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Spatial pattern of soil moisture and its temporal stability within profiles on a loessial slope in northwestern China

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SUMMARY

Temporal stability of spatial distributions of soil moisture are usually observed after repeated surveys of soil moisture across an area. To understand how temporal stability of soil moisture varied with soil depth under the combined influences of vegetation and local topography, we collected soil moisture data at intervals of 10 cm within 1-m profiles on a loessial slope in China in four plots (61 m × 5 m) under different types of vegetation (Korshinsk peashrub, KOP; purple alfalfa, ALF; natural fallow, NAF; millet, MIL). Measurements of soil water content were made by neutron probes on 15 occasions between 2010 and 2012. Soil moisture distributions in both the vertical and horizontal dimensions were investigated to describe its spatial pattern and to lay the groundwork for better understanding its temporal stability characteristics. The results indicated that: (1) soil moisture presented different vertical but similar horizontal trends in the four plots, with significant correlations of soil moisture occurring primarily among adjacent soil layers irrespective of vegetation types, mostly in soil profiles under KOP and ALF and less frequently in soil profiles under NAF and MIL; (2) based on Spearman rank correlation coefficients, with increasing depth temporal stability generally increased under KOP and MIL, but first increased and then decreased under ALF, and increased after the first three measurements under NAF; (3) based on the relative difference technique, points with extreme moisture tended to remain representative at more depths than did points with average moisture and their time stability increased with increasing soil depth; and (4) the correlation between MRD (mean relative differences) and the wetness index weakened with soil depth. The relationship between SDRD (the standard deviation of MRD) and the wetness index varied nonlinearly with soil depth. Vegetation type, soil depth and the wetness index, in descending order of influence, had significant effects on the temporal stability of soil moisture. Among selected soil properties, saturated hydraulic conductivity, bulk density and soil organic carbon all significantly affected the SDRDs. These observations are expected to add valuable information to the theory of temporal stability and for the practices of soil moisture management.

1. Introduction

When repeated surveys of soil moisture at fixed points across an area of interest are conducted, soil water contents at some points are often consistently higher than, equal to or lower than the areal mean (Guber et al., 2008; Pachepsky et al., 2005; Zhou et al., 2007). This phenomenon has been called the temporal stability of soil moisture (Vachaud et al., 1985), and is a reflection of the temporal persistence of soil moisture within a spatial distribution pattern (Kachanoski and De Jong, 1988; Schneider et al., 2008; Zhou et al., 2007). Applying this concept enables an assessment of the status of soil moisture in an area to be made using a relatively small number of observational points (Gao et al., 2011; Jacobs et al., 2004; Martínez-Fernández and Ceballos, 2005), which reduces time and labor costs as compared to sampling randomly at many points. This technique is also useful for providing missing soil-moisture data caused by the malfunction of probes or by other observational problems (Dumedah and Coulibaly, 2011; Pachepsky et al., 2005). Moreover, a field can be subdivided into areas with different conditions of soil moisture according to their temporal

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stability characteristics. For each such area, a particular plant species can be planted according to their adaptability to the moisture conditions, and soil water management practices such as mulching (De Souza et al., 2011) and irrigation (Starr, 2005) can be optimized. Given the great potential of these applications, the temporal stability of soil moisture has received much attention since Vachaud et al. (1985) proposed the concept.

Across study areas of various sizes, many environmental factors are linked to the temporal stability of soil moisture. Vachaud et al. (1985) considered soil texture, especially clay content, to be the main explanatory variable for the temporal stability of soil moisture. Locations with gentle slopes consistently exhibited time-stable features, but other landscapes, such as depressions, hilltops and steep slopes, were less time stable (Jacobs et al., 2004). Schneider et al. (2008) reported that the vegetative cover and the management of grazing in a steppe ecosystem affected the temporal stability of soil moisture. In addition to soil properties, topography and vegetation, the depth of observation is an important aspect in the study of the temporal stability of soil moisture (Martínez-Fernández and Ceballos, 2003; Starks et al., 2006). The temporal stability of soil water storage was consistently lower in shallow soil layers than in deeper layers in a wheat field in Carolina, based on the successively increasing magnitudes of the rank correlation coefficients for depths of 15, 23, 30 and 46 cm (Nielsen et al., 2000). Guber et al. (2008) drew a similar conclusion from the index of temporal stability calculated at depths of 10, 30 and 50 cm in agricultural fields in Maryland. In three layers (0–1, 1–2 and 2–3 m) of a deeper soil profile on a hillslope on the Loess Plateau of China, the temporal stability of soil water storage increased with increasing soil depth, using a relative-difference technique (Gao and Shao, 2012). However, similar results were not obtained on another hillslope in the same watershed (Hu et al., 2010), where the temporal stability of soil water content was less at 0.2 m than at depths of 0.6 and 0.8 m. Employing the same two indices used by Hu et al. (2010), i.e. the standard deviation of relative difference (SDRD) and the mean absolute bias error, Gao et al. (2011) found no change in temporal stability with soil depth in sloping jujube orchards on the Loess Plateau. Similarly, observational depth did not significantly affect the distribution of soil moisture in an Australian catchment, based on ranked mean relative differences (MRDs) of soil moisture in the 0–60 and 0–30 cm soil layers (Grayson and Western, 1998). Hence, the variation in temporal stability in soil moisture within a profile remains unknown and thus requires further study, especially by observing a sufficient number of sampling depths at regular intervals in the soil profiles.

The Loess Plateau is an area of the world suffering most from severe soil erosion. The terrestrial ecosystems of the Loess Plateau, due to their fragility, may exhibit early ecological responses to global climate change (Wang et al., 2011). On the Loess Plateau, loessial slope is a fundamental geomorphic type and is characterized by severe rain erosion and an urgent need for revegetation. The soil moisture profile of loessial slopes may deteriorate under the influence of planted vegetation (Chen et al., 2008; Wang et al., 2010), which was intended to prevent the loss of soil and water by influencing the hydrological processes on the slope. The length of the slope is an important factor controlling the hydrological processes (McCool et al., 1989; Moore and Burch, 1986). The relatively short lengths documented in earlier studies of these hydrological processes were not comparable in size to actual field conditions in this region (Fu et al., 2009). To address this issue, four adjacent plots with different types of vegetation, were established on a longer loessial slope (61 m) with similar gradients (12–14°) in 2003. Zeng et al. (2011) examined the temporal-spatial variability of soil moisture and the ability of the revegetation types to control erosion in the initial period (2004–2007). The distribution of moisture and nutrients in the soil during the intermediate period (2008–2009) and the depletion of soil moisture since the establishment of the different vegetation types have also been investigated (Fu et al., 2009, 2010, 2012). The type of revegetation combined with the time since revegetation occurred greatly influenced the temporal-spatial features of the soil moisture in various layers along the slope. As part of the effort to understand the response of soil moisture to vegetation restoration on loessial slopes, Jia and Shao (2013) investigated the temporal stability of water storage in the upper 1 m layer of the soil profiles between 2010 and 2011. Aside from that study, the temporal stability of soil moisture in the plots has been little studied. Moreover, the spatial distribution patterns of soil moisture, whether vertically in profiles or horizontally across the landscape, are still poorly understood.

The temporal stability of soil moisture is scale-dependent in terms of the extent of the study area (Brocca et al., 2009; Vanderlinden et al., 2012). Smaller spatial areas usually respond to smaller variations in topography and soil properties and are thus convenient for providing more detailed information on temporal stability. This study aimed to further understand the temporal stability of soil moisture within soil profiles on loessial slopes. The specific objectives of this study are: (1) to investigate the distribution patterns of soil moisture as a basis for subsequent analysis, (2) to detect variation in temporal stability in soil profiles and (3) to understand the mechanisms controlling temporal stability of soil moisture under the combined influences of vegetation type, soil depth and topography. These objectives are expected to resolve the spatial pattern and temporal stability of soil moisture, with the goal of helping to improve the management of soil water on loessial slopes.

2. Materials and methods

2.1. Study area and experimental layout

This study was conducted on a loessial slope within the Liudaogou catchment of Shenmu County in Shaanxi Province, China. The study area is located in the transitional belt between the Loess Plateau and the Mu Us desert, 38°46′–38°51′N and 110°21′–110°23′E, and covers an area of 6.89 km^2. The terrain is undulating, with an elevation ranging from 800 to 2600 m a.s.l. In the catchment, a series of deep gullies are widely distributed together with large tracts of sloping land. The regional climate is classified as moderate semi-arid with an annual mean temperature of 8.4 °C and a mean annual precipitation of 437 mm. Most of the rainfall occurs during the growing season, with 70% of the annual rainfall occurring from June to September.

In 2003, four adjacent plots, 5 m × 61 m, were established on a uniform loessial slope (12–14°) facing northwest (Fig. 1a). To facilitate measurement of soil water content, 11 aluminum probe access tubes were installed at equal intervals of 5 m along the midline of each plot. Fig. 1b shows the numbered tube positions in the plots (Jia and Shao, 2013). One plot was planted with Korshinsk peashrub (KOP) and one with purple alfalfa (ALF), one was natural fallow (NAF) and one was a millet field (MIL). The soil in all plots is Aeolian loess. The size distribution of the soil particles indicated a loamy texture (USDA system), with 44.1–47% sand, 41.8–43% silt and 10.6–13.3% clay. Detailed information about the plots can be found elsewhere (Fu et al., 2009, 2010, 2012; Jia and Shao, 2013; Zeng et al., 2011).

2.2. Measurement of soil moisture

Soil moisture is a common synonym of soil water (Chesworth, 2007). Neutron probes, a nondestructive but indirect tool commonly used for repetitive measurement of volumetric water

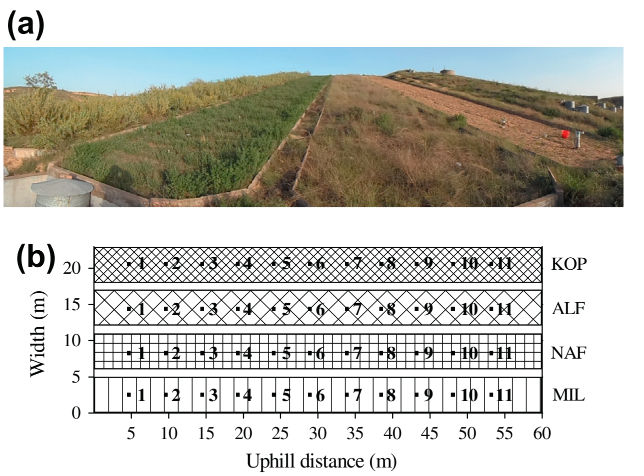

Fig. 1. The experimental plots on May 16, 2012 (a) showing from left to right: KOP (Korshinsk peashrub), ALF (purple alfalfa), NAF (natural fallow) and MIL (millet); and numbered neutron-probe access tube positions (b).

content (Warrick, 2002), were used to estimate soil moisture. When neutron probes are used near the surface (at a depth of 10 cm), a loss of fast thermal neutrons from the soil usually causes the need of a separate calibration (Bromley et al., 1997; Cuenca et al., 1997). The routinely calibrated and well-fitted piecewise linear equation for neutron probe device (CNC503DR, China) in this study was:

$$\theta = \begin{cases} 95.62CR - 1.15 & d \leqslant 10 \\ 62.45CR - 0.70 & d > 10 \end{cases} \tag{1}$$

where θ is volumetric soil water content in cm^3 cm^{-3} and CR is the slow-neutron counting rate at a particular soil depth of d (cm). Slow-neutron counting rates were computed as ratios of the slow-neutron counts at a specific depth of soil to a standard count obtained with the probe in its shield.

At each observational point in the four experimental plots, volumetric soil water content was measured throughout the 0–100 cm soil profile at 10-cm intervals. From July to October in 2010, from April to October in 2011 and from May to July in 2012, soil moisture was measured once a month and two times in June of 2012. In total, 6600 measurements of volumetric soil water content were collected during 15 days in this study.

2.3. Statistical analyses

For a specific plot, values of soil water content, θ, at point i, depth k and time j, $\theta_{i,j,k,}$ were used to calculate the mean soil water content at soil depth k, $\bar{\theta}_k$, and point i, $\bar{\theta}_i$, which respectively denote mean soil moisture in the vertical and horizontal dimensions in a plot:

$$\bar{\theta}_k = \frac{1}{N_i \cdot N_j} \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} \theta_{i,j,k} \tag{2}$$

$$\bar{\theta}_i = \frac{1}{N_j \cdot N_k} \sum_{j=1}^{N_j} \sum_{k=1}^{N_k} \theta_{i,j,k} \tag{3}$$

where N_i is the number of observational points in each plot and in this study is equal to 11, N_j represents the number of observational occasions and is 15, and N_k is the number of soil depths investigated and is 10. One-way analyses of variance (ANOVA) followed by Duncan's multiple range tests ($p < 0.05$) were used to evaluate the differences in soil moisture at the various depths and observational points within or among the experimental plots. Soil moisture correlation between soil layers or soil profiles was investigated using the Pearson correlation coefficient.

Nonparametric Spearman's tests examined the overall similarity of the soil-moisture spatial patterns between different dates of measurement. The index of Spearman's rank correlation coefficient (r_s) determined if the ranks at observational points at a certain depth persisted for the duration of the study, with unity corresponding to absolute temporal stability.

The relative-difference technique, proposed by Vachaud et al. (1985), evaluated the temporal stability of soil moisture for individual observational points. For each depth k at point i, the mean relative difference (MRD), $\bar{\delta}_{i,k}$, and the standard deviation of relative difference (SDRD) $\sigma(\delta_{i,k})$, are expressed as:

$$\bar{\delta}_{i,k} = \frac{1}{N_j} \sum_{j=1}^{N_j} \frac{\theta_{i,j,k} - \bar{\theta}_{j,k}}{\bar{\theta}_{j,k}} \tag{4}$$

$$\sigma(\delta_{i,k}) = \sqrt{\frac{1}{N_j - 1} \sum_{j=1}^{N_j} \left(\frac{\theta_{i,j,k} - \bar{\theta}_{j,k}}{\bar{\theta}_{j,k}} - \bar{\delta}_{i,k}\right)^2} \tag{5}$$

The value of the mean relative difference (MRD) for a point at a particular depth quantified whether that point was wetter or drier than the areal mean at the same depth. The standard deviation of the MRD (SDRD) characterized the variability of MRD at that point within the experimental period, i.e. SDRD was an indicator of temporal stability.

Factorial ANOVAs were conducted to decide the relative importance of vegetation types, soil depth and the wetness index in controlling MRD and SDRD. The wetness index is the natural logarithm of the upslope contributing area divided by the tangent of the slope (Beven and Kirkby, 1979).

The statistical computation for soil moisture data was performed with SPSS 16.0 software.

3. Results and discussion

3.1. Spatial distribution of soil moisture

3.1.1. Soil moisture distribution in vertical and horizontal dimensions

Mean soil water content, vertically in the soil profiles (Fig. 2) and horizontally down the slope (Fig. 3), were calculated for all plots from the data acquired over the 15 collection dates.

The trends of mean soil water content changes with increasing depth in the soil profiles were similar for the KOP and ALF plots. Both plots had maximum soil water contents (9.2% for KOP, 9.9% for ALF) at the first depth (10 cm), and values then decreased from the third depth (30 cm) to the lowest depths (90 cm or 100 cm). Soil water content was the same at the 20-cm and 30-cm depths in the KOP plot but was lower at 20 cm than at 30 cm in the ALF plot. Moreover, significant differences ($p < 0.05$) in soil water content were observed between the 10-cm depth and any other depth in the profile in both plots. A slight increase in mean soil water content occurred down the profile of the MIL plot, in which soil water content in the upper layers (<30 cm) was significantly lower than that at intermediate and lower depths (30–100 cm). In contrast, soil water content in the NAF plot was relatively constant throughout the profile, and no significant differences among the depths were observed.

The different patterns of profile soil water content could be ascribed to the vegetation. As perennial deep-rooted plants, KOP and ALF can access water stored in deeper soil layers, even deeper than those we monitored (Cheng et al., 2005; Zhang et al., 2009). Under the influences of such high water-consuming plants, the loss of profile soil water persistently exceeded the supply of percolating

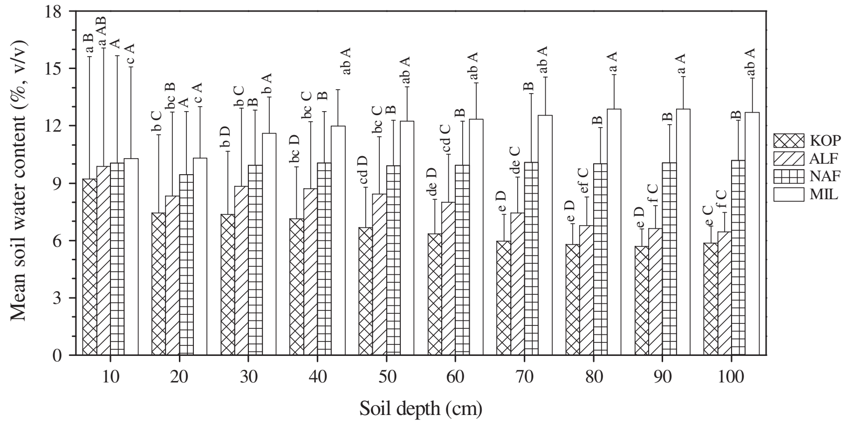

Fig. 2. Mean soil water content with standard error (vertical bar) for each depth under plots of KOP (Korshinsk peashrub), ALF (purple alfalfa), NAF (natural fallow) and MIL (millet). Different lowercase or uppercase letters indicate significant ($p < 0.05$) differences in mean soil water content at different depths in the same plots or at corresponding depths in different plots, respectively.

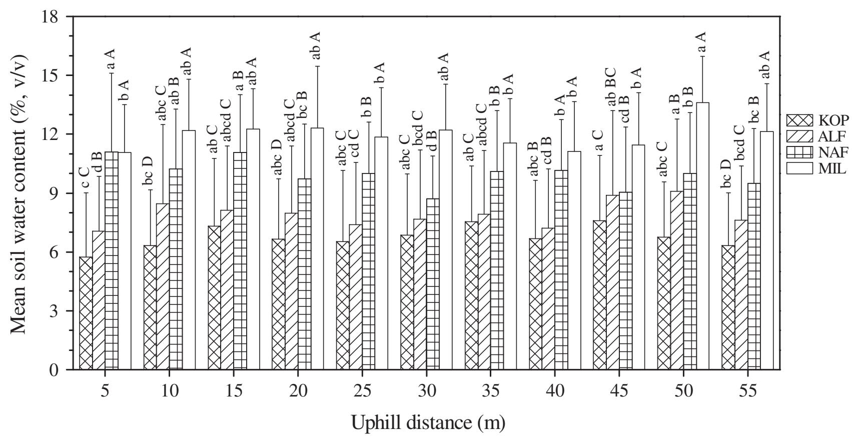

Fig. 3. Mean soil water content with standard error (vertical bar) for the observational points along the slopes of the experimental plots under plots of KOP (Korshinsk peashrub), ALF (bpurple alfalfa), NAF (natural fallow) and MIL (millet). Different lowercase or uppercase letters indicate significant ($p < 0.05$) differences in mean soil water content at different points in the same plots or at corresponding locations in different plots, respectively.

rainwater and thus dryer states occurred at deeper soil depths. MIL has fibrous roots that are only distributed in the upper soil layers and do not access the deeper soil moisture (Jia and Shao, 2013). NAF consists of natural herbaceous species, which are relatively better than MIL at obtaining water (Jia and Shao, 2013). The differences could account for the different vertical trends in soil water content under NAF and MIL.

For all soil depths, the mean soil water content followed the order: KOP < ALF < NAF < MIL. The differences in the mean soil water contents among these four plots were significant ($p < 0.05$). Specifically, from 30 to 90 cm, the mean soil water contents between any two plots were significantly different. However, no significant differences in soil water content were detected between the KOP and ALF plots or among the ALF, NAF and MIL plots at 10 cm. Similarly, the difference in water content between the NAF and MIL plots at 20 cm was not significant. Soil water content in the upper layers was influenced by a variety of natural processes (hydrologic, climatic, vegetational, etc.) that reduced the differentiation among the plots.

Mean soil water content for observational points located from the bottom to the top of the slope varied nonlinearly with the uphill distances (Fig. 3). It could be concluded that the local topography was not the only factor controlling the spatial soil moisture variation along the slope. At the bottom of the slope, the KOP and ALF plots had the lowest mean soil moisture values: point 1 in the KOP plot with 5.7% and point 1 in the ALF plot with 7.1%. The highest values of mean soil water content in these two plots were found on the upper slopes: point 9 in the KOP plot with 7.6% and point 10 in the ALF plot with 9.1%. Similar to the KOP and ALF plots, mean soil water content in the MIL plot was highest at the upper slope (point 10 with 13.6%) but was lowest at two points that were far apart (1 and 8 with 11.1%). In contrast, the NAF plot had maximum soil water contents lower on the slope (points 1 and 3 with 11.1%). Along a hillslope transect, Famiglietti et al. (1998) found an inverse relationship between relative elevation and surface soil water content as the hillslope dried following a rain. In the same experimental plots as those in the present study, Fu et al. (2012) found no tendency of a downhill accumulation of soil water in the 0–100 cm soil layer under the four vegetative types. These results may indicate that the horizontal distribution of soil water on the slope depended on the observational depth and condition of moisture. Moreover, significant differences were observed among slope positions both within and among plots. Regardless of the slope position, the magnitude of mean soil water content for all four plots consistently followed the orders: MIL > NAF > ALF > KOP. These plot rankings were consistent with those determined for the soil profiles, indicating an overall stable pattern of soil moisture distribution for all four plots. The dominant plants on each plot functioned primarily by extracting soil moisture through their roots, affecting the rate of evaporative drying by shading the soil surface and influencing throughfall by their canopies (Famiglietti et al., 1998). Thus, the vegetation type encompassed dominant plant type, aboveground biomass and vegetation cover, etc. (Jia and Shao, 2013). The present stable pattern of soil water content distribution on the slope could be attributed to the joint operation of these vegetation characteristics along with the local geographical attributes. Wang et al. (2013) also observed temporally stable relationships of mean soil water content among different vegetative types.

In the vertical dimension, the coefficients of variation for mean soil water content decreased with increases in depth from 0.7 to 0.2 for the KOP plot, from 0.6 to 0.2 for the ALF and NAF plots and from 0.5 to 0.1 for the MIL plot. These decreases indicated that the variation in soil water content among points at the same depth decreased in the vertical direction. Zeng et al. (2011) observed the largest variation in soil water content in the KOP and ALF plots at the 60-cm depth due to root uptake in the initial growing period (2004–2007). However, we noted that soil water content in both plots changed due to the increased growth of the vegetation over the years. In the horizontal dimension from the bottom to the top of the slope, the coefficients of variation ranged from 0.6 to 0.4 for the KOP plot, from 0.4 to 0.5 for the ALF plot, from 0.4 to 0.3 for the NAF plot and from 0.2 to 0.3 for the MIL plot, respectively. These differences suggested that soil water content at multiple depths varied greatly with the slope position. Variation in soil water content generally increased with increasing distance between observational points in the landscape (Nielsen et al., 1973). Even though the horizontal sampling interval (5 m) was much larger than the vertical sampling interval (10 cm), the variation in soil water content was still greater in the vertical dimension than in the horizontal dimension. This observation may indicate that the loessial slope was dominated by vertical fluxes of soil moisture, mainly by evapotranspiration and rainwater infiltration irrespective of vegetation. Such vertical fluxes are generally localized due to disconnected soil macropores and appear mainly under dry conditions (Grayson et al., 1997; Takagi and Lin, 2012).

3.1.2. Soil moisture relationships among soil layers and soil profiles

Table 1 shows the Pearson correlation coefficient matrix for all investigated soil layers in the corresponding plots. For most adjacent depths within the soil profiles, high correlation coefficient value and significant positive relationships ($p < 0.01$) were obtained, irrespective of vegetation type on the hillslope. This could be considered as a homogenous behavior in the context of homogenous conditions of soil moisture in a heterogeneous landscape, which was similar to the observation of Giraldo et al. (2009) about the high correlations between soil temperatures (at 10 cm depth) and surface temperatures. The maximum correlation coefficients obtained in the KOP, ALF, NAF and MIL plots were 0.973 for 60 cm vs. 70 cm, 0.941 for 50 cm vs. 60 cm,0.906 for 30 cm vs. 40 cm and 0.949 for 90 cm vs. 100 cm, respectively. With the exception of the MIL plot, the minimum correlation coefficients for adjacent depths in the KOP, ALF and NAF plots were all for 10 cm vs. 20 cm, and were 0.388, 0.814 and 0.406, respectively. This indicates clearly that the homogenous behavior of the soil moisture distribution in the horizontal dimension was greater in deeper layers than in upper soil layers. Soil moisture at 10 cm was also well correlated with moisture at some lower depths in the KOP and ALF plots, which could be due to vegetation effects that contributed to a similar distribution pattern between surface and deep soil layers. The absence of significant correlations between the 10-cm and 20-cm depths in both the KOP and NAF plots might result from the complicated hydrologic processes in the surface layers along the slope. Penna et al. (2009) found that the soil water content relationships for 0–6 cm vs. 0–20 cm layers were characterized by weaker correlations than those for 0–6 cm vs. 0–12 cm and for 0–12 cm vs. 0–20 cm on three hillslopes with contrasting steep relief and shallow soil depths in the Dolomites. Arya et al. (1983) found that the correlation coefficients were 0.77 for 5–9 cm vs. 9–15 cm layers, 0.41 for 9–15 cm vs. 15–30 cm, 0.46 for 15–30 vs. 30–45 cm for soil moisture in fallow fields in Kansas. The observed decreases in the strength of between-layer correlations with the increasing distance between soil layers in our study were in agreement with the findings of Arya et al. (1983) and Penna et al. (2009).

In the study of Penna et al. (2009), the coefficients of determination for the correlations among various soil depths were larger than those reported in other studies. Similarly, the correlation coefficient values were larger in our study than in that of Arya et al. (1983). Although derived from seemingly incomparable study regions and different observational depths, the discrepancy of mere values could be ascribed to the differences in climate, land-use types, soil, etc. Penna et al. (2009) considered the high correlations of soil moisture between upper soil layers were likely to be related to the effects of vertical rainwater percolation, which produced a reduced and/or lagged moisture response at depth compared to the dynamics at the surface. However, the strong correlations between adjacent depths in our study were associated with the generally dry soil state. A dry soil state is characterized by a vertical flow-dominated spatial pattern for most of the time and a lateral flow-dominated spatial pattern occasionally. In addition, there was a possible overlap of sampling depths in our study if the radius of the neutron probe measurements exceeded 10 cm (Netto et al., 1999), which might explain some of the high correlations between adjacent depths. Such a sampling interval of about 10-cm has been used in other studies (Gao and Shao, 2012; Green et al., 2006; Cuenca et al., 1997; Ireson et al., 2006; Vachaud et al., 1985; Vera et al., 2009), but it was not clear how much it could contribute to the overall correlation of soil moisture between soil layers.

The Pearson correlation coefficients among observational points at different distances from the bottom of the slope were used to evaluate the relationship of soil moisture among different soil profiles (Table 2). Positive and significant correlations ($p < 0.05$ or 0.01) occurred between most points in the KOP and ALF plots. These correlations were mainly due to the decreases in the linearity of the trends of soil moisture distributions within the soil profiles. In contrast, positive and significant correlations were observed between relatively few observational points in the NAF plot, including a pair of adjacent points (10 and 11). The MIL plot had more significant correlation coefficients than the NAF plot. Thus, soil moisture correlation among soil profiles could reflect the distribution pattern of soil moisture in the vertical dimension, under dry soil conditions that were mainly determined by the vegetation.

3.2. Temporal stability of soil moisture spatial patterns

3.2.1. Temporal stability of soil moisture at specific plots

The Spearman rank correlation coefficients (r_s) were used to quantify the persistence or similarity of soil moisture spatial patterns over time, generally in the form of half-matrix tables. The mean r_s of the different dates of measurement for each depth were used for clarity. The mean r_s at various depths of the soil profile and their evolution over time for each plot are displayed in the form of contour maps in Fig. 4.

The temporal stability of soil moisture expressed by r_s values was not uniform with depth in the four plots. Temporal stability generally increased with depth in the KOP and MIL plots, first increased and then decreased in the ALF plot and increased, but was somewhat unstable on the first three measurement dates, in the NAF plot. Over the entire experimental period, the pattern of soil moisture in the KOP plot tended to be more temporally stable

Table 1
The Pearson correlation coefficients among values of mean soil water content determined at different depths under plots of KOP (Korshinsk peashrub), ALF (purple alfalfa), NAF (natural fallow) and MIL (millet).

	20	30	40	50	60	70	80	90	100
KOP									
10	0.388	0.348	0.57	0.869**	0.815**	0.869**	0.768**	0.653*	0.492
20		0.940**	0.834**	0.375	0.067	0.091	−0.075	−0.106	0.017
30			0.833**	0.386	0.096	0.085	−0.149	−0.275	−0.229
40				0.725*	0.462	0.424	0.195	0.055	0.045
50					0.935**	0.903**	0.752**	0.568	0.385
60						0.973**	0.870**	0.671*	0.415
70							0.934**	0.778**	0.535
80								0.933**	0.707*
90									0.895**
ALF									
10	0.814**	0.572	0.737**	0.751**	0.717*	0.598	0.549	0.487	0.538
20		0.905**	0.888**	0.630*	0.6	0.355	0.214	0.303	0.286
30			0.932**	0.599	0.575	0.31	0.188	0.354	0.242
40				0.838**	0.792**	0.54	0.429	0.528	0.389
50					0.941**	0.764**	0.660*	0.691*	0.531
60						0.882**	0.755**	0.742**	0.554
70							0.892**	0.759**	0.642*
80								0.821**	0.751**
90									0.891**
NAF									
10	0.406	0.037	−0.115	0.094	0.119	0.119	0.092	0.029	−0.037
20		0.757**	0.517	0.388	0.409	0.382	0.296	−0.07	−0.387
30			0.906**	0.767**	0.773**	0.628*	0.622*	0.209	−0.209
40				0.852**	0.744**	0.607*	0.665*	0.268	−0.097
50					0.883**	0.801**	0.895**	0.601	0.237
60						0.901**	0.800**	0.561	0.214
70							0.752**	0.523	0.175
80								0.846**	0.429
90									0.796**
MIL									
10	0.806**	0.620*	0.212	0.117	0.13	−0.007	0.343	0.326	0.358
20		0.826**	0.408	0.163	−0.082	−0.247	0.067	0.176	0.281
30			0.725*	0.423	−0.098	−0.214	−0.025	0.128	0.159
40				0.862**	0.281	0.055	−0.118	−0.055	−0.135
50					0.694*	0.456	0.082	−0.055	−0.21
60						0.839**	0.468	0.179	0.005
70							0.739**	0.518	0.378
80								0.900**	0.801**
90									0.949**

**, * Correlation is significant at the 0.01 and 0.05 levels, respectively.

at depths from 70 to 100 cm than at depths from 10 to 70 cm. A similar degree of temporal stability was present at 20 cm and 30 cm in the ALF plot, which was stronger than the stability at other depths. In the NAF and MIL plots, r_s varied at most depths in the profile and tended to be higher at lower depths (90–100 cm). The higher stability of soil moisture at lower depths may be linked to the stable spatial pattern of pedogenetic variations (Kamgar et al., 1993; Nielsen et al., 2000). The isoline of r_s in the NAF plot extended to the lower depths for the earlier measurements. However, the lower values of r_s suggested a lack of temporal stability in the soil moisture pattern.

When soil depths were not explicitly considered, temporal stability for all plots was hierarchical, as shown by the mean values of r_s, which was caused by the differences in the vegetation type, especially those of vegetative cover and aboveground biomass (Jia and Shao, 2013). The temporal stability of soil moisture in this study varied with depth, which to a large extent affected our specific results. In a previous study, ALF exerted the highest temporal stability of all vegetation types (Jia and Shao, 2013). However, such high stabilities were only found between the depths of 20 cm and 30 cm, where soil moisture varied greatly. The active movement of water in this layer under all hydrological conditions may produce a spatial pattern of soil moisture very similar to the spatial pattern of the hydraulic properties of this layer at different times (Hu et al., 2009).

3.2.2. Temporal stability of soil moisture at individual points

Points that were representative of the experimental plots in terms of the plot average soil water content, could be identified by ranking the MRDs of all points in ascending order. The majority with negative or positive MRDs under- or overestimated the plot average, while the minority with MRDs close to zero were approximately equivalent to the plot average. Points characterized by the lowest SDRDs were considered to be the most time stable. Accordingly, four types of representative points, i.e. the driest, wettest, average moisture and most temporally stable, were identified at each depth for all plots. Given the large space the graphs may occupy, we presented only the relative difference results for selected soil depths (10, 20, 50, 80 and 100 cm) in Fig. 5. The specific information of the four types of representative points at each depth in the four plots, including point numbering, MRDs and SDRDs are showed in Table 3.

No point in any plot was consistently representative throughout the soil profile. For example, point 3 at 10 cm in the KOP plot represented the average moisture condition, but the representative point changed at other depths. However, the representative points of the extreme moisture conditions tended to remain representative at more depths than the points with average moisture conditions. The driest points, i.e. 5 and 1 in the KOP plot, 1 and 8 in the ALF plot, 9 in the NAF plot and 9 in the MIL plot as well as

Table 2
Pearson correlation coefficients among values of mean soil water content determined at different locations in plots of KOP (Korshinsk peashrub), ALF (purple alfalfa), NAF (natural fallow) and MIL (millet).

	2	3	4	5	6	7	8	9	10	11
KOP										
1	0.958**	0.919**	0.899**	0.362	0.861**	0.640*	0.896**	0.858**	0.777**	0.943**
2		0.892**	0.851**	0.36	0.780**	0.589	0.846**	0.769**	0.831**	0.959**
3			0.988**	0.690*	0.967**	0.855**	0.977**	0.908**	0.928**	0.947**
4				0.722*	0.989**	0.903**	0.993**	0.951**	0.888**	0.910**
5					0.742*	0.890**	0.708*	0.633*	0.742*	0.512
6						0.918**	0.980**	0.957**	0.846**	0.859**
7							0.911**	0.901**	0.780**	0.677*
8								0.969**	0.854**	0.883**
9									0.723*	0.787**
10										0.912**
ALF										
1	0.813**	0.857**	0.652*	0.832**	0.822**	0.928**	0.872**	0.699*	0.798**	0.821**
2		0.930**	0.916**	0.968**	0.969**	0.635*	0.953**	0.875**	0.956**	0.983**
3			0.825**	0.892**	0.908**	0.752*	0.946**	0.742*	0.974**	0.967**
4				0.913**	0.932**	0.413	0.873**	0.894**	0.916**	0.895**
5					0.987**	0.647*	0.910**	0.953**	0.909**	0.935**
6						0.63	0.924**	0.942**	0.933**	0.934**
7							0.759*	0.476	0.651*	0.664*
8								0.784**	0.968**	0.959**
9									0.784**	0.804**
10										0.979**
NAF										
1	−0.039	0.539	−0.16	0.185	−0.661*	0.074	−0.241	−0.183	−0.19	−0.014
2		0.208	0.253	0.868**	−0.104	0.267	−0.576	0.519	−0.556	−0.21
3			−0.392	0.098	−0.343	0.23	−0.355	−0.187	−0.439	−0.211
4				0.196	−0.097	−0.397	−0.101	0.873**	−0.069	0.025
5					−0.055	0.113	−0.574	0.499	−0.383	−0.149
6						−0.12	0.436	0.056	0.599	0.234
7							0.306	−0.427	−0.008	0.291
8								−0.367	0.873**	0.769**
9									−0.26	−0.165
10										0.785**
MIL										
1	0.917**	0.486	0.945**	0.44	0.800**	0.746*	0.835**	−0.031	0.971**	−0.266
2		0.621	0.975**	0.631	0.931**	0.604	0.931**	0.074	0.917**	−0.112
3			0.547	0.676*	0.656*	0.082	0.508	−0.141	0.5	0.393
4				0.614	0.870**	0.619	0.940**	−0.019	0.920**	−0.122
5					0.586	−0.2	0.622	−0.294	0.344	0.666*
6						0.573	0.930**	0.331	0.831**	−0.092
7							0.546	0.366	0.797**	−0.751*
8								0.215	0.840**	−0.109
9									0.116	−0.487
10										−0.396

**, * Correlation is significant at the 0.01 and 0.05 levels, respectively.

the wettest points, i.e. 9 and 7 in the KOP plot, 9 and 10 in the ALF plot, 1 in the NAF plot and 10 in the MIL plot, all remained representative at more than two adjacent depths. Some points even remained representative at six adjacent depths in the soil profile. This suggested that extreme moisture conditions in the soil profiles might be persistent over time and expand in space, especially in the vertical dimension. Points with average moisture conditions and most temporally stable points were more likely to be changed within a given depth. Even slight changes in MRD or SDRD might lead to the selection of different representative points. Some researchers have thus identified points with average moisture conditions as those with MRDs under 5% (Gao and Shao, 2012; Martínez-Fernández and Ceballos, 2003; Van Pelt and Wierenga, 2001). These cases, though, do not support a direct representation of the mean or extreme conditions of soil moisture at different soil depths with variant or invariant points.

Points with average moisture conditions in the upper (<30 cm) and upper-intermediate (30–50 cm) soil layers tended to be distributed in the middle of the slope in each plot. Some points that represented the plot average in these and lower layers, however, were located at the top of the slope, such as point 11 at depths of 40, 60 and 90 cm in the KOP, NAF and MIL plots, respectively. Point 11 in the ALF plot even represented two soil depths (60 and 70 cm). At the depths of 70 and 80 cm in the MIL plot, the average moisture point was the same as at point 1, which was located at the bottom of the slope. In contrast, the points with average moisture conditions have been found by others at positions with intermediate topographic attributes (Brocca et al., 2009; Grayson and Western, 1998; Jacobs et al., 2004). However, the a priori selection of points with average moisture conditions was not appropriate throughout a soil profile, since the representativeness of soil moisture in deeper soil layers could possibly be undermined by the increasing distances from the soil surface.

In the KOP and ALF plots, the driest points tended to be at the middle and bottom of the slope, while the wettest were at the top. Two factors may have contributed to these results. First, the nonlinear variation of soil moisture along the slope may have complicated the distribution of representative points. Second, the vegetation may have consumed some of the soil moisture. Soon after the vegetation was established, the dominant plants in the KOP and ALF plots were growing better at the bottom of the slope than at the top due to the higher water contents resulting from the

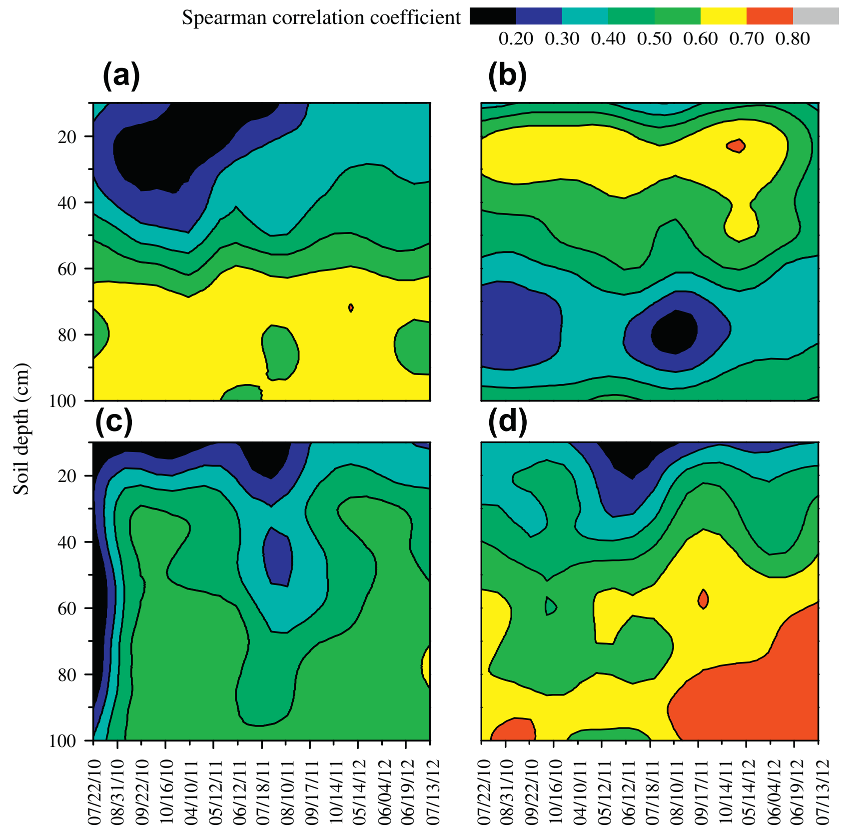

Fig. 4. The vertical distribution and temporal dynamics of the Spearman rank correlation coefficients for plots under (a) KOP (Korshinsk peashrub), (b) ALF (purple alfalfa), (c) NAF (natural fallow), and (d) MIL (millet).

redistribution of precipitation on the slope. Consequently, over time, the relatively larger plants at the bottom of the slope consumed more soil moisture than the smaller plants at the top, leading to the driest points being at the bottom and the wettest points being at the top. Without the strong effect of consumption by the vegetation, the driest and wettest points in the NAF plot were respectively located at the top and bottom of the slope. Points representing the driest and wettest conditions in the MIL plot were both distributed at the top of the slope. Adjacent points, 9 and 10 at 80 cm, had the opposite extreme moisture condition, most likely due to the effect of a dominant vertical flow of soil water at that depth. Although the distance between points 9 and 10 at 80 cm was small (5 m), the lateral movement of water was much less because the soil at this depth was always dry. Moreover, such a result may partially be ascribed to the weak variability of soil moisture in the lower soil layers. The differences in soil water contents between the driest and the wettest points were relatively small, especially in the MIL plot. The increasing cover of natural vegetation in the NAF plot and the intense evaporation and risk of runoff in the MIL plot resulted in their wettest points being at different positions along the slope. The most temporally stable points at various depths were dispersed on the slopes of the KOP and ALF plots, were concentrated at upslope positions in the NAF plot and were at intermediate positions in the MIL plot.

According to the SDRDs, most representative points (here not including the most temporally stable points) in the four plots were characterized by a comparatively lower temporal stability at the corresponding soil depths. The SDRDs at the driest, wettest and average moisture points tended to become smaller with depth, indicating that as external disturbances decreased down the soil profile, the temporal stability at those representative points increased. Moreover, the mean SDRDs of the driest points were smaller than those of the wettest points, suggesting that the temporal stability of soil moisture was greater under dry conditions than under wet conditions. This result was consistent with many other studies (Cosh et al., 2008; Hu et al., 2010; Jacobs et al., 2004; Martínez-Fernández and Ceballos, 2003).

Where representative points were not consistent in soil profiles, the use of multiple points with average moisture has been suggested as a theoretical alternative. Moreover, points of extreme moisture with high temporal stability might be an alternative to points of average moisture with low temporal stability (Jia and Shao, 2013).

3.3. Mechanism controlling temporal stability of soil moisture pattern

3.3.1. Influence of wetness index varying with soil depths

Allowing for the same aspect, slope gradient, regular layout of observational points and the small plot size, we selected the wetness index (Beven and Kirkby, 1979), which is the most commonly used hydrologically-based compound topographic index (Moore et al., 2006), as the main topographic factor in this study. In this section, we related MRDs and SDRDs to the wetness index at different depths and the relationships were expressed by Pearson correlation coefficients. The objective was to explore how the role of the wetness index in controlling temporal stability of soil moisture changed with soil depth. Figs. 6a and b shows the depth series of correlation coefficients between MRDs and the wetness index, and between SDRDs and the wetness index, respectively. This way of presenting the results was also used by Famiglietti et al. (1998) and it has also been used to display the soil profile pattern of relationships of time-averaged soil moisture with environmental indices (Qiu et al., 2001).

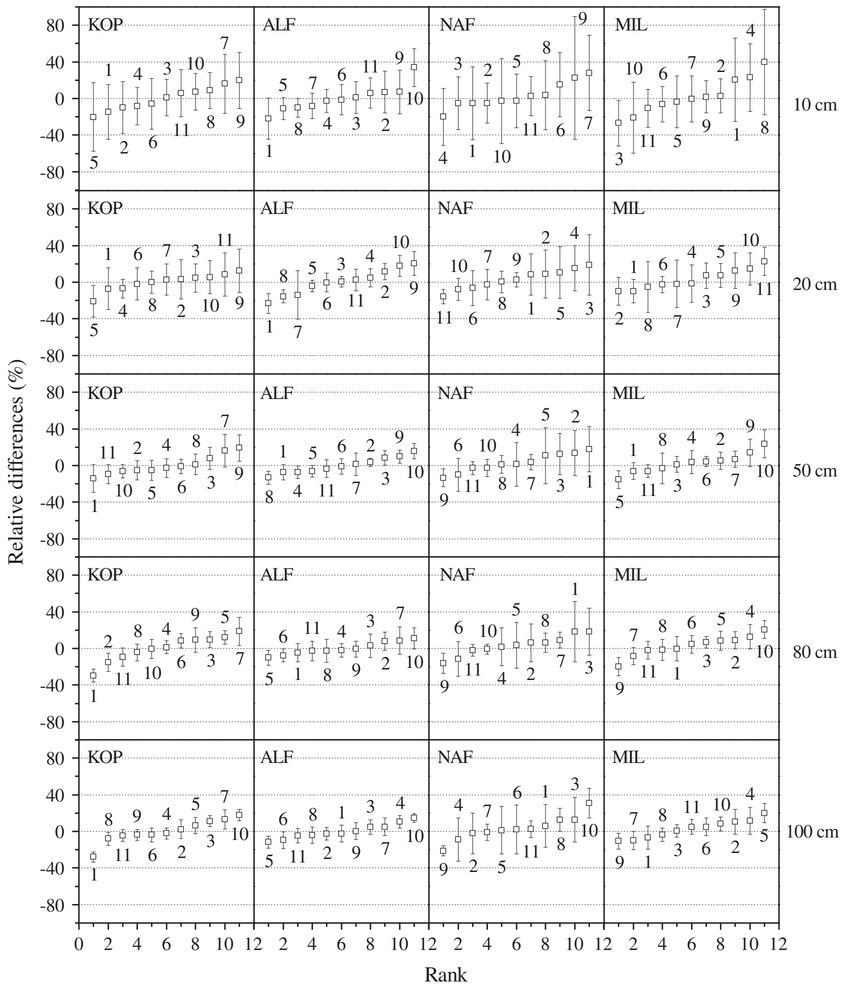

Fig. 5. Rank ordered mean relative differences (MRDs) with their standard deviation (vertical bars) for soil water contents at five selected depths (10, 20, 50, 80, 100 cm) in four plots (Korshinsk peashrub, KOP; purple alfalfa, ALF; natural fallow, NAF; millet, MIL).

Regardless of being positive or negative, the correlation between MRDs and the wetness index weakened with increasing soil depth (Fig. 6a). According to the evaluation criteria proposed by Famiglietti et al. (1998), correlation levels between 0 and 0.5 were referred to as weak, between 0.5 and 0.8 as moderate, and between 0.8 and 1.0 as strong. As shown in Fig. 6a, a moderate or strong negative correlation of MRDs with wetness index existed in the upper layer in all plots except NAF. The correlation in NAF plot was moderately or strongly positive in the upper and middle layers. Due to the consistent slope gradient of the four plots, the highest wetness index corresponds to the lowest observational point position. The negative correlation in the surface layers in the KOP, ALF and MIL plots indicated an overall wet soil condition on the upper slope and a dry soil condition on the lower slope, as noted previously. Similar results can be found in Famiglietti et al. (1998), where an inverse relationship between relative elevation and surface moisture content occurred. Therefore, another explanation for the result in the present study was the effect of dominant vertical fluxes on water redistribution, which lessened the hydrological connection between the points and the upslope area on the slope (Zhao et al., 2010). Positive correlations occurred in many soil layers in the NAF plot, which could be related to the looser cultivated soil condition relative to the other three plots (Jia and Shao, 2013).

Fig. 6b shows the depth series of the correlation coefficients between SDRDs and the wetness index. No single trend of the changes in the coefficient with depth was evident for all the four plots. The negative relationship of SDRDs with the wetness index in the ALF plot was most apparent at 40 cm depth. Beyond that, the temporal stability indicator of SDRD was weakly correlated with the wetness index for the KOP, ALF and MIL plots. This could be a consequence of the lessening topographic effect on deep soil moisture and to the dampening of topography effects on soil moisture by the transpiration of the vegetation (Ng and Miller, 1980). Temporal stability of soil moisture in the NAF plot was positively correlated with the wetness index, which highlighted the unique effects of natural fallow on soil moisture with soil depth.

3.3.2. Relative importance of main considered factors

Three main factors were concerned in the present study, namely vegetation type, soil depth and wetness index. We performed factorial ANOVA to decide their individual effects on MRD and SDRD. Interactions between the factors were not considered.

As shown in Table 4, in controlling MRD, the effect of wetness index ranked the first, followed by vegetation types. Both wetness index and vegetation types were statistically significant ($p < 0.01$ or $p < 0.05$) factors affecting MRDs, while soil depth had no significant effect on MRDs.

Table 3
Mean relative differences (MRD) and their standard deviation (SDRD) for the observational points identified as representing the driest, wettest, average moisture and most stable at each depth under plots of KOP (Korshinsk peashrub), ALF (purple alfalfa), NAF (natural fallow) and MIL (millet).

Depth (cm)	Driest points			Average moisture points			Wettest points			Most stable points		
	No.	MRD (%)	SDRD (%)	No.	MRD (%)	SDRD (%)	No.	MRD (%)	SDRD (%)	No.	SDRD (%)	MRD (%)
KOP												
10	5	−20.23	37.43	3	1.1	19.71	9	19.89	30.63	8	19.67	8.67
20	5	−21.02	17.45	8	0.07	12.16	9	12.53	23.35	4	10.09	−6.98
30	5	−20.61	6.36	8	0.13	6.03	9	12.38	10.82	8	6.03	0.13
40	5	−16.12	10.73	11	0.6	14.68	9	17.56	11.91	6	7.74	−3.18
50	1	−14.22	15.05	6	−1.14	7.88	9	19.12	14.51	10	7.24	−6.16
60	1	−21.43	12.85	4	−0.18	9.36	9	21.1	18.44	11	8.19	−18.82
70	1	−26.77	10.17	4	0.92	8.9	7	23.68	16.25	2	7.58	−18.21
80	1	−29.64	7.17	10	−0.54	10.3	7	18.76	15.45	4	7.11	1.23
90	1	−29.81	6.99	4	0.31	9.37	7	17.33	12.59	5	5.55	11.92
100	1	−27.91	5.46	2	2.18	10.17	10	17.81	6.24	1	5.46	−27.91
ALF												
10	1	−22.12	22.43	3	1.07	17.14	10	33.8	20.77	8	10.26	−10.05
20	1	−23.27	10.95	6	−0.45	10.15	9	20.53	13.07	3	5.65	0.56
30	1	−15.34	6.31	6	1.21	9.33	9	28.08	16.32	2	4.83	7.76
40	8	−12.24	7.76	3	0.09	7.99	9	17.66	14.61	5	5.62	−4.82
50	8	−13.17	7.08	6	−1.01	8.32	10	15.71	8.13	2	4.3	3.49
60	8	−9.93	8.7	11	−0.13	10.54	10	12.75	10.3	2	5.2	5.3
70	6	−9.16	8.36	11	1.01	11.33	10	10.4	11.7	5	6.64	−5.73
80	5	−10.14	8.02	9	−0.72	8.75	10	11.03	11.72	6	7.13	−7.64
90	6	−10.06	8.76	2	−3.43	7.41	10	13.02	10.04	2	7.41	−3.43
100	5	−11.63	6.6	9	0.25	9.16	10	14.64	4.75	10	4.75	14.64
NAF												
10	7	−20.05	31.28	5	−2.72	29.44	4	28.01	41.32	10	21.49	2.66
20	11	−15.74	7.96	8	0.41	11.73	3	18.71	33.06	9	7.84	2.54
30	10	−13.14	8.59	8	−1.95	8.81	3	21.21	19.47	11	4.74	−10.66
40	10	−9.71	10.41	8	−1.4	7.97	2	18.38	26.46	11	6.21	−6.99
50	9	−13.43	9.52	8	1.19	9.58	1	17.82	24.78	11	6.82	−2.88
60	9	−9.15	11.18	11	−0.82	6.54	1	24.42	32.3	11	6.54	−0.82
70	9	−13.26	11.13	7	0.21	10.99	1	40.95	58.8	10	8.15	−3.96
80	9	−16.07	11.03	10	−0.72	5.6	3	18.34	25.54	10	5.6	−0.72
90	9	−18.17	9.44	2	−0.5	22.8	3	17.16	24.22	11	7.53	2.74
100	9	−21.27	5.63	7	−0.85	8.93	10	30.97	16.2	9	5.63	−21.27
MIL												
10	8	−26.95	24.99	7	−0.53	25.04	3	39.62	57.6	5	17.38	1.81
20	2	−9.95	15.37	7	−1.91	26	11	22.61	15.5	6	8.99	−2.69
30	1	−12.26	10.14	7	0.61	14.3	9	13.2	15.12	3	8	5.74
40	1	−10.16	10.41	4	0.87	15.87	9	20.62	14.66	11	5.42	−2.12
50	5	−15.33	9.8	3	1.25	8.45	10	23.49	15.1	6	5.47	4.23
60	5	−12.32	6.9	6	2.49	16.73	10	25.6	14.91	3	6.25	−4.13
70	9	−15.45	10.96	1	−0.32	11	10	19.88	8.9	5	7.7	−5.93
80	9	−20.02	9.93	1	−0.46	13.37	10	20.5	9.75	3	6.23	6.61
90	9	−14.7	8.4	11	1.07	6.6	5	17.07	11.98	3	4.55	1.81
100	9	−10.7	8.64	3	0.45	6.66	5	19.94	10.36	3	6.66	0.45

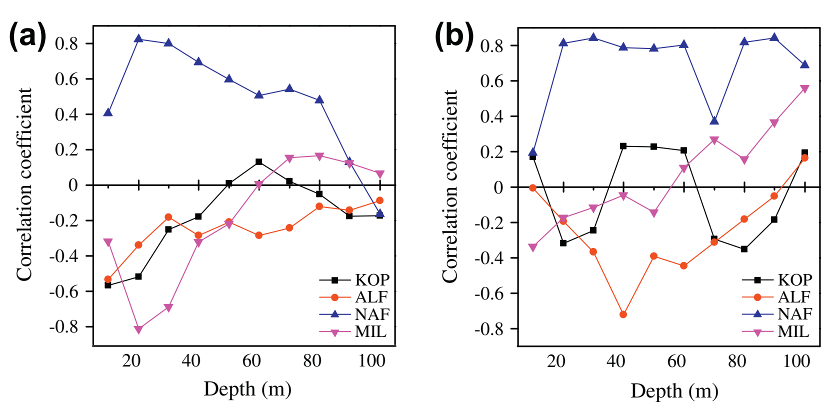

Fig. 6. Depth series of Pearson correlation coefficients between (a) the mean relative difference (MRD) and the wetness index, and (b) the standard deviation of the relative difference (SDRD) and the wetness index for plots under KOP (Korshinsk peashrub), ALF (purple alfalfa), NAF (natural fallow) and MIL (millet).

In controlling the temporal stability of soil moisture, vegetation type outweighed soil depth, while the wetness index was of least importance, although all three factors had significant effects on SDRD ($p < 0.01$).

3.3.3. Effects of profile soil properties

Five soil profile properties of the four plots were considered in order to interpret the role of soil in affecting MRD of profile soil moisture and its SDRD. Pearson correlation analysis showed that

Table 4
Factorial ANOVA results for evaluating factors influencing the mean relative difference (MRD) and their standard deviation (SDRD).

Factors	DF	MRD		SDRD	
		F Value	Sig.	*F* Value	Sig.
Vegetation types	3	2.642	0.049	49.720	0.000
Soil depth	9	0.004	1.000	28.127	0.000
Wetness index	10	6.957	0.000	2.859	0.002

DF, degree of freedom; Sig., significance level.

Table 5
Pearson correlation coefficients between some selected soil properties and the mean relative differences (MRD) and their standard deviation (SDRD).

	Soil organic carbon	Soil saturated hydraulic conductivity (K_s)	Bulk density	Total porosity	Clay percentage
MRD	−0.084	0.506**	−0.523**	0.218	−0.089
SDRD	0.667**	0.371*	−0.451**	−0.088	−0.207

**, * Correlation is significant at the 0.01 and 0.05 levels, respectively.

Table 6
Field capacity (%) of soil at surface and subsurface layers in the four experimental plots with different vegetation.

Soil depth	KOP	ALF	NAF	MIL
0–10 cm	0.14 ± 0.03	0.13 ± 0.01	0.13 ± 0.02	0.12 ± 0.01
10–20 cm	0.14 ± 0.03	0.14 ± 0.02	0.13 ± 0.01	0.13 ± 0.02

KOP, ALF, NAF and MIL stand for the vegetation types of Korshinsk peashrub, purple alfalfa, natural fallow and millet, respectively.

MRD was significantly correlated with soil saturated hydraulic conductivity (K_s) and bulk density (Table 5). These two factors were mainly responsible for soil moisture variability induced by soil properties in the plots. Martinez et al. (2012) reported an explicit effect of soil saturated hydraulic conductivity on MRD based on the linear relationship between simulated ln K_s and MRD values across a range of soils and depths. Cosh et al. (2008) found bulk density was the most important soil parameter affecting MRD and accounted for 31.8% of the variability in MRD. However, Hu et al. (2009) found no significant correlation between MRD and bulk density.

Along with soil saturated hydraulic conductivity and bulk density, soil organic carbon was significantly correlated with the temporal stability indicator, SDRD. Martinez et al. (2012) found an increase in the spatial variability of K_s would result in a decrease in temporal stability. However, when only the simulated data of K_s varied, a high correlation between SDRD and MRD occurred that could not be found with field data. The significant negative correlation between bulk density and MRD and SDRD were in contrast to Hu et al. (2009) who found positive but insignificant correlations between the comparative indices. Neither total porosity nor clay content were significantly correlated with MRD or SDRD. This was linked to the different varying pattern of MRD and SDRD across small study areas in present study.

3.3.4. The contribution of water retention within the upper soil layers

Soils with high retentions can store more precipitation. Soil water retention at a water potential of −33 kPa has often been considered as the field capacity (Díaz-Zorita and Grosso, 2000; Hudson, 1994; Saxton and Rawls, 2006). From the bottom to the top of the slope, field capacities at depths of 10 and 20 cm in the four plots were measured using centrifuge tests. As shown in Table 6, the field capacities were very similar. Statistical analysis indicated that the field capacities of the two soil layers and among the four plots were not significantly different, suggesting that the different vegetative types did not influence the ability of the soil in the four plots to retain water.

Moreover, MRD and SDRD at the same depth were only very weakly correlated with field capacity (not significant at the 0.05 level). Field capacity thus cannot account for the temporal stability of water content in our study. Studies conducted in heterogeneous soil, however, have indicated that the retention of soil water was closely related to the temporal stability of soil water. Jacobs et al. (2004) considered that fields with lower sand contents and thus higher soil water retentions may have patterns of soil moisture that are more temporally stable. Consistent with these findings of Jacobs et al. (2004), Zhao et al. (2010) observed that the mean relative difference was positively correlated with both soil organic carbon and clay contents but negatively with sand content and bulk density. In comparison, the weak effect of field capacity on temporal stability of soil water in our study can be ascribed to the small size of the investigated area and to its homogeneity of soil textural properties.

4. Conclusions

Trends in the spatial distributions of soil moisture under four vegetation types on a loessial slope were obtained through long-term monitoring. Soil moisture presented different vertical but similar horizontal trends in the four vegetation type plots. Strong correlations in soil moisture for adjacent soil layers, while horizontal correlation was widely observed among soil profiles on the slope.

Temporal stability of the soil moisture profile expressed by Spearman rank correlation coefficients generally increased with increasing depth in the KOP and MIL plots, first increased and then decreased in the ALF plot and increased, but were somewhat unstable on the first three measurement dates in the NAF plot.

Four types of representative points, the driest, wettest, average moisture and most time-stable, for various soil depths in the four plots were identified by a relative-difference technique. Points with extreme moisture tended to remain representative at more depths than did points with average moisture and increased in temporal stability with increasing soil depth.

The correlation between MRDs and wetness index weakened with soil depth. In contrast, the relationship of SDRD to the wetness index varied nonlinearly with soil depth for all the plots. Vegetation type, soil depth and the wetness index, in order of importance, had a significant effect on the temporal stability of soil moisture. Among selected soil properties, saturated hydraulic conductivity and bulk density significantly affected the MRD and SDRD. In addition, soil organic carbon had a significant effect on SDRD.

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References

Arya, L.M., Richter, J.C., Paris, J.F., 1983. Estimating profile water storage from surface zone soil moisture measurements under bare field conditions. Water Resour. Res. 19 (2), 403–412.

Beven, K., Kirkby, M., 1979. A physically based, variable contributing area model of basin hydrology. Hydrol. Sci. J. 24 (1), 43–69.

Brocca, L., Melone, F., Moramarco, T., Morbidelli, R., 2009. Soil moisture temporal stability over experimental areas in Central Italy. Geoderma 148 (3–4), 364–374.

Bromley, J., Brouwer, J., Barker, A., Gaze, S., Valentine, C., 1997. The role of surface water redistribution in an area of patterned vegetation in a semi-arid environment, south-west Niger. J. Hydrol. 198 (1–4), 1–29.

Chen, H., Shao, M., Li, Y., 2008. Soil desiccation in the Loess Plateau of China. Geoderma 143 (1), 91–100.

Cheng, J., Wan, H., Wang, J., 2005. Alfalfa growth and its relation with soil water status in loess hilly and gully region. Chin. J. Appl. Ecol. 16 (3), 435–438 (in Chinese with English abstract).

Chesworth, W., 2007. Encyclopedia of Soil Science. Springer.

Cosh, M.H., Jackson, T.J., Moran, S., Bindlish, R., 2008. Temporal persistence and stability of surface soil moisture in a semi-arid watershed. Remote Sens. Environ. 112 (2), 304–313.

Cuenca, R. et al., 1997. Soil measurements during HAPEX-Sahel intensive observation period. J. Hydrol. 188, 224–266.

De Souza, E.R., Montenegro, A.A.d.A., Montenegro, S.M.G., de Matos, J.d.A., 2011. Temporal stability of soil moisture in irrigated carrot crops in Northeast Brazil. Agric. Water Manage. 99 (1), 26–32.

Díaz-Zorita, M., Grosso, G.A., 2000. Effect of soil texture, organic carbon and water retention on the compactability of soils from the Argentinean pampas. Soil Till. Res. 54 (1), 121–126.

Dumedah, G., Coulibaly, P., 2011. Evaluation of statistical methods for infilling missing values in high-resolution soil moisture data. J. Hydrol. 400 (1), 95–102.

Famiglietti, J., Rudnicki, J., Rodell, M., 1998. Variability in surface moisture content along a hillslope transect, Rattlesnake Hill, Texas. J. Hydrol. 210 (1), 259–281.

Fu, X., Shao, M., Wei, X., Horton, R., 2009. Effects of two perennials, fallow and millet on distribution of phosphorous in soil and biomass on sloping loess land, China. Catena 77 (3), 200–206.

Fu, X., Shao, M., Wei, X., Horton, R., 2010. Soil organic carbon and total nitrogen as affected by vegetation types in Northern Loess Plateau of China. Geoderma 155 (1), 31–35.

Fu, X., Shao, M., Wei, X., Wang, H., Zeng, C., 2012. Effects of mono-vegetation restoration types on soil water distribution and balance on a hillslope in northern Loess Plateau of China. J. Hydrol. Eng., doi: 10.1061/(ASCE)HE.1943-5584.0000628.

Gao, L., Shao, M., 2012. Temporal stability of soil water storage in diverse soil layers. Catena 95, 24–32.

Gao, X., Wu, P., Zhao, X., Shi, Y., Wang, J., 2011. Estimating spatial mean soil water contents of sloping jujube orchards using temporal stability. Agric. Water Manage. 102 (1), 66–73.

Giraldo, M.A., Bosch, D., Madden, M., Usery, L., Finn, M., 2009. Ground and surface temperature variability for remote sensing of soil moisture in a heterogeneous landscape. J. Hydrol. 368 (1), 214–223.

Grayson, R.B., Western, A.W., 1998. Towards areal estimation of soil water content from point measurements, time and space stability of mean response. J. Hydrol. 207 (1), 68–82.

Grayson, R.B., Western, A.W., Chiew, F.H.S., Blöschl, G., 1997. Preferred states in spatial soil moisture patterns, local and nonlocal controls. Water Resour. Res. 33 (12), 2897–2908.

Green, J.C., Reid, I., Calder, I.R., Nisbet, T.R., 2006. Four-year comparison of water contents beneath a grass ley and a deciduous oak wood overlying Triassic sandstone in lowland England. J. Hydrol. 329 (1), 16–25.

Guber, A.K. et al., 2008. Temporal stability in soil water content patterns across agricultural fields. Catena 73 (1), 125–133.

Hu, W., Shao, M., Han, F., Reichardt, K., Tan, J., 2010. Watershed scale temporal stability of soil water content. Geoderma 158 (3–4), 181–198.

Hu, W., Shao, M., Wang, Q., Reichardt, K., 2009. Time stability of soil water storage measured by neutron probe and the effects of calibration procedures in a small watershed. Catena 79 (1), 72–82.

Hudson, B.D., 1994. Soil organic matter and available water capacity. J. Soil Water Conserv. 49 (2), 189–194.

Ireson, A. et al., 2006. Hydrological processes in the Chalk unsaturated zone – insights from an intensive field monitoring programme. J. Hydrol. 330 (1), 29–43.

Jacobs, J.M., Mohanty, B.P., Hsu, E.C., Miller, D., 2004. SMEX02, field scale variability, time stability and similarity of soil moisture. Remote Sens. Environ. 92 (4), 436–446.

Jia, Y.H., Shao, M.A., 2013. Temporal stability of soil water storage under four types of revegetation on the northern Loess Plateau of China. Agric. Water Manage. 117, 33–42.

Kachanoski, R., De Jong, E., 1988. Scale dependence and the temporal persistence of spatial patterns of soil water storage. Water Resour. Res. 24 (1), 85–91.

Kamgar, A., Hopmans, J., Wallender, W., Wendroth, O., 1993. Plotsize and sample number for neutron probe measurements in small field trials. Soil Sci. 156 (4), 213.

Martínez -Fernández, J., Ceballos, A., 2003. Temporal stability of soil moisture in a large-field experiment in Spain. Soil Sci. Soc. Am. J. 67 (6), 1647–1656.

Martinez, G. et al., 2013. Modeling local control effects on the temporal stability of soil water content. J. Hydrol. 481, 106–118.

Martínez-Fernández, J., Ceballos, A., 2005. Mean soil moisture estimation using temporal stability analysis. J. Hydrol. 312 (1–4), 28–38.

McCool, D., Foster, G., Mutchler, C., Meyer, L., 1989. Revised slope length factor for the universal soil loss equation. Trans ASAE 32.

Moore, I.D., Burch, G.J., 1986. Physical basis of the length-slope factor in the universal soil loss equation. Soil Sci. Soc. Am. J. 50 (5), 1294–1298.

Moore, I.D., Grayson, R., Ladson, A., 2006. Digital terrain modelling, a review of hydrological, geomorphological, and biological applications. Hydrol. Process. 5 (1), 3–30.

Netto, A., Pieritz, R., Gaudet, J., 1999. Field study on the local variability of soil water content and solute concentration. J. Hydrol. 215 (1), 23–37.

Ng, E., Miller, P.C., 1980. Soil moisture relations in the southern California chaparral. Ecology, 98–107.

Nielsen, D., Cassel, D., Wendroth, O., 2000. Assessing spatial variability in an agricultural experiment station field, opportunities arising from spatial dependence. Agron. J. 92 (4), 706–714.

Nielsen, D.R., Biggar, J.W., Erh, K.T., 1973. Spatial variability of field-measured soil–water properties. Hilgardia 42, 215–259.

Pachepsky, Y.A., Guber, A.K., Jacques, D., 2005. Temporal persistence in vertical distributions of soil moisture contents. Soil Sci. Soc. Am. J. 69, 347–352.

Penna, D., Borga, M., Norbiato, D., Dalla Fontana, G., 2009. Hillslope scale soil moisture variability in a steep alpine terrain. J. Hydrol. 364 (3), 311–327.

Qiu, Y., Fu, B., Wang, J., Chen, L., 2001. Spatial variability of soil moisture content and its relation to environmental indices in a semi-arid gully catchment of the Loess Plateau, China. J. Arid Environ. 49 (4), 723–750.

Saxton, K., Rawls, W., 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70 (5), 1569–1578.

Schneider, K., Huisman, J.A., Breuer, L., Zhao, Y., Frede, H.G., 2008. Temporal stability of soil moisture in various semi-arid steppe ecosystems and its application in remote sensing. J. Hydrol. 359 (1–2), 16–29.

Starks, P.J., Heathman, G.C., Jackson, T.J., Cosh, M.H., 2006. Temporal stability of soil moisture profile. J. Hydrol. 324 (1–4), 400–411.

Starr, G.C., 2005. Assessing temporal stability and spatial variability of soil water patterns with implications for precision water management. Agric. Water Manage. 72 (3), 223–243.

Takagi, K., Lin, H., 2012. Changing controls of soil moisture spatial organization in the Shale Hills Catchment. Geoderma 173, 289–302.

Vachaud, G., Passerat de Silans, A., Balabanis, P., Vauclin, M., 1985. Temporal stability of spatially measured soil water probability density function. Soil Sci. Soc. Am. J. 49 (4), 822–828.

Van Pelt, R.S., Wierenga, P.J., 2001. Temporal stability of spatially measured soil matric potential probability density function. Soil Sci. Soc. Am. J. 65 (3), 668–677.

Vanderlinden, K. et al., 2012. Temporal stability of soil water contents: a review of data and analyses. Vadose Zone J. 11 (4).

Vera, J. et al., 2009. Soil water balance trial involving capacitance and neutron probe measurements. Agric. Water Manage. 96 (6), 905–911.

Wang, S., Fu, B., Gao, G., Liu, Y., Zhou, J., 2013. Responses of soil moisture in different land cover types to rainfall events in a re-vegetation catchment area of the Loess Plateau, China. CATENA 101, 122–128.

Wang, Y., Shao, M., Liu, Z., 2010. Large-scale spatial variability of dried soil layers and related factors across the entire Loess Plateau of China. Geoderma 159 (1), 99–108.

Wang, Y., Shao, M.a., Zhu, Y., Liu, Z., 2011. Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China. Agric. Forest Meteorol. 151 (4), 437–448.

Warrick, A.W., 2002. Soil Physics Companion. CRC PressI Llc.

Zeng, C., Shao, M., Wang, Q., Zhang, J., 2011. Effects of land use on temporal–spatial variability of soil water and soil–water conservation. Acta Agric. Scand. Section B-Soil Plant Sci. 61 (1), 1–13.

Zhang, Z.S., Li, X.R., Liu, L.C., Jia, R.L., Zhang, J.G., Wang, T., 2009. Distribution, biomass, and dynamics of roots in a revegetated stand of Caragana korshinskii in the Tengger Desert, northwestern China. J. Plant. Res. 122 (1), 109–119.

Zhao, Y., Peth, S., Wang, X.Y., Lin, H., Horn, R., 2010. Controls of surface soil moisture spatial patterns and their temporal stability in a semi-arid steppe. Hydrol. Process. 24 (18), 2507–2519.

Zhou, X., Lin, H., Zhu, Q., 2007. Temporal stability of soil moisture spatial variability at two scales and its implication for optimal field monitoring. Hydrol. Earth Syst. Sci. Discuss. 4 (3), 1185–1214.