few studies have focused on the spatio-temporal variability of soil moisture in gullied regions, likely due to the difficulty of obtaining samples in gully areas (Gao *et al.* 2011). Melliger & Niemann (2010) characterized gully effects on the spatial patterns of near-surface (0–10 cm) soil moisture in southeastern Colorado; they demonstrated that gullies increased soil moisture spatial variability but did not have a significant influence on the spatial means. These authors also reported that gully bottoms tend to be wetter and their sidewalls tend to be drier than upland soils, likely due to the lower evapotranspiration rates and the rapid drainage of gully bottoms and sidewalls, respectively. Gao *et al.* (2011) examined deep soil moisture (0–160 cm) and its variability along three transects within a well-developed gully in the Chinese Loess Plateau; they reported that the mean value, the standard deviation (SD), and the coefficient of variation (CV) of soil moisture varied with depth and time. Furthermore, Gao *et al.* (2013) also studied the root-zone soil moisture (0–80 cm) within the Loess Plateau and illustrated that the gullies in this region present lower soil moisture content than the nearby uplands; however, the authors did not examine the effects of gullies on soil moisture spatial variability. Gao *et al.* (2016) subsequently used statistical and geostatistical methods to analyze the spatial behavior of soil moisture in a heavily gullied catchment within the Loess Plateau; they observed that gullies clearly increased the spatial variability of soil moisture but only weakly affected the spatial mean, consistent with the results obtained by Melliger & Niemann (2010). However, Hu (2009) characterized the effects of large gullies on the spatial distribution of soil moisture in the Loess Plateau and discovered that the spatial mean and variability of soil moisture increased in the presence of gullies, likely because the sampling locations involved were mostly distributed in gully bottoms, where soils are generally wetter.

The Loess Plateau of China is a region featuring large gullies. Overall, gullies cover approximately 40% of its total area at a density of 1.5–4.0 km·km^{-2} (Zheng *et al.* 2006). The proportion and density of these gullies increase to approximately 50–60% and 3–8 km·km^{-2}, respectively, in the hilly areas of the Plateau (Huang & Ren 2006). Within the past decade, the 'Grain for Green' project has resulted in a 25% increase in vegetation coverage in this area (Feng *et al.* 2016). However, less research has focused on the behavior of soil moisture within the gullies in this region, and many researchers have drawn conclusions regarding the entire catchment based on results obtained in the uplands (Hu *et al.* 2010; Gao *et al.* 2014). Thus, the effects of micro-topography and vegetation type on soil moisture in large gullies of the Loess Plateau remain poorly understood.

The goal of this study is to characterize (1) the effects of vegetation and micro-topography on the root-zone soil moisture profiles (at depths of 0–100 cm, defined as the root-zone soil layer here); (2) the effects of vegetation and micro-topography type on the spatial-temporal variations of soil moisture at different soil layers and the correlations between mean soil moisture and its corresponding variance; and (3) the relationships between soil moisture content and terrain attributes in a large gully within the Loess Plateau of China.

MATERIALS AND METHODS

Study area

This study was performed in the Jiegou catchment (36°56′N, 110°46′E), which is located in the western part of Shanxi Province, China (Figure 1). This catchment represents a

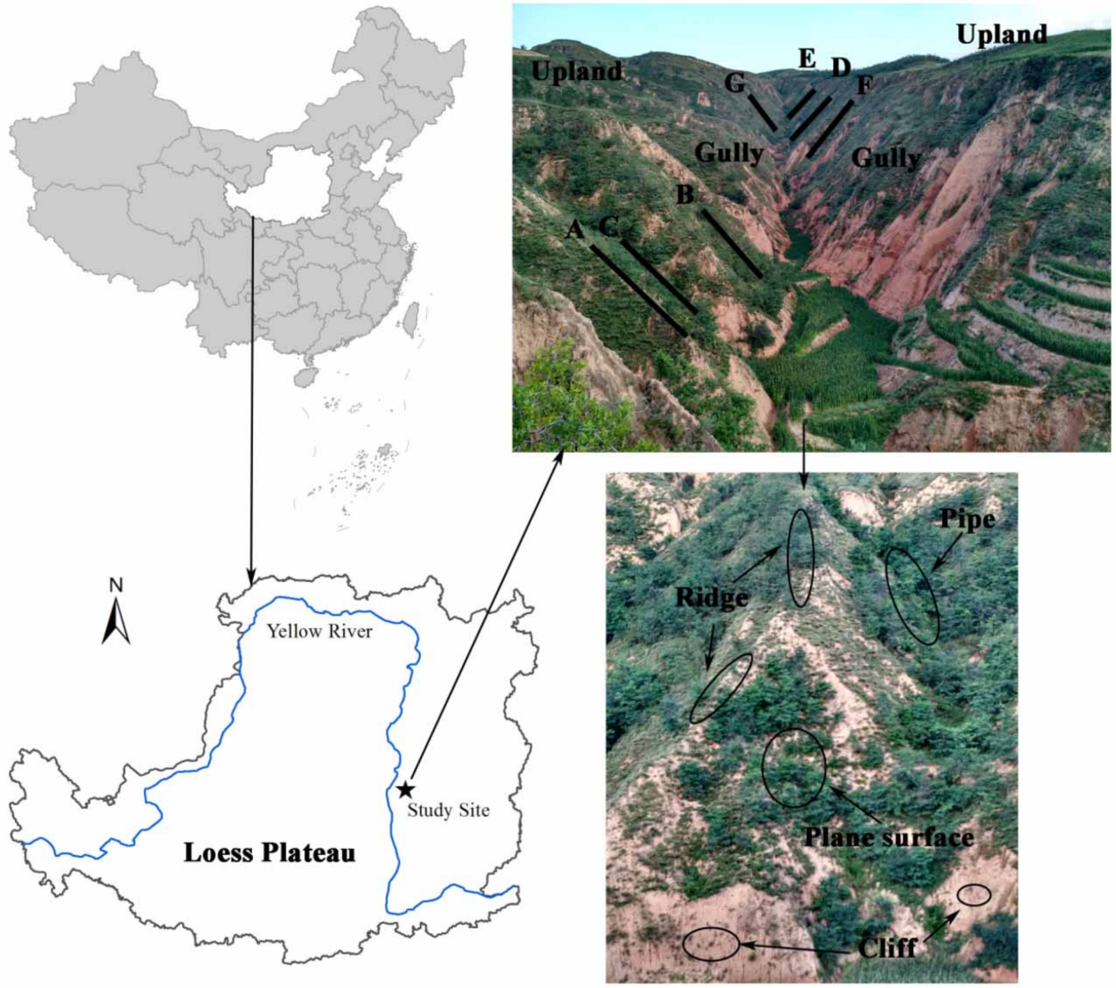

Figure 1 | Study site in the Loess Plateau and photographs illustrating the locations of the sampling transects in the Jiegou small catchment. A, ridge woodland; B, plane surface woodland; C, pipe woodland; D, ridge woodland; E, plane surface woodland; F, pipe woodland; G, grassland.

typical gullied catchment in the hilly region of the Loess Plateau; it spans an area of 0.49 km^2, 49% of which is covered by gullies. This region has a semi-arid continental climate with a mean annual temperature of approximately 9.8°C and a mean annual precipitation of 465 mm. Most rainfall is concentrated during June to September, and the mean monthly temperature ranges from −6.0°C in January to 23.2°C in July. The potential annual evaporation (pan evaporation) is approximately 1,850 mm. The elevation of the Jiegou catchment ranges from 1,047 to 1,251 m. The main gully extends from south to north direction, and the slope gradients range from 25° to 90°.

Gully sidewalls are the main features of gullies. The distinctive irregularities of gully sidewall reliefs are used to classify gullies according to their main micro-topographic features, which consist of ridges, plane surfaces, pipes, and cliffs (Figure 1). More detailed descriptions of these micro-topographic types can be found in Gao *et al.* (2011). The soil in the study site mainly consists of loess with silt loam textures, and these soils are vulnerable to soil erosion. The basic properties of the soil are shown in Table 1. The soil thickness varies from 40 m to 60 m.

Three land use types occur in the gullies in the Jiegou catchment: rain-fed farmland, sparse native grassland, and woodland. Farmland is cropped with maize at the gully bottom, which is typically planted in April and harvested manually at the end of October. After harvest, a fallow period occurs from November to March of the

Table 1 | Soil properties and growing features of different vegetation types selected in the study

Vegetation type	Woodland	Native grassland
Year	5–6	>10
Plant cover (%)	82	74
Mean canopy height (m)	3.3	0.5
Mean tree DBH (cm)	2.4	–
Planting density	1.5 × 3.0 m	–
Bulk density (g/cm^3)	1.18	1.26
Porosity (%)	55.35	52.30
Sand (%)	39	25
Silt (%)	49	59
Clay (%)	12	16
Soil organic matter (g/kg)	8.75	13.10

Note: The plant cover is the percentage of area covered by plant; the mean canopy height in native grassland is the mean height of herbs and grasses and in woodland is the mean value of trees; the tree DBH is the average tree diameter at breast height. The soil properties are mean values of sampling points at a depth of 0–10 cm.

next year. In this study, two land uses, native grassland and woodland, are considered. Native grassland is the dominant indigenous species community in gullies. The main species are native grasses and herbs that demand little water, including *Artemisia gmelinii*, *Potentilla chinensis*, *Bothriochloa ischemum*, and others. These annual grasses are sparsely distributed in the gully sidewalls, and shallow roots are observed. According to local farmers and stakeholders, the natural grasslands are rarely disturbed by human activities. Woodlands converted from native grasslands were mainly planted with black locust (*R. pseudoacacia*) in 2010–2011 over the gully sidewalls. These trees have been kept free of human disturbance since planting. According to field investigations conducted in August 2016, the average tree height is approximately 3.3 m, and the average diameter of the trees at breast height (DBH) is approximately 2.4 cm (Table 1). The greatest vertical main root depth varies from 70 to 100 cm. This planting project was proposed and funded by the Hong Kong Green Action Charity Foundation for controlling land degradation and providing continuous ecosystem services in the gullied environments. However, because the study site is located within a semi-arid climatic zone, soil moisture is one of the primary limiting factors for plant growth in this region.

To study the effects of planted black locust (*R. pseudoacacia*) on soil moisture, the soil moisture profiles of native grasslands are used as a reference for the moisture conditions prior to this land use conversion. Differences in soil moisture between the native grassland and converted woodlands thus reflect the responses of soil moisture to the presence of different vegetation types. Similarly, differences in soil moisture among different micro-topographic types (ridges, plane surfaces, and pipes) represent the effects of micro-topography on soil moisture content.

Soil moisture sampling

Seven typical transects (A–G, Figure 1) were selected to investigate variations in soil moisture: transects A and D were located in ridge woodlands; transects B and E were located in plane surface woodlands; transects C and F were located in pipe woodlands; and transect G was located in the associated control grassland. Six sampling points were located over transect A, and five sampling points were located over each of the transects B–G; the sampling points were spaced approximately 10–15 m apart. These points represent different aspects and topographic positions (except for cliffs) in the gully sidewalls where soil samples could be obtained. The gully bottom was not sampled because it mainly consists of farmland with only a thin layer of soil. Soil moisture samples were collected on August 15, September 1, September 15, and October 15 of 2016 at depths of 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm using hand augers (4 cm in diameter). After the soil samples were taken out, they were immediately sealed in airtight aluminum cylinders and taken to the laboratory to measure the gravimetric soil moisture content (in units of g/g or %). The soil moisture content was determined using the oven-drying method (for additional details, please refer to Penna *et al.* (2009)). All field sampling and laboratory work were completed in 2 days and no precipitation occurred during the sampling period. The precipitation prior to the four sampling periods was 10.4 mm (August 10, 2016), 24.2 mm (August 24, 2016), 1.2 mm (September 12, 2016), and 2.6 mm (October 11, 2016). The details of precipitation during the study period are shown in Figure 2 (the automatic weather station is located approximately 150 m from the study site).

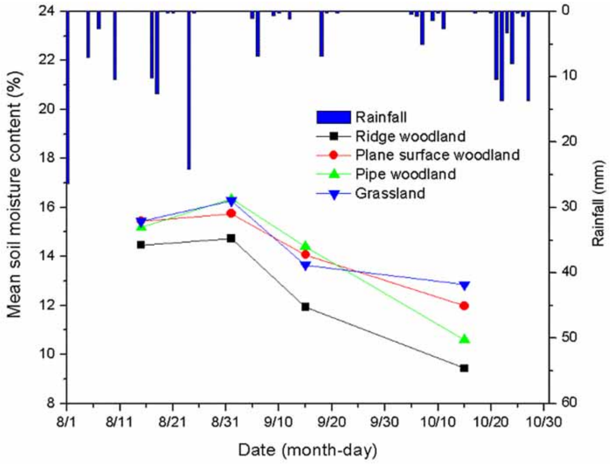

Figure 2 | Precipitation at the study site during the study period and soil moisture content in different micro-topography and vegetation types.

A portable Trimble GPS receiver was used to determine the latitude, longitude, and elevation of each sampling point. A geological compass was also used to determine the slope gradient and slope aspect of all sampling points. Table 2 presents an overview of the terrain attributes of these sampling points.

Table 2 | Overview of terrain attributes at all sampling points

ID of point	Land use	Micro-topography	Relative elevation (m)	Slope gradient (tanα)	Slope aspect (cosβ)
A1	Woodland	Ridge	83	28.67	0.24
A2	Woodland	Ridge	73	28.67	0.44
A3	Woodland	Ridge	65	34.43	0.12
A4	Woodland	Ridge	61	36.40	0.21
A5	Woodland	Ridge	54	53.17	0.03
A6	Woodland	Ridge	39	48.77	−0.28
B1	Woodland	Plane surface	76	70.02	−0.24
B2	Woodland	Plane surface	68	67.45	−0.12
B3	Woodland	Plane surface	33	64.94	0.14
B4	Woodland	Plane surface	30	67.45	0.00
B5	Woodland	Plane surface	23	64.94	−0.09
C1	Woodland	Pipe	48	26.79	0.34
C2	Woodland	Pipe	34	44.52	0.54
C3	Woodland	Pipe	31	48.77	0.53
C4	Woodland	Pipe	25	53.17	0.34
C5	Woodland	Pipe	21	48.77	0.19
D1	Woodland	Ridge	148	28.67	−0.80
D2	Woodland	Ridge	139	46.63	−0.39
D3	Woodland	Ridge	133	48.77	−0.42
D4	Woodland	Ridge	126	36.40	−0.60
D5	Woodland	Ridge	112	48.77	−0.34
E1	Woodland	Plane surface	151	64.94	−0.73
E2	Woodland	Plane surface	142	67.45	−0.87
E3	Woodland	Plane surface	135	64.94	−0.82
E4	Woodland	Plane surface	128	60.09	−0.71
E5	Woodland	Plane surface	121	57.74	−0.80
F1	Woodland	Pipe	148	48.77	−1.00
F2	Woodland	Pipe	127	40.40	−0.37
F3	Woodland	Pipe	112	72.65	−0.42
F4	Woodland	Pipe	108	64.94	−0.22
F5	Woodland	Pipe	96	53.17	−0.10
G1	Grassland	–	139	62.49	−0.87
G2	Grassland	–	132	48.77	−0.95
G3	Grassland	–	123	67.45	−0.77
G4	Grassland	–	113	72.65	−0.80
G5	Grassland	–	105	67.45	−0.90

Analytical methods

This study uses gravimetric soil moisture data obtained at depths of 0–100 cm. The depth, spatial and temporally averaged soil moisture ($\bar{\theta}_{i,j}$, $\bar{\theta}_{j,k}$, $\bar{\theta}_{i,k}$) are calculated, respectively, as follows:

$$\bar{\theta}_{i,j} = \frac{1}{N_k}\sum_{k=1}^{N_k} \theta_{i,j,k} \quad (1)$$

$$\bar{\theta}_{j,k} = \frac{1}{N_i}\sum_{i=1}^{N_i} \theta_{i,j,k} \quad (2)$$

$$\bar{\theta}_{i,k} = \frac{1}{N_j}\sum_{j=1}^{N_j} \theta_{i,j,k} \quad (3)$$

where $\theta_{i,j,k}$ represents soil moisture at position i, time j, and depth k; N_k represents the number of measurement layers at each position ($N_k = 6$, $k_1 = 0$–10 cm, $k_2 = 10$–20 cm, …, $k_6 = 80$–100 cm); N_i is the number of measurement positions obtained for each type (ridge, $N_i = 11$; plane surface, $N_i = 10$; pipe, $N_i = 10$; and grassland, $N_i = 5$); N_j is the total number of observational times ($N_j = 4$). The corresponding depth and temporal variances at each position are defined, respectively, as follows:

$$S_{i,j}^2 = \frac{1}{N_k - 1}\sum_{k=1}^{N_k}(\theta_{i,j,k} - \bar{\theta}_{i,j}) \tag{4}$$

$$S_{i,k}^2 = \frac{1}{N_j - 1}\sum_{j=1}^{N_j}(\theta_{i,j,k} - \bar{\theta}_{i,k}) \tag{5}$$

Furthermore, the temporally averaged soil moisture at each position i and each depth k is calculated, respectively, as follows:

$$\bar{\theta}_i = \frac{1}{N_j}\sum_{j=1}^{N_j}\bar{\theta}_{i,j} \tag{6}$$

$$\bar{\theta}_k = \frac{1}{N_j}\sum_{j=1}^{N_j}\bar{\theta}_{j,k} \tag{7}$$

The corresponding variance at each position i and each depth k is as follows:

$$S_i^2 = \frac{1}{N_j - 1}\sum_{j=1}^{N_j}(\bar{\theta}_{i,j} - \bar{\theta}_i) \tag{8}$$

$$S_k^2 = \frac{1}{N_j - 1}\sum_{j=1}^{N_j}(\bar{\theta}_{j,k} - \bar{\theta}_k) \tag{9}$$

In addition, the total mean of the root-zone moisture profile and its corresponding variance are further calculated using the following equations:

$$\bar{\theta} = \frac{1}{N_i}\sum_{i=1}^{N_i}\bar{\theta}_i \tag{10}$$

$$S^2 = \frac{1}{N_i \times N_j - 1}\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}(\bar{\theta}_{i,j} - \bar{\theta}) \tag{11}$$

The CV, which is defined as the ratio of the SD to the mean, is then calculated for the temporally averaged soil moisture value at every position and depth of each terrain type. CV values between 0 and 0.1 indicate low variability; values between 0.1 and 1 indicate moderate variability; and values greater than 1 indicate high variability.

We then calculated the linear correlations of the mean values and variances obtained on different measurement occasions and at different soil depths. Pearson correlation coefficients were used to quantify the relationships between the time series of soil moisture and the relationships between soil moisture and topographic indices in terms of the relative elevation, slope gradient, and slope aspects at each soil depth for each micro-topography and vegetation type.

RESULTS

Soil moisture variability of the root-zone profiles

Table 3 summarizes the statistics of the root-zone soil moisture profiles obtained at all measurement times. These profiles can be used to characterize the effects of micro-topography and vegetation type on the depth-averaged soil moisture. In general, the soil is wetter in grassland and drier in woodland regardless of the micro-topography type, indicating that woodland consumes more soil moisture than grassland in gullied areas. Furthermore, soil moisture varies significantly among the three micro-topography types. The root-zone soil moisture profile is significantly higher ($P < 0.05$) in the plane surface and in the pipe than in the ridge, suggesting that soil moisture in ridges is more prone to be lost. The soil is wettest in the plane surface, not in the pipe as expected, likely because trees in the pipe grow larger than those in plane surface areas and thus produce higher evapotranspiration. In general, soil moisture variability (SD and CV) is largest in the pipe and smallest in the plane surface, which indicates that the higher the moisture, the lower the moisture variability in gully regions. The skewness and kurtosis values are highly dependent on micro-topography and vegetation type. Skewness is highest in the ridge but decreases from the plane surface to the pipe to the grassland; however, kurtosis shows the opposite trend.

Figure 3 displays the temporally averaged root-zone moisture profiles at each point obtained for transects A–F and the corresponding variability values for the three gully micro-topography types along the transects. Because these transects traversed opposite sides of the gully, we were

Table 3 | Summary characteristics of the root-zone soil moisture profiles of different micro-topography and vegetation types obtained from all measured events (from Equations (1), (6), (10), and (11))

Vegetation type	Micro-topography	Min (%)	Max (%)	Mean (%)	SD (%)	CV	Skewness	Kurtosis
Woodland	Ridge	7.0	18.8	12.6b*	3.07	0.24	−0.06	−1.01
Woodland	Plane surface	9.4	18.4	14.3a	2.26	0.16	−0.09	−0.57
Woodland	Pipe	6.5	19.6	14.1a	3.34	0.24	−0.58	−0.50
Grassland	–	8.5	18.1	14.6a	2.57	0.18	−0.79	0.16

*Different lower-case letters represent significant differences at the 0.05 probability level (determined using the least significant difference (LSD) test).

able to observe moisture behavior across the entire gully (Figure 1). With the exception of ridge transect A, the mean moisture profiles generally show highly irregular increases as the sampling area moves downslope along the transects (Figure 3(a) and 3(b)). There are two potential explanations for this. First, transect A is much longer and narrower than the others; thus, the soil in this transect experiences less infiltration during and after the

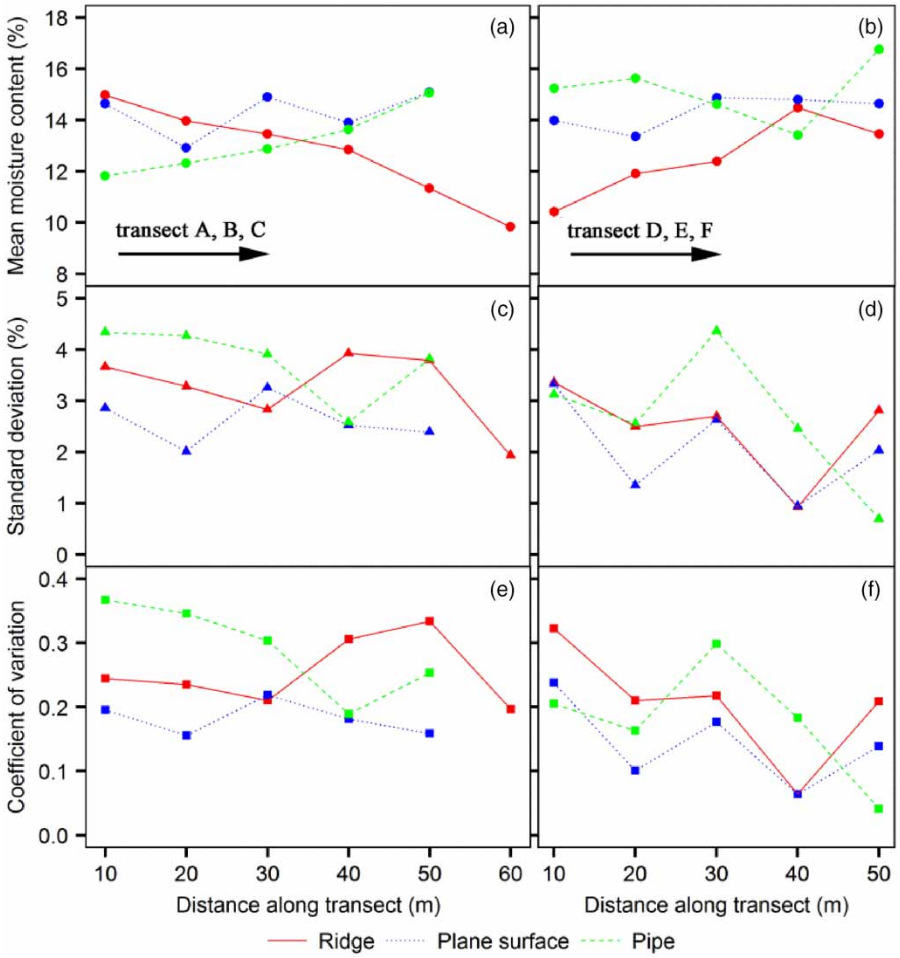

Figure 3 | Temporally averaged root-zone moisture and its variations in different micro-topography types downslope along sampling transects A–F (from Equations (1), (6), and (8)). *Note:* Transect A represents ridge, transect B represents plane surface, transect C represents pipe, transect D represents ridge, transect E represents plane surface, and transect F represents pipe.

rainfall than that in the other transects. Second, grasses distributed under the ridge borderline may also use the soil moisture there. Overall, although almost all points record moderate variations, the SDs and CVs do not show obvious changes as one proceeds downslope along the transects (Figure 3(c)–3(f)).

Patterns of soil moisture variability at different soil layers

In general, the effects of micro-topography on soil moisture behavior are dependent on the soil layers (Figure 4). For example, the mean soil moisture content of the pipe is highest at depths of 0–10 cm and 10–20 cm, but the mean soil moisture content of the plane surface is highest at depths below 20 cm. As expected, the ridge displays the lowest soil moisture content in all soil layers. Furthermore, the trend differs with soil depth for a given micro-topography type. For example, the mean soil moisture content in the pipe decreases with depth, but an opposite pattern of change is found in the ridge below 20 cm, probably because the pipe experiences fewer hours of sunshine than the ridge due to shading of the uplands. Generally, the soil moisture content of grassland is higher than that of woodland at deeper layers in gully environments (>40 cm depth) (Figure 4). CVs are used to describe the extent of variation in soil moisture over time. CVs of soil moisture for different types of micro-topography are also dependent on the soil layers (Figure 4). For example, the highest CV value is found for depth of 20–40 cm in the plane surface and pipe, whereas in the ridge the highest CV value is found for depth of 10–20 cm. In general, grassland has lower CV values than woodland at depths below 10 cm (Figure 4).

A correlation analysis of the time series of mean moisture values at different soil layers can provide relevant information on the temporal variability of soil moisture. Table 4 shows the results of such an analysis. The correlation coefficients of soil moisture in the ridge, plane surface, and pipe display similar change patterns, in which the correlation coefficients decrease with increasing depth. However, the correlation coefficients of the time series of mean moisture values in the grasslands vary without showing explicitly increasing or decreasing trends. The correlation coefficients measured at depths above 20 cm in the ridge and plane surface woodlands are not significant ($P > 0.05$), although significant values are observed at soil depths below 20 cm ($P < 0.01$ or $P < 0.05$) and between the following intervals: 20–40 cm and 40–60 cm, 20–40 cm and 60–80 cm, 40–60 cm and 60–80 cm, and 60–80 cm and 80–100 cm. The correlation coefficients in the pipe are significant at depths of less than 60 cm but not in deep soils (>60 cm). These results indicate that the correlations among the observed time series of mean soil moisture in these gullied regions depend on the soil layer.

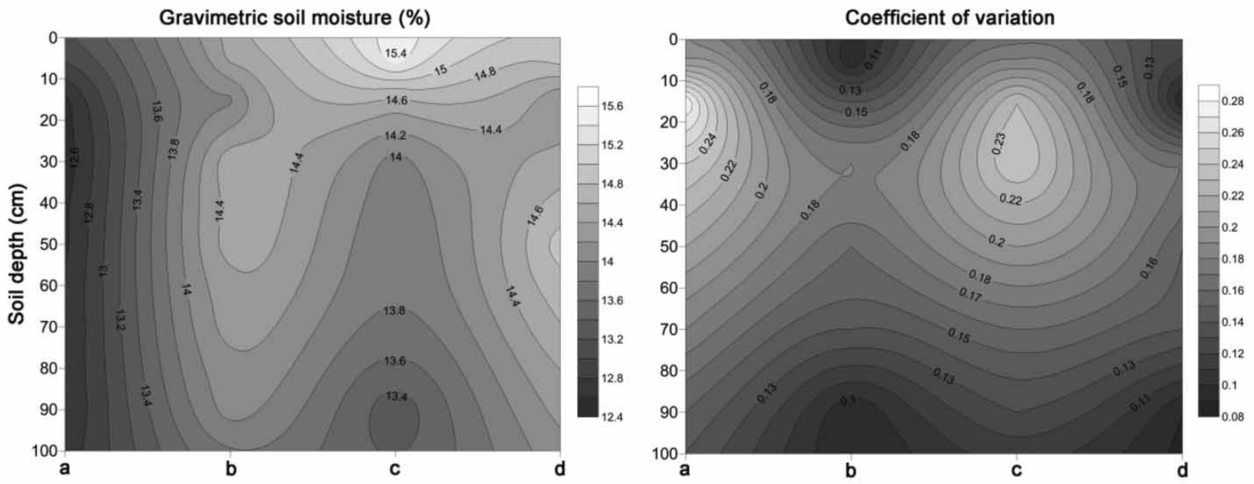

Figure 4 | The vertical distribution of soil moisture means and coefficients of variation (CV) under different micro-topography and vegetation types, interpolated by the Kriging method: a, ridge woodland; b, plane surface woodland; c, pipe woodland; d, grassland (from Equations (2), (7), and (9)).

Table 4 | Pearson correlation values between different depths with all soil moisture measurements in each micro-topography and vegetation type

Vegetation type	Micro-topography	Depth (cm)	10–20	20–40	40–60	60–80	80–100
Woodland	Ridge	0–10	0.95	0.70	0.60	0.52	0.50
Woodland	Ridge	10–20		0.89	0.83	0.77	0.74
Woodland	Ridge	20–40			0.99**	0.96*	0.93
Woodland	Ridge	40–60				0.99*	0.97*
Woodland	Ridge	60–80					0.99**
Woodland	Plane surface	0–10	0.72	0.54	0.44	0.35	0.11
Woodland	Plane surface	10–20		0.84	0.83	0.83	0.67
Woodland	Plane surface	20–40			0.99**	0.96*	0.89
Woodland	Plane surface	40–60				0.99**	0.94
Woodland	Plane surface	60–80					0.97*
Woodland	Pipe	0–10	0.95*	0.92	0.91	0.86	0.40
Woodland	Pipe	10–20		0.98*	0.98*	0.83	0.40
Woodland	Pipe	20–40			0.99**	0.89	0.55
Woodland	Pipe	40–60				0.88	0.54
Woodland	Pipe	60–80					0.81
Grassland	–	0–10	0.49	−0.05	0.13	0.13	0.55
Grassland	–	10–20		0.73	0.83	0.85	0.91
Grassland	–	20–40			0.98*	0.98*	0.81
Grassland	–	40–60				0.99**	0.90
Grassland	–	60–80					0.90

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively.

Correlation between the mean and variance of moisture content

In general, the overall absolute variability of soil moisture is determined by measuring the variance in soil moisture. Therefore, linear correlations of the mean soil moisture values with the corresponding variances can reflect the influence of the soil moisture level on the heterogeneity of moisture within a soil profile. Figure 5 displays the correlations between the depth-averaged soil moisture and the associated variance as well as the changing trends in the correlations observed over time. Figure 6 demonstrates the correlation between temporally averaged soil moisture and the associated variance changing with depth.

The correlation between the depth-averaged moisture and the associated variance is affected by the date on which the soil moisture measurement was obtained and by the micro-topographic type. For the ridge, significant positive correlations ($P < 0.05$) between the depth-averaged moisture and the associated variance are observed for 15 October 2016, whereas no significant correlations ($P > 0.05$) are observed at the other three sampling times (Figure 5(a)). Generally, positive correlations are observed for most events in the plane surface and pipe woodlands (Figure 5(b) and 5(c)). These observations indicate that the variance in soil moisture tends to increase with increasing soil moisture in the plane surface and pipe woodlands, whereas this trend is not observed in the grasslands (Figure 5(d)). Additionally, positive correlations between the temporally averaged moisture and the associated variances are also observed at surface (0–10 cm) and subsurface (10–20 cm) layers in the ridge woodland, but negative correlations are observed in these layers in the plane surface woodland (Figure 6(a) and 6(b)). In the pipe woodland, negative correlations are observed for all soil depths, and are statistically significant ($P < 0.05$) at the surface and subsurface layers (Figure 6(c)). However, in the grassland, a positive correlation is found at the surface layer

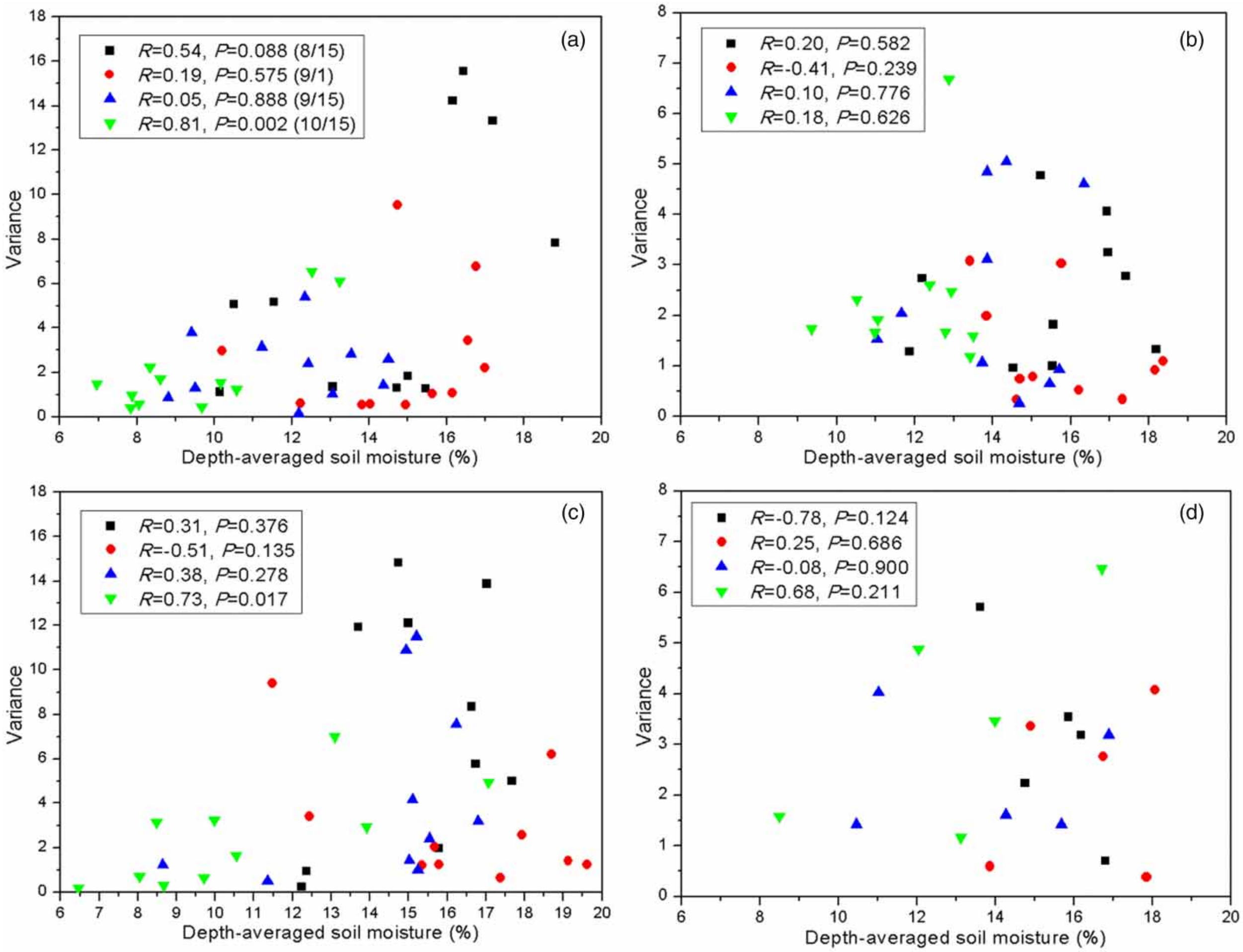

Figure 5 | Correlations between the depth-averaged soil moisture and its corresponding variance over time: (a) ridge woodland; (b) plane surface woodland; (c) pipe woodland; (d) grassland (from Equations (1) and (4)).

(Figure 6(d)). These results indicate that micro-topography and vegetation type have important effects on the correlation between moisture condition and its variance at different sampling times and soil layers.

Relationship between soil moisture and terrain attributes

Topography is generally one of the primary environmental factors affecting the spatial variability of soil moisture on small scales (Biswas & Si 2011; Zhu & Lin 2011; Hu & Si 2014). Therefore, this study focuses primarily on the relationship between soil moisture and topography in terms of elevation, slope gradient, and slope aspect. Generally, the correlations between soil moisture and topographic indices are dependent on the gully micro-topography type and the soil depth (Table 5). For example, soil moisture in the ridge is negatively correlated with the slope gradient at all depths but positively correlated with relative elevation at soil depths greater than 20 cm. The slope aspect is also positively correlated with soil moisture in the ridge woodlands, especially in the surface layer (0–10 cm). However, soil moisture in the pipe is positively correlated with slope gradient at all depths except within the subsurface layer (10–20 cm), and it is positively correlated with relative elevation at all depths, particularly at deep layer (80–100 cm). Additionally, the slope aspect is negatively correlated with soil moisture at all depths in the pipe.

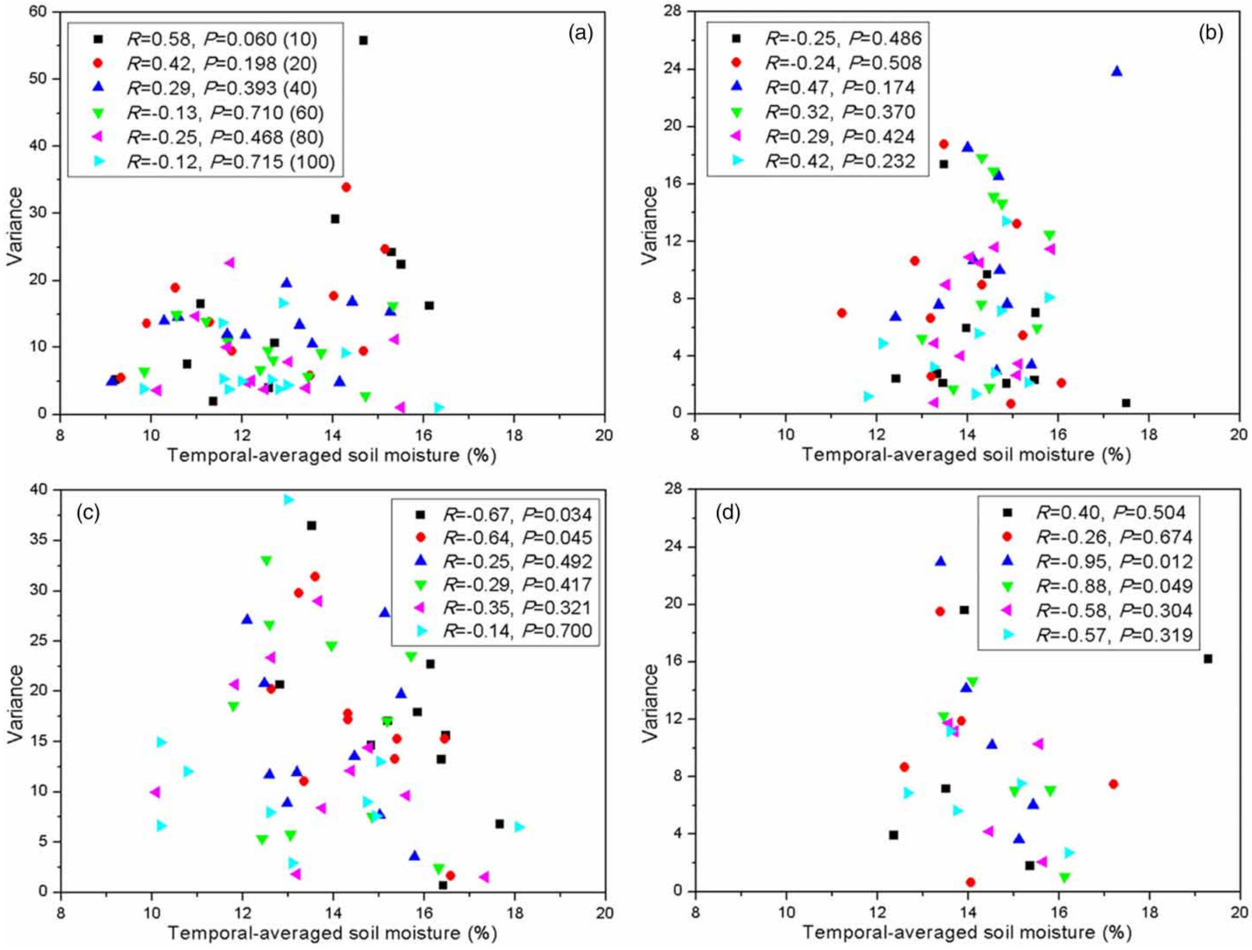

Figure 6 | Correlations between the temporally averaged soil moisture and its corresponding variance at different depths: (a) ridge woodland; (b) plane surface woodland; (c) pipe woodland; (d), grassland (from Equations (3) and (5)).

DISCUSSION

Effects of micro-topography on soil moisture

Soil moisture is the most important state variable controlling plant growth on the Loess Plateau of China. Characterizing soil moisture profiles at gullied areas has profound implications for understanding hydrological processes and contributing to the sustainability of vegetation restoration, especially in arid and semi-arid regions (Wang *et al.* 2014). Micro-topography type influences soil moisture distribution in regions with complex terrain (Gao *et al.* 2016), a finding that is important for the improvement of land use management in gullied areas. In the present study, significant differences ($P < 0.05$) in soil moisture profiles were detected among micro-topography types (Table 3). The highest soil moisture content occurs in the plane surface, which is inconsistent with the findings of Gao *et al.* (2011), who found that pipes rather than plane surfaces had the highest moisture content. This discrepancy is probably due to the fact that trees in pipes grow larger than those in plane surfaces; therefore, in the present study, more of the soil moisture in the pipes was consumed. The ridge displays the lowest moisture values, in agreement with the previous study (Gao *et al.* 2011), implying that soil moisture should primarily be taken into account for afforestation in ridge areas. In general, soil moisture wavily increases downslope along transects, consistent with the results of an earlier study of the Loess Plateau (Gao *et al.* 2011).

Table 5 | Pearson correlation coefficients of mean soil moisture and topographic indices

Vegetation type	Micro-topography	Soil layer (cm)	Relative elevation (m)	Slope gradient (tanα)	Slope aspect (cosβ)
Woodland	Ridge	0–10	−0.131	−0.109	0.301*
Woodland	Ridge	10–20	−0.025	−0.212	0.251
Woodland	Ridge	20–40	0.020	−0.280	0.259
Woodland	Ridge	40–60	0.036	−0.268	0.208
Woodland	Ridge	60–80	0.125	−0.223	0.100
Woodland	Ridge	80–100	0.215	−0.150	−0.022
Woodland	Plane surface	0–10	−0.241	−0.173	0.146
Woodland	Plane surface	10–20	−0.114	−0.134	0.044
Woodland	Plane surface	20–40	−0.125	−0.094	0.052
Woodland	Plane surface	40–60	0.016	−0.072	−0.028
Woodland	Plane surface	60–80	0.062	−0.098	−0.042
Woodland	Plane surface	80–100	0.219	−0.081	−0.143
Woodland	Pipe	0–10	0.195	0.123	−0.226
Woodland	Pipe	10–20	0.177	−0.039	−0.202
Woodland	Pipe	20–40	0.165	0.122	−0.198
Woodland	Pipe	40–60	0.177	0.074	−0.213
Woodland	Pipe	60–80	0.237	0.195	−0.288
Woodland	Pipe	80–100	0.314*	0.159	−0.354*
Grassland	–	0–10	−0.254	−0.078	−0.515*
Grassland	–	10–20	−0.268	0.026	−0.275
Grassland	–	20–40	0.081	−0.091	−0.153
Grassland	–	40–60	0.048	−0.130	−0.258
Grassland	–	60–80	−0.021	−0.211	−0.323
Grassland	–	80–100	−0.137	−0.203	−0.347

*Indicates significance at the 0.05 probability level.

The effects of micro-topography on the soil moisture pattern are dependent on the soil layer. As expected, the ridge has the lowest soil moisture content in all soil layers (Table 3), consistent with the findings of Gao *et al.* (2011), who also found lower moisture content in ridges because the ridge is narrow, allowing less infiltration during and after rainfall events. However, the plane surface has higher moisture content than the pipe at depths of below 20 cm in the present study. This finding is inconsistent with the findings of Gao *et al.* (2011), who found that pipes had the highest moisture content in all soil layers. This discrepancy may be attributed to the different vegetation types analyzed in the two studies; that is, the present study was conducted in woodland, whereas Gao *et al.*'s study was conducted in perennial grassland.

Micro-topography also influences soil moisture variability. The least variation in the moisture profile was observed for the plane surface, implying that soil moisture is more stable in plane surface sites. In general, the soil moisture variability decreased with soil depth below 20 cm for all three considered micro-topography types (Figure 4). These results are consistent with previous findings in which variations in soil moisture were shown to be higher for surface soil depths due to the frequent exchange of water and energy in the Loess Plateau (Jia & Shao 2014).

The significance of the correlations in soil moisture in the upper and lower soil layers differs among the three micro-topography types. For example, soil moisture in the ridge and plane surfaces displays significant correlations ($P < 0.05$) in the lower layers (40–100 cm), whereas soil moisture in the pipe display significant correlations ($P < 0.05$) in the upper layers (0–40 cm). These findings suggest that the maximum depths of correlation are inconsistent, further indicating that the feasibility and accuracy of predicting soil moisture using time series (Zou *et al.* 2010) can be affected by micro-topography. The correlations between the variances of soil moisture and their corresponding mean values are not always significant due to the influence of micro-topography type, observational date and depth, consistent with the results of an earlier study (Jia & Shao 2014).

Generally, soil properties and topography represent the primary environmental factors that affect the spatial variability of soil moisture on small scales (Biswas & Si 2011; Zhu & Lin 2011; Hu & Si 2014). Within our study site, the soil properties in the top meter of soil are generally uniform; however, the topography varies distinctively across the entire catchment. Therefore, in this study, we mainly focused on constraining the relationship between soil moisture and topography based on the relative elevation, slope gradient, and slope aspect. The relationship between soil moisture and topography was also influenced by micro-topography type. The slope aspect clearly influenced soil moisture in the pipe but not in the plane surface or ridge. Gao *et al.* (2016) found that the slope aspect displayed obviously higher correlation with soil moisture than with slope gradient or elevation, but those authors did not divide the topography into different types. Huang *et al.* (2012) also found that slope aspect exerts a significant influence on soil moisture, whereas other topographic factors (including relative elevation, slope gradient, slope position, and slope profile curvature) have a very weak influence on soil moisture in a small gully catchment of the Loess Plateau. Unlike slope aspect, the slope gradient displays a negative but statistically non-significant correlation with soil moisture than with elevation or slope aspect in the ridge and plane surfaces, especially at depths greater than 40 cm (Table 5). These results demonstrate that slope aspect and slope gradient exert stronger topographic control of soil moisture variability than other topography factors in gullied areas.

Effects of vegetation type on soil moisture in gully areas

In the present study, differences in soil moisture content between natural grasslands and woodlands are used to determine the differences in soil moisture resulting from different vegetation types in gully areas. Wang *et al.* (2013) found that vegetation type significantly influenced mean soil moisture profiles; that is, grassland had more soil moisture content than woodland. Therefore, soil desiccation is more likely to occur in woodland, which is consistent with the results of the present study and previous studies (Qiu *et al.* 2001; Yang *et al.* 2012; Wang *et al.* 2014; Tian *et al.* 2017), although the latter studies were conducted on hillslopes (uplands). The increased likelihood of soil desiccation in woodland occurs mainly because trees have strong root systems (February & Higgins 2010) and strong evapotranspiration (Gao *et al.* 2014), which could result in continuously low soil moisture content in woodland. Furthermore, in this study, the observed variability (SD and CV) in the moisture content of woodland is generally larger than that of natural grasslands (Table 3), most likely because of the dominant contribution of black locust (*R. pseudoacacia*). This result is similar to the results of previous studies conducted on the Loess Plateau (Qiu *et al.* 2001; Fu *et al.* 2003). Additionally, the CV values in the woodlands and grasslands decrease with increasing soil depth, consistent with the results obtained in a previous study (Gao *et al.* 2011). However, woodlands and grasslands present different patterns of correlation within the soil moisture time series. In woodlands, the correlation coefficients decrease as the distance between two observational depths increases, whereas no significant correlations among any of the measured events are observed in grasslands, mainly because woodland and grassland have different vegetation characteristics (Table 1), and these characteristics have important effects on the infiltration process (Zhang & Li 2018). The results indicate that the combined effects of vegetation type, micro-topography, and soil depth complicate the correlation between the variance and the mean values of soil moisture.

Implications for gully afforestation

In general, soil moisture varies widely across a range of spatial and temporal scales due to small-scale components that are dominated by soil type, topography, and vegetation (Entin *et al.* 2000). In our study, both vegetation type and gully micro-topography were found to exert clear influences on the depth-averaged and temporally averaged soil moisture values and their corresponding variances. These results are consistent with those of a previous study of the Loess Plateau conducted by Wang *et al.* (2001).

One of the main objectives of implementing afforestation with black locust (*R. pseudoacacia*) trees on the Loess Plateau is the inhibition of soil erosion by wind and water (Jiao *et al.* 2012). Indeed, large-scale vegetation rehabilitation has reduced the average sediment transport in this region by 57% (0.23 Gt yr^{-1}) between 2000 and 2010 (Wang *et al.* 2015). However, the positive vegetation restoration achieved by controlling soil erosion is counterbalanced by the associated negative effects of increased competition for water (Yang *et al.* 2014). Therefore, to achieve sustainable vegetation restoration in the semi-arid Loess Plateau, soil moisture conditions should first be considered.

In our study, the soil moisture content of the plane surface and the pipe is relatively higher than the moisture content of the ridge; thus, afforestation can be implemented in these two micro-topography types in gully regions. The ridge has low rainwater infiltration and is thus more likely to undergo the formation of dried soil layers. Therefore, within the semi-arid regions of the Loess Plateau, natural grasslands may represent the optimal vegetation type for restoration along ridges, especially considering that native grasslands appear to be able to successfully control erosion from runoff (El Kateb *et al.* 2013).

In the current study, soil moisture was sampled four times in August, September, and October of 2016. In fact, the mean, variability, and correlations of soil moisture are expected to vary throughout the year, particularly during the growth season for vegetation, due to seasonal changes in rainfall and evapotranspiration. In theory, long-term research on the effects of micro-topography and vegetation type on soil moisture dynamics is needed to support the development of more effective restoration policies for gullied areas. However, this may be difficult in practice due to the extensive cost of the labor, time, and instruments required to restore areas with heavily gullied topography (Gao *et al.* 2016). In addition, gully micro-topography is rather complex and gullies with different ages and forms generally coexist in the Loess Plateau. Therefore, soil moisture variability would probably be greater if more sampling points were collected on various types of micro-topography in gullies. Nevertheless, the 36 sampling points in this study could represent largely the effects of micro-topography on soil moisture in this area, since the locations of these sampling points covered the main micro-topography types (ridges, plane surfaces, and pipes) of large gullies. To explore the spatio-temporal variation characteristics of soil moisture in gullied areas, further effort is needed since gullies play a critical role in hydrological and ecological processes and in agricultural productivity in gullied areas (Melliger & Niemann 2010). Given that the effects of micro-topography and vegetation type on soil moisture remain poorly understood, the results of this study are expected to improve the understanding of the role of micro-topography and vegetation on soil moisture in gullies and to provide a scientific basis for the optimization of micro-topography reconstruction and vegetation restoration efforts in gullied areas, especially those in semi-arid regions.

CONCLUSIONS

This paper reports a study of the effects of micro-topography and vegetation type on soil moisture in a typical gully within the Loess Plateau of China. The results indicate that soil moisture in the root-zone profiles of woodlands is 6.2% lower than that of natural grasslands. We observed significant differences in root-zone soil moisture among micro-topography types, with ridge woodlands presenting the lowest soil moisture and plane surface woodlands presenting the highest soil moisture. In general, soil moisture in root-zones steadily increases downslope along all transects.

The woodland regions in the gully show increased spatial variability in soil moisture, as indicated by the observed average increase of 17.1% in the SD and 22.2% in the CV and by the average observed decrease of 6.2% in the spatial mean values. These results demonstrate that afforestation in gullies mainly alters the spatial patterns of soil moisture variability and that it exerts only a weak influence on the spatial mean values. Furthermore, the observed increases in the Pearson correlation coefficient indicate that gullies that have undergone afforestation display increasing spatial correlations among the measured soil moisture values in shallow soil layers at depths of 0–40 cm.

Overall, these results demonstrate that the statistical distribution of soil moisture is highly dependent on micro-topography and vegetation type. Therefore, micro-topography and vegetation type should be considered when attempting to characterize the variability of soil moisture within large gullies of the Loess Plateau and when characterizing soil moisture variability in other heavily gullied regions worldwide. To achieve sustainable vegetation restoration in semi-arid gullied regions, micro-topography should be scientifically evaluated, and its effects on local soil moisture variability should be determined.

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