

Effects of topographic domain and land use on spatial variability of deep soil moisture in the semi-arid Loess Plateau of China

Bowei Yu, Gaohuan Liu, Qingsheng Liu, Chong Huang and He Li

ABSTRACT

Deep soil moisture is fundamental to hydrological cycle and ecosystem sustainability in arid and semi-arid regions. This study examined the combined effects of topographic domain and land use on the spatial variability of deep soil moisture (0–5 m) on the semi-arid Loess Plateau of China. Our results showed that deep soil moisture was generally temporally stable due to the thick loess soil in the plateau region. The depth-averaged soil moisture was slightly lower in the gully domain compared to the hillslope domain but was dependent on the soil depths. Soil moisture variability was clearly larger in the gully domain when compared with that in the hillslope domain in the 0–5 m profile. The mean soil moisture contents in comparable soil depths were lower in forestland than in grassland (and farmland), particularly in the hillslope domain. Land uses had similar vertical distribution characteristics of deep soil moisture for each topographic domain. Soil moisture showed highly significant positive correlations with slope aspect in the hillslope domain and with profile curvature in the gully domain.

Key words | deep soil moisture, land use, Loess Plateau, spatial distribution, topographic domain

Bowei Yu

Gaohuan Liu (corresponding author)

Qingsheng Liu

Chong Huang

He Li

State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
E-mail: liugh@reis.ac.cn

Bowei Yu

University of Chinese Academy of Sciences, Beijing 100049, China

INTRODUCTION

Catchments generally consist of the hillslope domain and the gully domain on the semi-arid Loess Plateau (Gao *et al.* 2016). The hillslope domain is located in higher parts of a catchment and has gentle slopes (generally $<25^\circ$). The gully domain is composed of various gullies that are generally connected to form a natural geographical unit (Liu & Li 2017). The gully domain covers approximately 40% of the total area with a density of $1.5\text{--}4.0\text{ km}\cdot\text{km}^{-2}$ on the semi-arid Loess Plateau (Zheng *et al.* 2006). Specifically, gullies are located in the lower parts of catchments and generally have steep slopes from 25° to 90° (Gao *et al.* 2016). Moreover, gullies, which often occur in loess, represent an important form of severe land degradation in the world (Melliger & Niemann 2010). For example, they reduce the agricultural potential and grazing value in gullied

regions (Krause *et al.* 2003). The gully domain should be considered separate from the hillslope domain to examine soil moisture spatial variability in water-limited regions (Grayson & Western 2001). Therefore, characterizing soil moisture spatial variability individually in the hillslope domain and the gully domain is important for practical applications involving soil erosion, surface runoff, agricultural production, and ecological restoration.

Soil moisture is a main component of terrestrial water resources and has an important influence on many ecological and hydrological processes in both topographic domains (Zhu & Shao 2008). In general, soil moisture stored in deep layers (usually below 1–2 m) is an important water resource for plant growth and ecosystem health in semi-arid regions (Ferreira *et al.* 2007). Soil moisture varies greatly due to

the variability of soils, topographic factors, land uses and precipitation (Western *et al.* 2004; Brocca *et al.* 2007; Vereecken *et al.* 2014). Specifically, the topographic variability, as represented mainly by the topographic domains in gullies regions, can significantly affect the redistribution of precipitation, surface runoff and solar radiation (Qiu *et al.* 2010), inevitably resulting in spatial variability of soil moisture (Meerveld & McDonnell 2006). Because soil properties and precipitation have overall low spatial variability in small gully catchments, topography and land use are key factors that influence soil moisture variations. Furthermore, topographically routed subsurface lateral flow may be important in wet situations, but the hydrological connectivity between gullies and nearby hillslopes may be weak under dry conditions because vertical fluxes dominate over lateral (Grayson *et al.* 1997).

Soil moisture spatial variations have been intensively explored over the past two decades (Qiu *et al.* 2001; Penna *et al.* 2009; Brocca *et al.* 2010; Hu *et al.* 2010; Yang *et al.* 2012; Biswas *et al.* 2014; Mascaro & Vivoni 2016). However, few studies have been conducted in the gully domain, likely due to the sampling difficulty. Melliger & Niemann (2010) and Gao *et al.* (2016) reported the impacts of gullies on soil moisture variability in southeastern Colorado and the Loess Plateau, respectively, and both found that gullies had weak effects on spatially averaged values of soil moisture but obviously increased spatial variability. Yu *et al.* (2018) demonstrated that the root zone soil moisture (0–1 m) was significantly influenced by microtopographic types in a large gully region. Despite these efforts, the relationships between the topographic domain and soil moisture are still unclear, because research in the gully domain has focused mainly on shallow soil layers (above 1 m). Moreover, the land use type can disrupt the water balance due to transpiration and root uptake (Fu *et al.* 2003; Zhu & Shao 2008).

To reduce serious soil loss on the Loess Plateau, the central government launched the 'Grain to Green' large-scale revegetation project in 1999. In the project, afforestation has been encouraged in both the hillslope domain and the gully domain. Planting trees could reduce surface runoff (Duan *et al.* 2016), control soil erosion (Deng *et al.* 2012), regulate the hydrological regime (Yaseef *et al.* 2010) and increase carbon sequestration (Feng *et al.* 2013). However,

planting trees could also decrease the soil moisture content due to root water uptake (Wang *et al.* 2010; Jian *et al.* 2015). Recent studies have found that forests have caused excessive depletion of deep soil moisture in some areas of the Loess Plateau (Chen *et al.* 2008a; Jia *et al.* 2017). Furthermore, while most studies have focused on the hillslope domain, conclusions were drawn at the whole catchment scale (Fu *et al.* 2003; Hu *et al.* 2010). Although soil moisture has been paid increasing attention on the Loess Plateau, little information is available regarding the distribution characteristics of deep soil moisture based on topographic domains and land uses. Therefore, examining the effects of topographic domain and land use on the spatial variability of deep soil moisture is important, which could provide insights into soil moisture spatial variability and their controlling factors, hence promoting the sustainability of ecological restoration on the semi-arid Loess Plateau.

In this study, we examined how topographic domains and land use types affect deep soil moisture spatial variability on the semi-arid Loess Plateau. The specific objectives are to examine: (1) the effect of topographic domain on deep soil moisture; (2) the effect of land use on deep soil moisture; and (3) the relations between deep soil moisture and topographic attributes in different topographic domains.

MATERIALS AND METHODS

Study area

The study area is located in the Jiegou catchment (36°56'N, 110°46'E), western Shanxi Province of China (Figure 1). This catchment has an area of 0.19 km² in the hillslope domain and 0.30 km² in the gully domain. The site has a semi-arid continental climate: mean annual temperature of approximately 9.8 °C and mean annual rainfall of 465 mm. Most rainfall generally occurs from July to September in the form of thunderstorms, which account for more than 60% of the annual total. As shown in Figure 1, the elevation of the catchment ranges from 1,042 to 1,261 m. The hillslope domain comprises higher parts of the catchment with relatively gentle slopes (<25°), and the gully domain encompasses lower parts of the catchment with steep slopes (>25°). The gully depth ranges from 50 to 200 m,

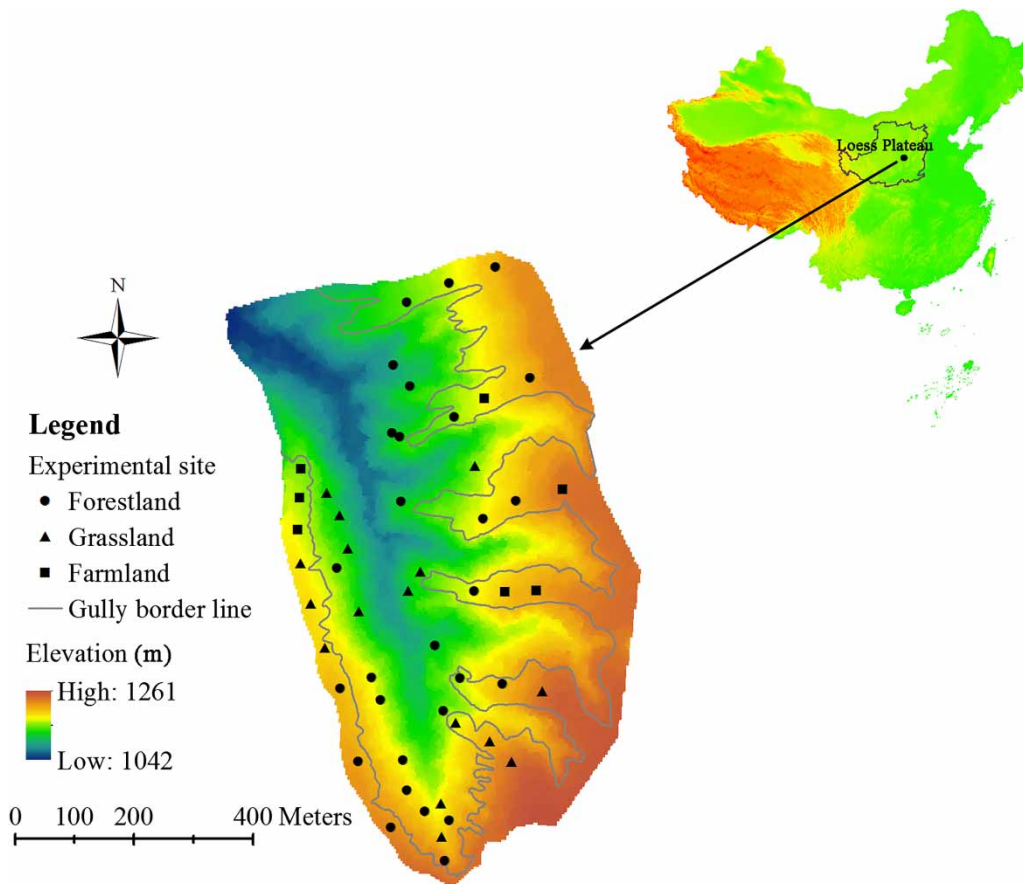


Figure 1 | Location of the study area and spatial distribution of experimental sites in the two topographic domains.

depending on the topography. A thin soil layer mainly covers the gully bottom (generally <0.5 m). The dominant soil type is loess (silt to loam textural classes) with overall low spatial variability of soil properties. The groundwater levels are generally 40–100 m below the surface; therefore, soil moisture is the main water source for plants (Yang *et al.* 2012).

Forestland, native grassland and rain-fed farmland are the dominant land use types in the catchment. For forestland, black locust (*Robinia pseudoacacia*) was planted in 2010–2011. This planting project was initiated and funded by the Hong Kong Green Action Charity Foundation, and these forestlands were converted from farmland in the hillslope domain or grassland in the gully domain. Grassland is the dominant community, with native grasses and herbs, such as *Artemisia gmelinii*, *Potentilla chinensis* and *Artemisia scoparia*. Farmland has been planted with annual crops (e.g.,

maize) for more than 30 years. Crops are usually sown in April and manually harvested in October.

Soil moisture data collection

We selected 27 experimental sites in the hillslope domain and 24 experimental sites in the gully domain (Figure 1). These experimental sites were selected based on various topographic domains and land uses, and were distributed in different spatial positions over the hillslope and gully domains. According to Gao *et al.* (2011), the microtopography in the gully domain includes ridges, pipes, plane surfaces and cliffs. Experimental sites were selected to cover these different microtopographic positions (except for cliffs which have much steep inaccessible slopes) in the gully domain. Soil moisture collected from these sites is therefore expected to be representative of the different

topographic domains and land uses. Soil moisture in the hillslope domain was measured in May, July and September 2017, corresponding to spring, summer and fall on the semi-arid Loess Plateau; soil moisture in the gully domain was measured once in September. The main reason for this was the difficulty in sampling deep soil moisture (0–5 m) over complex topography. The soil moisture content data collected in the hillslope domain were used to examine seasonal variations in deep soil moisture. The soil moisture data collected in September were compared between different topographic domains. We sampled soil moisture from depths of 0–5 m using a drill (4.5 cm in diameter) at intervals of 20 cm. A total of 25 samples were collected at each experimental site. The gravimetric moisture content was measured using the oven-dry method (24 h at 105 °C) in the laboratory. It took 5 days to complete field sampling and laboratory work.

Topographic attributes

Topographic attributes for each experimental site, including the elevation (h), slope gradient (α), slope aspect (β), plan curvature (K_h), profile curvature (K_p), topographical wetness index (TWI) and stream power index (SPI), were derived from a digital elevation model (DEM) with a 4-m resolution. The DEM obtained from unmanned aerial vehicle remote sensing data and the accuracy in an aerial DEM is 0.89 m. The TWI was calculated by the following equation:

$$\text{TWI} = \ln(Ac/\tan \alpha) \quad (1)$$

where Ac is the upslope contribution area per unit contour length. The SPI was calculated as follows:

$$\text{SPI} = \ln(Ac + \tan \alpha \times 100) \quad (2)$$

See Moore *et al.* (1991) and Western *et al.* (1999) for a detailed introduction on these topographic indices.

Data analysis

The soil moisture profile was analyzed to determine the mean and standard deviation (SD) using samples from all

experimental sites at each spatial domain or land use type. The depth-averaged soil moisture at each experimental site ($\bar{\theta}_j$) was calculated as follows:

$$\bar{\theta}_j = \frac{1}{N_i} \sum_{i=1}^{N_i} \theta_i \quad (3)$$

where N_i is the number of soil layers at site j and θ_i is the final soil moisture content of layer i . Then, the depth-averaged soil moisture content for each land use ($\bar{\theta}$) was calculated as follows:

$$\bar{\theta} = \frac{1}{N_k} \sum_{k=1}^{N_k} \bar{\theta}_j \quad (4)$$

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

The spatial distribution of soil moisture was interpolated using the Kriging method in ArcGIS 10.1 (ESRI, Redlands, CA, USA). One-way analysis of variance (ANOVA) was used to evaluate the mean soil moisture contents among land use types in each topographic domain. Multiple comparisons were conducted using the least significant difference (LSD) method at the 0.05 level. Pearson correlation coefficients were used to examine the relationships between soil moisture and topographic attributes. Statistical analyses were performed using the SPSS software (Version 16.0, SPSS Inc., IL, USA).

RESULTS

Seasonal variation of soil moisture profile in the hillslope domain

Soil moisture content data collected in the hillslope domain were analyzed to determine seasonal moisture variations. The vertical distribution of soil moisture in 0–5 m soil profile at 27 experimental sites during different seasons in the hillslope domain is shown in Figure 2. Generally, soil moisture fluctuated largely in shallow layers across seasons in the hillslope domain. The depth-averaged soil moisture below 2 m was 10.5%, 9.9% and 10.1% in spring, summer and fall, respectively. Furthermore, Figure 3 plots the profile

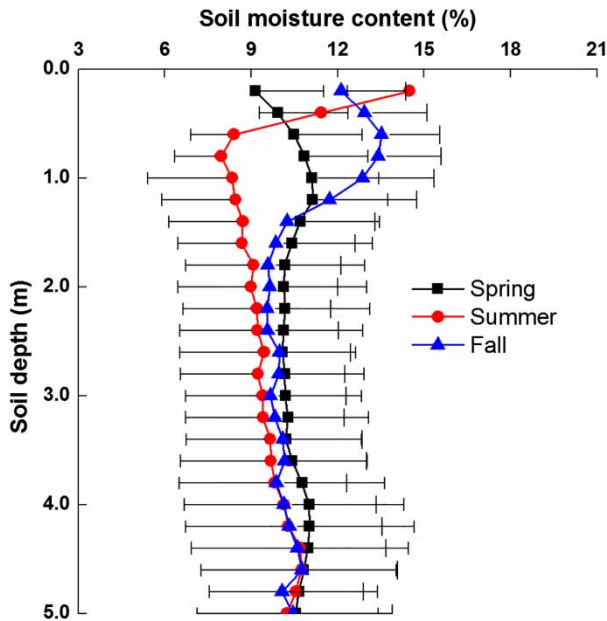


Figure 2 | Profile distribution of soil moisture during different seasons in the hillslope domain. The error bar represents the standard deviation.

soil moisture for land uses in spring, summer and fall. In general, forestland had lower soil moisture content than fields under grassland and farmland over the growing season. For all land use types, soil moisture was stable until 1 m in spring and summer and until 1.5 m in fall.

These results suggest that the infiltration depth of annual rainfall does not exceed 2 m and soil moisture content below this depth is temporally stable.

Soil moisture profile in two topographic domains

The profile distribution of mean soil moisture content in two different topographic domains is shown in Figure 4. Some differences in soil moisture can be observed between the hillslope and gully topographic domains based on the 0–5 m profile, but these differences are dependent on the soil depths. The depth-averaged soil moisture in the gully domain was approximately 8.9% lower than that in the hillslope domain above 2 m depth and approximately 5.6% higher than that in the hillslope domain below 2 m depth. Unlike the mean soil moisture, the hillslope domain exhibited lower SD values than the gully domain in 0–5 m soil depths. Overall, the mean soil moisture content in the gully domain was lower by an average of 0.7% in depths from 0 to 5 m, and the moisture variability was higher by an average of 10.0%, when compared with these values in the hillslope domain.

As shown in Figure 5, the mean soil moisture content in comparable soil depths was lowest in forestland compared

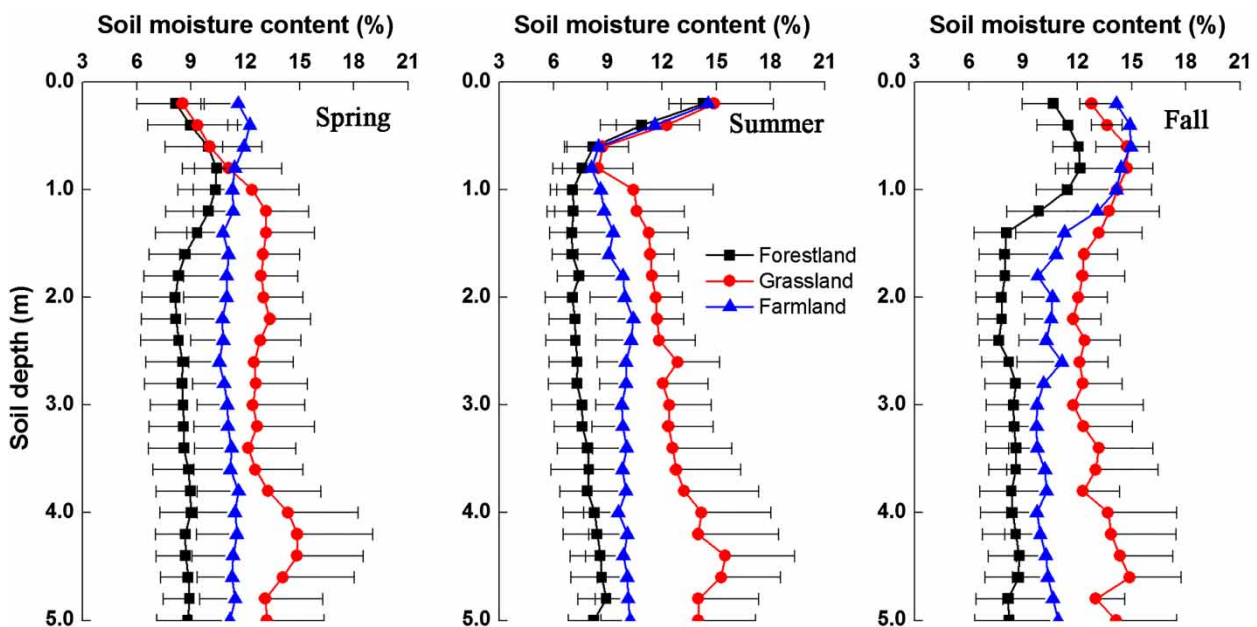


Figure 3 | Seasonal distribution of soil moisture profile for different land use types in the hillslope domain. The error bar represents the standard deviation.

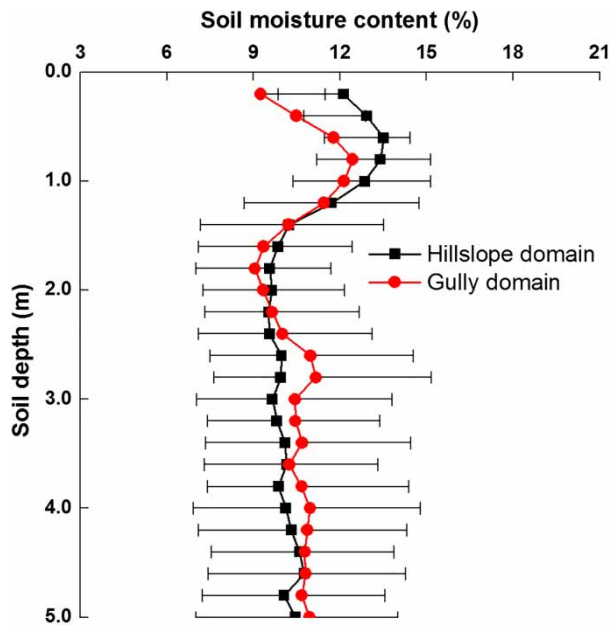


Figure 4 | Profile distribution of soil moisture in two topographic domains. The error bar represents the standard deviation.

with farmland and grassland in both topographic domains. The LSD test illustrated that forestland had significantly lower soil moisture content than grassland in the hillslope domain ($p < 0.05$). However, no statistically significant

difference was found between forestland and grassland in the gully domain ($p > 0.05$) (Table 1). The mean moisture content displayed similar vertical distribution characteristics among land use types in the two topographic domains (Figure 5). However, there were different trends and patterns between the two domains. For example, soil moisture was relatively stable until 1.5 m in the hillslope domain, and the relatively stable depth reached 3 m in the gully domain in all considered land use types (Figure 5). Furthermore, soil moisture in forestland was higher in the hillslope domain in shallow soil layers (< 0.8 m) but higher in the gully domain in deep soil layers (> 0.8 m). Generally, soil moisture in grassland was higher in the hillslope domain than in the gully domain in 0–5 m (Figure 5 and Table 1). Overall, gully forestland was 10.8% higher in depth-averaged moisture content than hillslope forestland in the 0–5 m profile, and hillslope grassland was 13.3% higher than gully grassland. These results mean that the moisture discrepancy between hillslope and gully domains was clearly dependent on land use types.

Similar to the mean values, the SDs of soil moisture in comparable soil depths of forestland were relatively lower than those of other land use types in both topographic domains (Figure 5 and Table 1). Compared with the

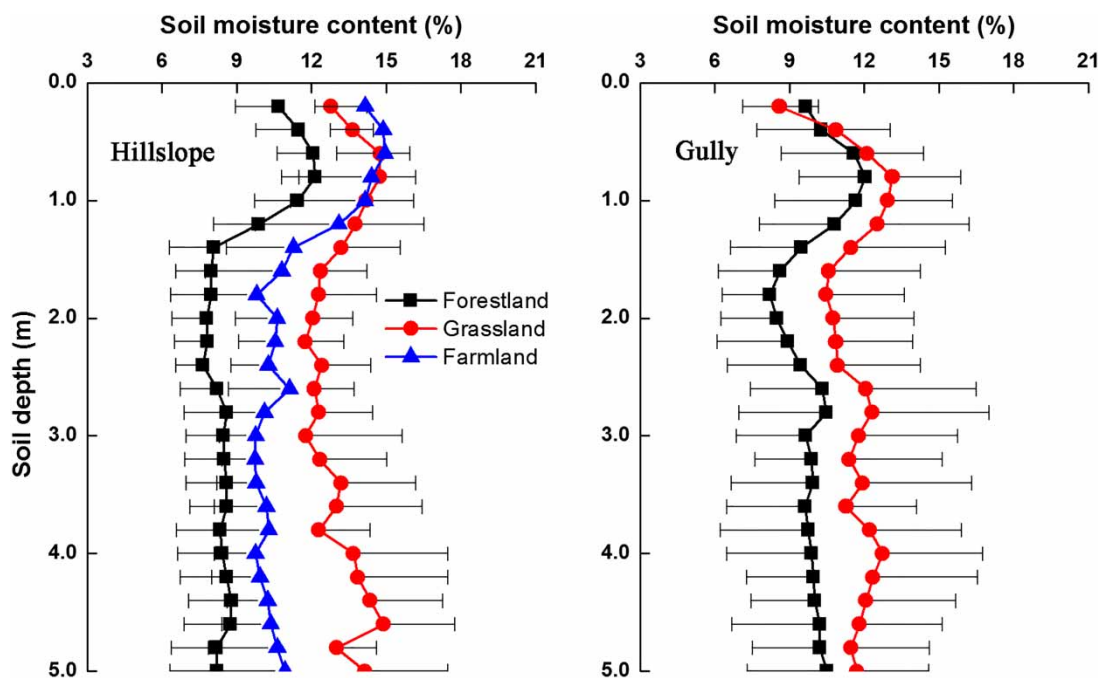


Figure 5 | Vertical distribution of soil moisture among land use types in the hillslope domain and the gully domain. The error bar represents the standard deviation.

Table 1 | Soil moisture from 0 to 5 m for different land use types

Topographic domain	Soil depth (m)	Forestland		Grassland		Farmland	
		Mean (%)	SD	Mean (%)	SD	Mean (%)	SD
Hillslope	0–1	11.57b*	1.40	14.02a	1.09	14.51a	2.17
	1–2	8.34b	1.28	12.73a	2.01	11.12a	2.39
	2–3	8.14c	1.23	12.07a	1.81	10.37b	1.48
	3–4	8.49b	1.52	12.90a	2.59	9.95b	1.61
	4–5	8.51b	1.77	14.05a	2.32	10.42b	2.02
Gully	0–1	11.04a	2.56	11.53a	2.05	–	–
	1–2	9.12a	2.28	11.16a	3.40	–	–
	2–3	9.77a	2.65	11.59a	3.74	–	–
	3–4	9.82a	3.01	11.92a	3.53	–	–
	4–5	10.18a	2.76	11.88a	3.12	–	–

*The same letters in the same row denote that values are not significantly different at the 0.05 level.

hillslope domain, the SD values in the gully domain were higher in all considered land use types. For example, in the 0–5 m profile, the SD values of forestland ranged from 1.07 to 1.88 in the hillslope domain but from 1.91 to 3.53 in the gully domain. Overall, for forestland and grassland, the depth-averaged SD values in the gully domain were 77.8% and 44.8% higher than those in the hillslope domain, respectively.

Soil moisture spatial patterns in different soil depths

Figure 6 was created using the Kriging approach to determine the spatial distribution of soil moisture in both topographic domains. Additionally, the basic statistics of the spatial properties of soil moisture were calculated for different soil depths (Table 2). The Kriging maps indicated that the soil moisture distribution in the hillslope domain exhibited a descending trend in soil depths from 2 to 4 m, and the soil moisture distribution in the gully domain displayed an ascending trend in soil depths from 2 to 5 m. The spatial mean soil moisture contents in the hillslope domain were higher than those in the gully domain above 2 m, but the gully domain exhibited higher spatial mean values of soil moisture than those in the hillslope domain below 2 m. Furthermore, the soil moisture spatial distribution was closely related to land use patterns (Figures 1 and 6). For example, relatively low soil moisture contents were generally observed in forestland areas, independent

of topographic domains and soil depths. In addition, the spatially averaged soil moisture content was higher in the top 1 m of the soil than in other soil depths in both topographic domains (Figure 6 and Table 2).

Relationships between soil moisture and topographic attributes

Pearson correlation coefficients were calculated to examine the relationships between soil moisture and topographic attributes in each topographic domain, as presented in Table 3. In general, the correlation coefficients were dependent on the topographic domains and soil depths. In the hillslope domain, soil moisture demonstrated strong positive correlations with slope aspect, especially in deep soil layers. In addition, soil moisture showed significant negative correlations with slope gradient in the top 1 m ($p < 0.05$), but no significant correlations were observed in depths below 1 m ($p > 0.05$). In the gully domain, soil moisture observed strong positive correlations with profile curvature, particularly in deep soil layers. In contrast, soil moisture and profile curvature showed weak negative correlations in the hillslope domain. In summary, soil moisture in the hillslope domain was affected by the slope gradient and aspect, and in the gully domain, it was profile curvature. Other topographic attributes, including elevation, plan curvature, the topographic wetness index, and the stream power index, had weak influences on soil moisture in both topographic domains.

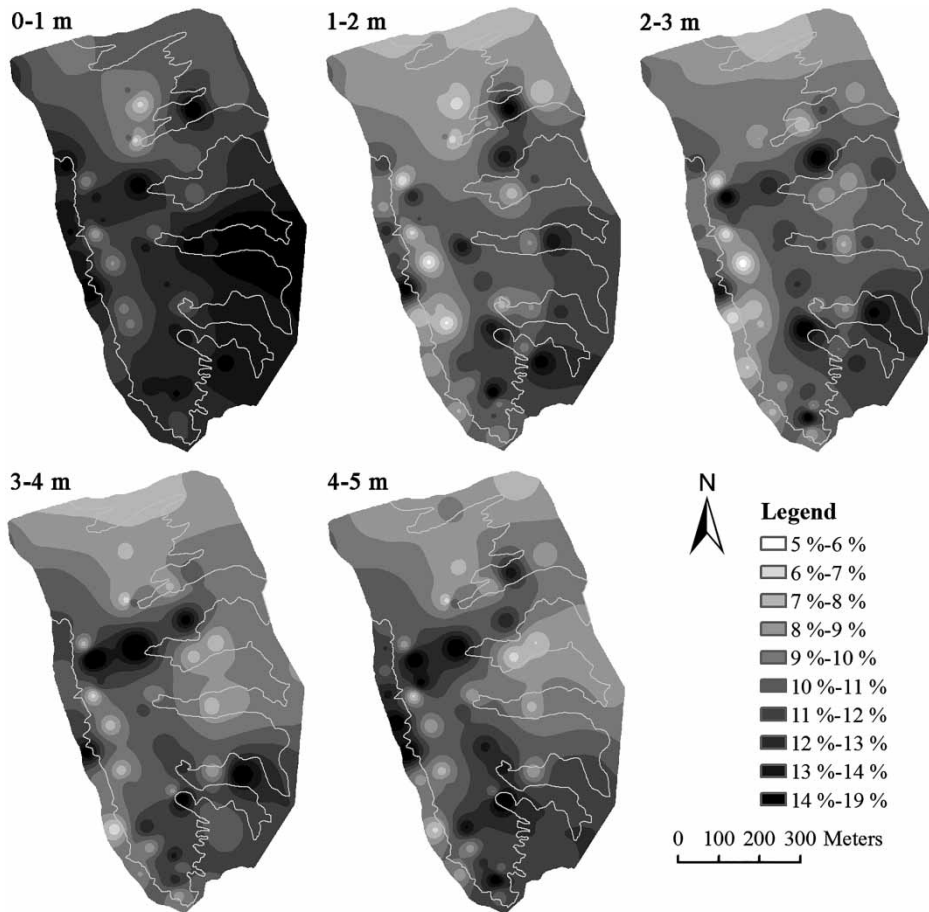


Figure 6 | Spatial distribution of soil moisture in the 0-1, 1-2, 2-3, 3-4 and 4-5 m soil depths, interpolated by the Kriging method.

Table 2 | Spatial properties of soil moisture in different soil depths

Soil depth (m)	Hillslope domain					Gully domain				
	Minimum (%)	Maximum (%)	Mean (%)	SD	CV	Minimum (%)	Maximum (%)	Mean (%)	SD	CV
0-1	7.47	18.86	12.51	1.54	0.12	6.47	17.47	11.85	1.47	0.12
1-2	7.01	15.31	10.20	1.61	0.16	5.84	15.71	9.90	1.34	0.14
2-3	6.41	15.23	10.03	1.44	0.14	5.53	16.88	10.14	1.26	0.12
3-4	6.41	16.40	9.84	1.52	0.15	6.15	18.60	10.18	1.49	0.15
4-5	6.67	17.92	10.03	1.68	0.17	6.40	16.08	10.37	1.39	0.13

DISCUSSION

Deep soil moisture distribution in different topographic domains

The Loess Plateau of China has a typical arid and semi-arid climate. In this region, the average annual rainfall and pan

evaporation ranges from 300 to 650 mm and from 1,400 to 2,000 mm, respectively (Chen *et al.* 2008a). When evapotranspiration exceeds rainfall, the hydraulic conductivity is low, and any rainfall that occurs essentially wets up the surface soil and is evapotranspired before any significant lateral redistribution takes place (Grayson *et al.* 1997). According to Grayson *et al.* (1997), under dry conditions when soil

Table 3 | Pearson correlation coefficients between soil moisture and topographic attributes

Topographic domain	Soil depth (m)	h (m)	$TAN\alpha$	$COS\beta$	K_h	K_v	TWI	SPI
Hillslope	0–1	0.202	–0.396*	0.371	–0.153	–0.167	0.032	–0.358
	1–2	0.144	–0.099	0.343	–0.033	–0.127	–0.160	–0.245
	2–3	0.214	–0.170	0.367	0.138	–0.220	–0.179	–0.296
	3–4	–0.020	–0.005	0.468*	0.248	–0.007	–0.037	0.017
	4–5	–0.189	–0.016	0.403*	0.333	0.180	0.030	0.085
Gully	0–1	0.213	0.088	0.000	0.126	0.153	–0.273	–0.150
	1–2	0.134	–0.170	–0.022	0.118	0.251	–0.149	–0.123
	2–3	–0.037	–0.130	0.189	–0.006	0.256	–0.274	–0.302
	3–4	–0.067	–0.130	0.133	0.020	0.288	–0.178	–0.222
	4–5	0.060	–0.099	0.089	–0.036	0.425*	–0.250	–0.264

*Significant at the 0.05 level.

moisture is well below saturation, the macropore flow mechanism cannot operate. This means that there will be negligible lateral flow between different areas of the catchments and that only (local) terrain, (local) vegetation, and possibly radiation can influence the soil moisture patterns (Takagi & Lin 2012).

In this study, deep soil moisture showed differences in the two topographic domains on the semi-arid Loess Plateau (Figure 4). The result partly agreed with the findings of Basnet et al. (1993), who discovered that significant differences in soil moisture existed among different topographic positions (ridges, slopes and valleys). The gully domain observed lower depth-averaged moisture content than the hillslope domain (Figure 4), which disagreed with the results of Hu (2009) and Gao et al. (2011), who reported that the gullies illustrated higher moisture content than the upper hillslope. This discrepancy is likely because most of the experimental sites used by Hu (2009) and Gao et al. (2011) were located in the gully bottoms. Furthermore, the differences in soil moisture between the two topographic domains were dependent on the soil depths (Figure 4). For example, soil moisture was higher in the hillslope domain than that of the gully domain in shallow soil layers (above 2 m), but lower values were found in deep soil layers (below 2 m). However, Gao et al. (2013) demonstrated that the moisture difference in hillslopes and gullies increased at all soil depths. These contrasting results are likely due to the differences in the sampled depths, sampling locations and experimental areas.

Soil moisture in the semi-arid Loess Plateau is highly temporally variable in shallow layers because of changes in

precipitation and evapotranspiration. However, the temporal dynamics of deep soil moisture decreases as rainfall infiltration decreases on the Loess Plateau (Yang et al. 2017). In the vertical direction, deep soil moisture exhibits different patterns than shallow soil moisture (Yang et al. 2012), and in general, soil moisture is relatively stable below the rainfall infiltration depth in loess regions (Yang et al. 2014). In this study, soil moisture exhibited small fluctuations below 2 and 3 m in the hillslope and gully domains, respectively. These fluctuations are likely because of differences in evapotranspiration and lateral transport in the hillslope and gully domains.

Unlike the mean values of soil moisture, the spatial variability in soil moisture was clearly larger in the gully domain than in the hillslope domain at all soil depths (Figure 4). Similar findings were reported by Gao et al. (2016) on the Loess Plateau and Melliger & Niemann (2010) in southeastern Colorado. This means that including gully observations obviously increase soil moisture variability, which partly agrees with the results of Brocca et al. (2010) who found that the soil moisture variability increased with the extent of the investigated area and remained quite constant for greater extents at the catchment scale. Therefore, the occurrence of gullies weakly affects the mean values but obviously affects deep soil moisture spatial variability on the semi-arid Loess Plateau.

Effects of land use types and topographic attributes on deep soil moisture

In the semi-arid loess regions where precipitation is usually the only water input for soil moisture, land use is thought to affect deep soil moisture levels primarily due to the

distribution patterns of rainfall and the rooting depth and water consumption characteristics of vegetation (Xiao *et al.* 2014). In this study, deep soil moisture differed among land use types in the different topographic domains, suggesting that the distribution of deep soil moisture was influenced by land use type. This finding is consistent with previous studies (Chen *et al.* 2008b; Wang *et al.* 2011), which reported that land use had a significant influence on the deep soil moisture content. Furthermore, a similar vertical pattern of soil moisture distribution was observed among land use types in the hillslope and gully domains (Figure 5). The findings suggest that land use and the topographic domain jointly affect the soil moisture content and its spatial patterns. In addition, forestland exhibited significantly lower soil moisture contents than other land use types in both considered topographic domains ($p < 0.05$) (Table 1), likely because of the interception of rainfall by leaves, higher potential evapotranspiration and deeper roots (Jian *et al.* 2015). Grassland exhibited a higher level of variability at greater depths than did the soil moisture in other land use types in both the hillslope and gully domains (Figure 5). This was probably because the development of roots by the various plants in grassland prevented a stable variability (Jia & Shao 2014).

In the present study, the correlation coefficients indicate that slope aspect was the main topographic factor that affected soil moisture in the hillslope domain, and profile curvature was the main topographic factor of influence in the gully domain (Table 3). This is in partial agreement with Gao *et al.* (2016) and Huang *et al.* (2012), who showed that slope aspect had a strong topographic control on hillslope soil moisture.

Implications for afforestation

Gullies are expected to have higher moisture contents than the higher position hillslopes. However, the moisture differences in the two topographic domains are dependent on the soil depths and land use types (Figures 4 and 5). This suggests that both topography and land use have an impact on soil moisture spatial patterns in complex terrain regions (Kornelsen & Coulibaly 2013). Forestland exhibited a lower deep soil moisture content than farmland or grassland in both the hillslope and gully domains (Table 1). Furthermore, the depletion of deep soil moisture was more severe in the

hillslope domain than in the gully domain (Figure 5 and Table 1). This may lead to deficits in deep soil moisture in the hillslope domain because of lower recharge by rainfall (Wang *et al.* 2010). Because of the imbalance in soil moisture availability and utilization by trees, dry soil layers have been formed on the semi-arid Loess Plateau (Wang *et al.* 2011).

Planting black locust (*R. pseudoacacia*) has caused the decline of deep soil moisture in both topographic domains (Figure 5). Previous studies also found that the introduction of exotic tree species intensified soil moisture depletion on the Loess Plateau (Wang *et al.* 2010; Jia *et al.* 2017). For sustainable ecological restoration, revegetation should have the potential to control soil erosion without increasing soil moisture deficits (Jia *et al.* 2017). Furthermore, according to this study, soil moisture was different in two topographic domains (Figure 4). To maintain sustainable soil moisture regimes, reforestation should also consider topographic domain in the water-limited Loess Plateau.

A limitation of the present study is the lack of long-term monitoring of deep soil moisture data. Nevertheless, the findings of this study provide insights for the influence of large gullies on the spatial distribution behavior of deep soil moisture in water-limited regions, because the temporal variability of soil moisture in deep profiles is relatively low and stable, especially at depths below 2 m (Fang *et al.* 2016; Yang *et al.* 2017). The infiltration depth of annual rainfall does not exceed 2 m, and soil moisture content below this depth was temporally stable (Figures 2 and 3). This agrees with the findings of Liu & Shao (2014) who showed that soil moisture above 1 m reacted markedly to precipitation inputs, while less response to precipitation below this depth was evident, based on over 10 years of observation on the Loess Plateau. Nevertheless, there is the need for long-term continuous soil moisture monitoring at multiple depths linked with ecological restoration in different topographic domains, as these datasets can contain important information regarding hydrological processes and allow for space-time geostatistical modeling.

CONCLUSIONS

This study demonstrates the influence of topographic domain and land use on deep soil moisture spatial

variability on the semi-arid Loess Plateau. Temporal changes in the mean soil moisture content decreased with increasing soil depth and were stable beyond 2 m. Compared with the hillslope domain, the gully domain exhibited larger spatial variability in deep soil moisture but slightly lower mean values. The profile distribution patterns of deep soil moisture were similar in various land use types in each hillslope and gully domain, but different trends and patterns were observed in the two topographic domains. Deep soil moisture has been reduced due to afforestation, especially in the hillslope domain. In summary, the land use and topographic domain jointly determined the deep soil moisture spatial pattern and variability. The results might provide significant insights for afforestation based on deep soil moisture spatial variability in heavily gullied regions.

ACKNOWLEDGEMENTS

This work is jointly supported by the International Scientific Cooperation Program of the National Natural Science Foundation of China (Nos. 41661144030 and 41561144012) and the State Key Laboratory of Resources and Environmental Information System of the Chinese Academy of Sciences (Nos. 08R8A010YA and 088RA20CYA).

REFERENCES

- Basnet, K., Scatena, F. N., Likens, G. E. & Lugo, A. E. 1993 Ecological consequences of root grafting in tabonuco (*Dacryodes excelsa*) trees in the Luquillo experimental forest, Puerto Rico. *Biotropica* **25**, 28–35.
- Biswas, A., Cresswell, H. P., Rossel, R. A. V. & Si, B. C. 2014 Curve let transform to study scale-dependent anisotropic soil spatial variation. *Geoderma* **213**, 589–599.
- Brocca, L., Morbidelli, R., Melone, F. & Moramarco, T. 2007 Soil moisture spatial variability in experimental areas of central Italy. *J. Hydrol.* **333**, 356–373.
- Brocca, L., Melone, F., Moramarco, T. & Morbidelli, R. 2010 Spatial-temporal variability of soil moisture and its estimation across scales. *Water Resour. Res.* **46**, W02516.
- Chen, H. S., Shao, M. G. & Li, Y. Y. 2008a Soil desiccation in the Loess Plateau of China. *Geoderma* **143**, 91–100.
- Chen, H. S., Shao, M. G. & Li, Y. Y. 2008b The characteristics of soil water cycle and water balance on steep grassland under natural and simulated rainfall conditions in the Loess Plateau of China. *J. Hydrol.* **360**, 242–251.
- Deng, L., Shangguan, Z. P. & Li, R. 2012 Effects of the grain-for-green program on soil erosion in China. *Int. J. Sediment Res.* **27**, 120–127.
- Duan, L. X., Huang, M. B. & Zhang, L. D. 2016 Differences in hydrological responses for different vegetation types on a steep slope on the Loess Plateau, China. *J. Hydrol.* **537**, 356–366.
- Fang, X. N., Zhao, W. W., Wang, L. X., Feng, Q., Ding, J. Y., Liu, Y. X. & Zhang, X. 2016 Variations of deep soil moisture under different vegetation types and influencing factors in a watershed of the Loess Plateau, China. *Hydrol. Earth Syst. Sci.* **20**, 3309–3323.
- Feng, X. M., Fu, B. J., Lu, N., Zeng, Y. & Wu, B. F. 2013 How ecological restoration alters ecosystem services: an analysis of carbon sequestration in China's Loess Plateau. *Sci. Rep.* **3**, 2846.
- Ferreira, J. N., Bustamante, M., Garcia-Montiel, D. C., Caylor, K. K. & Davidson, E. A. 2007 Spatial variation in vegetation structure coupled to plant available water determined by two-dimensional soil resistivity profiling in a Brazilian savanna. *Oecologia* **153**, 417–430.
- Fu, B. J., Wang, J., Chen, L. D. & Qiu, Y. 2003 The effects of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. *Catena* **54**, 197–213.
- Gao, X. D., Wu, P. T., Zhao, X. N., Shi, Y. G., Wang, J. W. & Zhang, B. Q. 2011 Soil moisture variability along transects over a well-developed gully in the Loess Plateau, China. *Catena* **87**, 357–367.
- Gao, X. D., Wu, P. T., Zhao, X. N., Zhang, B. Q., Wang, J. W. & Shi, Y. G. 2013 Estimating the spatial means and variability of root-zone soil moisture in gullies using measurements from nearby uplands. *J. Hydrol.* **476**, 28–41.
- Gao, X. D., Zhao, X. N., Wu, P. T., Brocca, L. & Zhang, B. Q. 2016 Effects of large gullies on catchment-scale soil moisture spatial behaviors: a case study on the Loess Plateau of China. *Geoderma* **261**, 1–10.
- Grayson, R. & Western, A. 2001 Terrain and the distribution of soil moisture. *Hydrol. Process.* **15**, 2689–2690.
- Grayson, R. B., Western, A. W., Chiew, F. H. S. & Bloschl, G. 1997 Preferred states in spatial soil moisture patterns: local and nonlocal controls. *Water Resour. Res.* **33**, 2897–2908.
- Hu, W. 2009 *Temporal–Spatial Variability of Soil Water Content and Saturated Hydraulic Conductivity in A Small Watershed on the Loess Plateau*. PhD Thesis, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science, Beijing, China (in Chinese).
- Hu, W., Shao, M. A., Han, F. P., Reichardt, K. & Tan, J. 2010 Watershed scale temporal stability of soil water content. *Geoderma* **158**, 181–198.
- Huang, Y. L., Chen, L. D., Fu, B. J., Huang, Z. L., Gong, J. & Lu, X. X. 2012 Effect of land use and topography on spatial variability of soil moisture in a gully catchment of the Loess Plateau, China. *Ecohydrology* **5**, 826–833.

- Jia, Y. H. & Shao, M. A. 2014 Dynamics of deep soil moisture in response to vegetational restoration on the Loess Plateau of China. *J. Hydrol.* **519**, 523–531.
- Jia, X. X., Shao, M. A., Zhu, Y. J. & Luo, Y. 2017 Soil moisture decline due to afforestation across the Loess Plateau, China. *J. Hydrol.* **546**, 113–122.
- Jian, S. Q., Zhao, C. Y., Fang, S. M. & Yu, K. 2015 Effects of different vegetation restoration on soil water storage and water balance in the Chinese Loess Plateau. *Agric. For. Meteorol.* **206**, 85–96.
- Kornelsen, K. C. & Coulibaly, P. 2013 McMaster Mesonet soil moisture dataset: description and spatio-temporal variability analysis. *Hydrol. Earth Syst. Sci.* **17**, 1589–1606.
- Krause, A. K., Franks, S. W., Kalma, J. D., Loughran, R. J. & Rowan, J. S. 2003 Multi-parameter fingerprinting of sediment deposition in a small gullied catchment in SE Australia. *Catena* **53**, 327–348.
- Liu, Y. & Li, Y. 2017 Engineering philosophy and design scheme of gully land consolidation in Loess Plateau. *Trans. CSAE* **33**, 1–9.
- Liu, B. X. & Shao, M. A. 2014 Estimation of soil water storage using temporal stability in four land uses over 10 years on the Loess Plateau, China. *J. Hydrol.* **517**, 974–984.
- Mascaro, G. & Vivoni, E. R. 2016 On the observed hysteresis in field-scale soil moisture variability and its physical controls. *Environ. Res. Lett.* **11**, 084008.
- Meerveld, H. & McDonnell, J. 2006 On the interrelations between topography, soil depth, soil moisture, transpiration rates and species distribution at the hillslope scale. *Adv. Water Resour.* **29**, 293–310.
- Melliger, J. J. & Niemann, J. D. 2010 Effects of gullies on space-time patterns of soil moisture in a semiarid grassland. *J. Hydrol.* **389**, 289–300.
- Moore, I. D., Grayson, R. B. & Ladson, A. R. 1991 Digital terrain modeling: a review of hydrological, geomorphological, and biological applications. *Hydrol. Process.* **5**, 3–30.
- Penna, D., Borga, M., Norbiato, D. & Dalla Fontana, G. 2009 Hillslope scale soil moisture variability in a steep alpine terrain. *J. Hydrol.* **364**, 311–327.
- Qiu, Y., Fu, B., Wang, J. & Chen, L. 2001 Soil moisture variation in relation to topography and land use in a hillslope catchment of the Loess Plateau, China. *J. Hydrol.* **240**, 243–263.
- Qiu, Y., Fu, B., Wang, J., Chen, L., Meng, Q. & Zhang, Y. 2010 Spatial prediction of soil moisture content using multiple-linear regressions in a gully catchment of the Loess Plateau, China. *J. Arid Environ.* **74**, 208–220.
- Takagi, K. & Lin, H. S. 2012 Changing controls of soil moisture spatial organization in the Shale Hills Catchment. *Geoderma* **173**, 289–302.
- Vereecken, H., Huisman, J. A., Pachepsky, Y., Montzka, C., van der Kruk, J., Bogena, H., Weihermuller, L., Herbst, M., Martinez, G. & Vanderborght, J. 2014 On the spatio-temporal dynamics of soil moisture at the field scale. *J. Hydrol.* **516**, 76–96.
- Wang, Y. Q., Shao, M. A. & Shao, H. B. 2010 A preliminary investigation of the dynamic characteristics of dried soil layers on the Loess Plateau of China. *J. Hydrol.* **381**, 9–17.
- Wang, Y. Q., Shao, M. A., Zhu, Y. J. & Liu, Z. P. 2011 Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China. *Agric. For. Meteorol.* **151**, 437–448.
- Western, A. W., Grayson, R. B., Bloschl, G., Willgoose, G. R. & McMahon, T. A. 1999 Observed spatial organization of soil moisture and its relation to terrain indices. *Water Resour. Res.* **35**, 797–810.
- Western, A. W., Zhou, S. L., Grayson, R. B., McMahon, T. A., Bloschl, G. & Wilson, D. J. 2004 Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes. *J. Hydrol.* **286**, 113–134.
- Xiao, L., Xue, S., Liu, G. B. & Zhang, C. 2014 Soil moisture variability under different land uses in the Zhifanggou Catchment of the Loess Plateau, China. *Arid Land Res. Manage.* **28**, 274–290.
- Yang, L., Wei, W., Chen, L. D. & Mo, B. R. 2012 Response of deep soil moisture to land use and afforestation in the semi-arid Loess Plateau, China. *J. Hydrol.* **475**, 111–122.
- Yang, L., Chen, L. D., Wei, W., Yu, Y. & Zhang, H. D. 2014 Comparison of deep soil moisture in two re-vegetation watersheds in semi-arid regions. *J. Hydrol.* **513**, 314–321.
- Yang, Y., Dou, Y. X., Liu, D. & An, S. S. 2017 Spatial pattern and heterogeneity of soil moisture along a transect in a small catchment on the Loess Plateau. *J. Hydrol.* **550**, 466–477.
- Yaseef, N. R., Yakir, D., Rotenberg, E., Schiller, G. & Cohen, S. 2010 Ecohydrology of a semi-arid forest: partitioning among water balance components and its implications for predicted precipitation changes. *Ecohydrology* **3**, 143–154.
- Yu, B. W., Liu, G. H., Liu, Q. S., Feng, J. L., Wang, X. P., Han, G. Z. & Huang, C. 2018 Effects of micro-topography and vegetation type on soil moisture in a large gully on the Loess Plateau of China. *Hydrol. Res.* **49** (4), 1255–1270.
- Zheng, J. Y., Wang, L. M., Shao, M. A., Wang, Q. J. & Li, S. Q. 2006 Gully impact on soil moisture in the gully bank. *Pedosphere* **16**, 339–344.
- Zhu, Y. J. & Shao, M. A. 2008 Variability and pattern of surface moisture on a small-scale hillslope in Liudaogou catchment on the northern Loess Plateau of China. *Geoderma* **147**, 185–191.

First received 9 August 2018; accepted in revised form 5 July 2019. Available online 12 August 2019