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Dynamics of deep soil moisture in response to vegetational restoration on the Loess Plateau of China

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SUMMARY

The limitation of soil water in semiarid regions restricts the formation of a good cover of vegetation. The Loess Plateau in China, well known for its severe soil erosion, has a thick loessial soil that holds substantial volumes of water and provides the basis of a sustainable restoration of vegetation. Our limited understanding of the dynamics of deep soil moisture, however, could lead to the mismanagement of soil–water resources or could even misguide the policies of vegetational reconstruction. To evaluate the temporal response of deep soil moisture in different types of revegetation, we observed soil moisture to a depth of 340 cm in four plots, planted with Korshinsk peashrub (KOP), purple alfalfa (ALF), native plants (natural fallow, NAF), and millet (MIL), on 15 measurement events from 2010 to 2012. Our analysis provided four main conclusions. (1) The quantitative difference of potential evapotranspiration and actual precipitation resulted in natural deficits of soil moisture. The dynamics of deep soil moisture, however, were mainly dominated by the type of vegetation. Deep soils in plots of KOP and ALF became drier than the soil in plots of NAF and MIL. (2) Deep soil moisture in KOP and ALF was weakly variable. Correlations of time series of soil moisture between the upper and lower layers tended not to be significant. Dried soil layer, a special hydrological phenomenon, had formed in the plots. (3) The correlation between variances of soil moisture and the corresponding mean values were not always significantly positive due to the influence of vegetational type, observational depth, and date. (4) Fallow may be the best cover for achieving adequate hydrological sustainability of the soil. These results are expected to help improve the understanding of the response of deep soil moisture to vegetational restoration and to provide insight into the dynamics of deep soil moisture influenced by vegetation on loessial slopes.

1. Introduction

Soil water is a significant component of the terrestrial water resource, particularly in semiarid regions of the world such as the Loess Plateau of China where groundwater is buried below the thick unsaturated loessial soil (Atsushi Tsunekawa et al., 2014; Li, 2001), and concentrated precipitation is excessively wasted in the form of overland flow (Yang, 2001; Yu, 1992).

The national Grain for Green project was initiated in 1999 to control soil erosion and ecosystemic degradation. The Loess Plateau mainly has a semi-arid climate and a very fragile ecosystem due to its infamous erosion. As a prioritized pilot region for the project (Feng et al., 2013), the Loess Plateau has converted much agricultural land to other uses during the past few decades. For example, Ansai county has substantially increased its forested land at the cost of both cropland and shrubland (Fu et al., 2006; Zhou et al., 2012). Various types of vegetational restoration have been applied across the different geomorphic units, especially on the loessial slopes common among the widely distributed deep gullies. The effectiveness of vegetational restoration is generally restricted by climatic, pedological, hydrological, and topographic factors once proper vegetational types have been selected (Cao et al., 2011; Chen et al., 2008). The consequences of large-scale afforestation have been associated with an increased severity of water shortages (Cao et al., 2009). At present, some nonnative plants such as peashrub and alfalfa have been introduced (Yang et al., 2012b) and cover a large area of the region. Assessments of the impacts of vegetational restoration on soil–water resources, which generally require long-term observation however, have

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been neglected. Information on the dynamics of soil moisture needed for vegetational restoration is essential for managing the water resources and would be helpful for adjusting relevant governmental policies.

The quantity of the soil–water resources depends to a large extent on soil depth, especially the subjectively investigated depths. Agronomic, hydrological, pedological, and environmental studies have tended to focus on soil water in the shallow layers (Famiglietti et al., 1998; Gao and Shao, 2012; Poesen et al., 1990; Tombul, 2007; Wang et al., 2013; Zhu et al., 2014; Zhu et al., 2009). Soil water in deeper layers has largely been ignored due to the high cost of labor and time required for such investigation. Water resources in deep soil profiles are relatively stable for vegetational growth due to the insulating effect of the upper soil (Wang et al., 2012b). Perennial plants may extend their root systems into previously unexplored depths of the soil where the total available water may be greater. When soil moisture is below field capacity, the adaptive strategy of the root systems of perennial plants to acquire deep soil water facilitates the increase of actual evapotranspiration and the decrease of deep drainage (Eilers et al., 2007).

Water resources can be used differently in the various soil layers. For example, Wang et al. (2012b) found that the levels and patterns of distribution of soil moisture in the soil profile differed notably among three types of vegetation (forest, grassland, and farmland) due to differences in the distribution of root systems, the characteristics of transpiration, and the amounts of water taken up by roots. Large spatial variation in deep soil moisture may thus be induced by vegetational consumption (Yang et al., 2012a). On the western Loess Plateau, deficits of deep soil moisture have appeared in various areas with introduced vegetation (Yang et al., 2012b). When dried soil layers form, deep soil water can only be fully replenished on rare occasions (Liu et al., 2010). The functions or effects of deep soil water are much more than the statement above. For example, the unique water conditions in the deep soil profile of active sand dunes may be associated with the protection of soil seed banks (Liu et al., 2007). Additionally, the movement of soil water into the deep unsaturated layers is coupled with the migration of the soluble portion of decomposed organic matter from the top 10 cm of soil (Corvasce et al., 2006). Water resources in deep soil profiles thus play an important role in ensuring a well-established cover of vegetation in semiarid regions, and understanding the response of deep soil moisture to vegetational restoration is essential for estimating the productivity and sustainability of semiarid ecosystems.

To investigate the response of the dynamics of deep soil moisture to vegetational restoration, four adjacent experimental plots with different vegetational types were selected for observation. The experiment was conducted at the Shenmu Erosion and Environment Research Station on the Loess Plateau of China. This study presents the dynamics of soil moisture to a depth of 340 cm, correlations among time series, and the relationship between variability and means.

2. Materials and methods

2.1. Site and data description

This study was conducted on a loessial slope in the Liudaogou catchment of Shenmu County in Shannxi Province, China. The Liudaogou catchment lies within 38°46′–38°51′N and 110°21′–110°23′E in a transitional belt between the Loess Plateau and the Mu Us desert. It is dominated by a semiarid and temperate continental climate and has an annual mean temperature of 8.4 °C and monthly mean temperatures of −9.7 °C in January and 23.7 °C in July. The mean annual precipitation is 437 mm, 70% of which occurs from June to September. The soils are Loessial (10.7%), Castanozems (32.0%), Skeletal (35.9%), and Aeolian (13.5%), which belong to the major soil orders of Regosols, Cambisols, Chernozems, and Arenosols, respectively (Wei et al., 2013).

Four adjacent well-established plots on the loessial slope were selected (Jia et al., 2013). Each plot was 5 × 61 m and contained one of four vegetational types: Korshinsk peashrub (KOP), purple alfalfa (ALF), natural fallow (NAF), and millet (MIL). The uniform conditions of slope gradient (12–14°), aspect (northwest), soil type (Aeolian loess), soil texture (loamy), and layout of neutron access tubes (11 positions in each plot at 5-m intervals along the midline) ensured that differences in mean soil moisture at the same depth among these four plots could only be attributed to the effect of the vegetation. The layout of the experimental plots and other background information are described elsewhere (Fu et al., 2009; Jia et al., 2013; Jia and Shao, 2013).

We measured soil moisture at various positions and depths in each plot using neutron probes (CNC503DR, China) from July 2010 to July 2012. The designed depth interval was 10 cm in the upper 100 cm of soil and 20 cm in layers deeper than 100 cm. Measurement frequency was once a month from July to October 2010, April to October 2011, and in May and July 2012 and twice a month in June 2012. The soil moisture is relatively stable outside the growing season due to limited precipitation and evapotranspiration, so data for soil moisture were not collected for these periods.

2.2. Methods of analysis

Volumetric soil-moisture data ($cm^3\ cm^{-3}$ or%) for depths of 10–340 cm were used in this study. The plot average at time j and depth k, $\bar{\theta}_{j,k}$, is thus calculated as:

$$\bar{\theta}_{j,k} = \frac{1}{N_i}\sum_{i=1}^{N_i}\theta_{i,j,k} \tag{1}$$

where $\theta_{i,j,k}$ is the soil moisture at position i, depth k, and time j, and N_i is the number of measurement positions at each depth (11). At time j, the depth-averaged soil moisture of a plot is:

$$\bar{\theta}_j = \frac{1}{N_k \cdot N_i}\sum_{k=10}^{N_k}\sum_{i=1}^{N_i}\theta_{i,j,k} \tag{2}$$

where N_k is the number of measurement depths at each position (22, k = 10 cm, 20 cm,. . ., 100 cm, 120 cm,. . ., 340 cm). The variance of soil moisture at time j and depth k is:

$$s^2 = \frac{1}{N_k - 1}\sum_{k=10}^{N_k}\left(\bar{\theta}_{k,j} - \bar{\theta}_j\right)^2 \tag{3}$$

The temporal-averaged soil moisture at depth k of a plot is calculated as:

$$\bar{\theta}_k = \frac{1}{N_j \cdot N_i}\sum_{j=1}^{N_j}\sum_{i=1}^{N_i}\theta_{i,j,k} \tag{4}$$

where N_j is the total number of observational times (15). The corresponding variance of soil moisture at depth k and time j is:

$$s^2 = \frac{1}{N_j - 1}\sum_{k=10}^{N_k}\left(\bar{\theta}_{k,j} - \bar{\theta}_k\right)^2 \tag{5}$$

We calculated the coefficient of variation (CV, the ratio of the standard deviation to the mean) for the temporal-averaged soil moisture at each depth in each plot. Low variability corresponded to values between 0 and 0.1, medium variability corresponded to values between 0.1 and 1, and high variability corresponded to values larger than 1.

Linear correlations of the variances and mean values at different depths and measured events, and the Pearson correlations between time series of soil moisture at each depth, were calculated using SPSS statistical software.

Daily meteorological data from January 2010 to September 2012 from the Shenmu national weather station were used to calculate the potential evapotranspiration at a scale larger than the plots. Potential evapotranspiration is a compound meteorological index, which is calculated with Penman–Monteith methods (Allen et al., 1998).

3. Results

3.1. Dynamics of areal potential evapotranspiration

The redistribution of soil water in semiarid areas is usually dominated by vertical fluxes (Grayson et al., 1997). Soil water in the study area is mainly recharged by the infiltration of precipitation. Evapotranspiration in this semiarid climate is the major component of soil–water output. Among the meteorological factors affecting soil water, potential evapotranspiration is considered to be equally important to temperature and precipitation (Thomas, 2000). The dynamics of potential evapotranspiration is essential background information for our research target. Fig. 1 shows the variation of monthly evapotranspiration for Shenmu County from January 2010 to September 2012. Monthly evapotranspiration increased each year during the three growing seasons (May–September). The accumulative potential evapotranspiration reached 478.5 mm from May to September 2011, and the accumulated precipitation in our experimental plots was 321 mm (Jia and Shao, 2013), so the water deficit over this period could be as high as 157.5 mm. These results formed the basis of a continuous decrease of soil moisture in our experimental plots.

3.2. Dynamics of soil moisture in the plot profiles

The status of soil moisture at various depths in the profile of each plot for all measured events is shown as contour maps in Fig. 2.

The status of soil moisture had an apparent vertical differentiation in 2010 within 100-cm depths in the KOP and ALF plots, being wet in the upper layers and dry in the lower layers. Rain prior to September 2011 (Jia and Shao, 2013) produced relatively high levels of soil moisture, but not as high as in 2010. The soil in the same layers became drier in 2011 than in 2010. More seriously, the driest status among the three years was in 2012, when soil moisture fell below 5%.

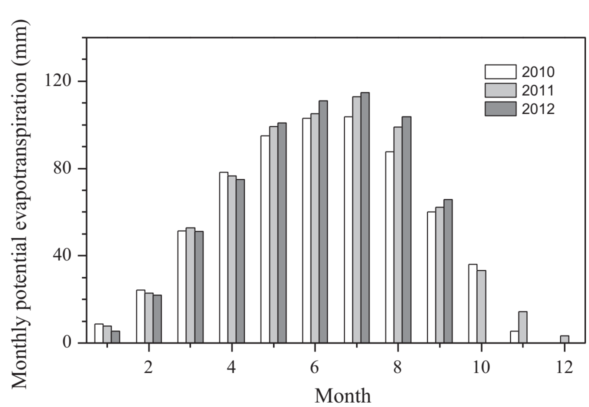

Fig. 1. Monthly potential evapotranspiration for Shenmu county from January 2010 to September 2012.

Soil moisture along the soil profiles in KOP and ALF varied mainly between 5% and 7%. The 7% isoline changed prominently over time, which extended down the soil profile. The downward 7% isoline in ALF exceeded the range of observational depths since October 2010. Even though the layers in the deep profile in KOP with water contents higher than 7% persisted over the observational period, their thickness decreased over time.

NAF and MIL maintained higher soil moistures than did KOP and ALF. The 11% isoline in NAF declined over time. The 13% isoline of soil moisture in MIL partitioned into two time stages: before and after 2010. These results indicated that the soils in the profiles in NAF and MIL also became dry after the second year of observation.

3.3. Patterns of variability of deep soil moisture down the profiles

We employed CVs to describe the extent of changes in soil moisture over time. The CV of soil moisture at a particular depth varied with the type of vegetation (Tables 1–4). The surface layers (10 cm) had the highest CVs. The CVs in KOP, ALF, NAF, and MIL decreased from the surface layer to depths of 70, 90, 80, and 30 cm, respectively, below which no consistent trends appeared in each plot. Soil moisture in KOP had medium and low variation at depths less than and more than 70 cm, respectively. As expected, layers within 90 cm in ALF had medium variation. NAF and MIL had medium variation below 80 cm and within 20 cm, respectively. The order of CV magnitude was KOP > ALF > NAF > MIL in the surface and subsurface layers (0–20 cm), although ALF > KOP at 30 cm. The order at 70 cm was ALF > NAF > KOP > MIL.

The mean soil moistures observed on different dates constituted a time series. Moreover, the mean soil moistures at each depth were synchronized with one another. Correlation analysis among time series of mean soil moistures at different depths would help to explore the relevant information of temporal variability of deep soil moisture. The relevant results are shown in Tables 1–4. The correlation coefficients in KOP and ALF had different patterns above and below the boundary between medium and low variation. The correlation coefficients decreased with increasing depth in KOP and ALF at all depths above 70 and 90 cm, respectively. The correlation coefficients below these depths varied without definitely increasing or decreasing trends. The correlation coefficients above 70 and 90 cm in KOP and ALF, respectively, were all significant ($p < 0.01$ or 0.05). Moreover, the time series of soil moisture for any two adjacent depths in all plots had highly significant correlations ($p < 0.01$). Correlations, however, tended not to be significant between the upper and lower layers, such as 10–70 vs. 90–340 cm in KOP, 10–90 vs. 100–340 cm in ALF, and 10–100 vs. 120–340 cm in NAF. The time series of soil moisture at depths within 50 cm in NAF and within 70 cm in MIL were not significantly correlated with those below these depths. The time series of soil moisture were highly correlated in MIL at any two depths below 10 cm.

3.4. Effect of soil moisture on its variability

Soil-moisture variability depends to some degree on the status of the moisture at a particular spatiotemporal scale (Brocca et al., 2007; Famiglietti et al., 1998; Pan and Peters-Lidard, 2008). The overall absolute variability of soil moisture is generally identified by the variance. The linear correlation of mean soil moistures with their variances can thus reflect the effect of the status of soil moisture on its heterogeneity. The correlation between depth-averaged soil moisture and its corresponding variance, and the trend of correlations over time, are shown in Table 5. Table 6 shows the changing correlations with depth of temporal-averaged soil moisture and its variance.

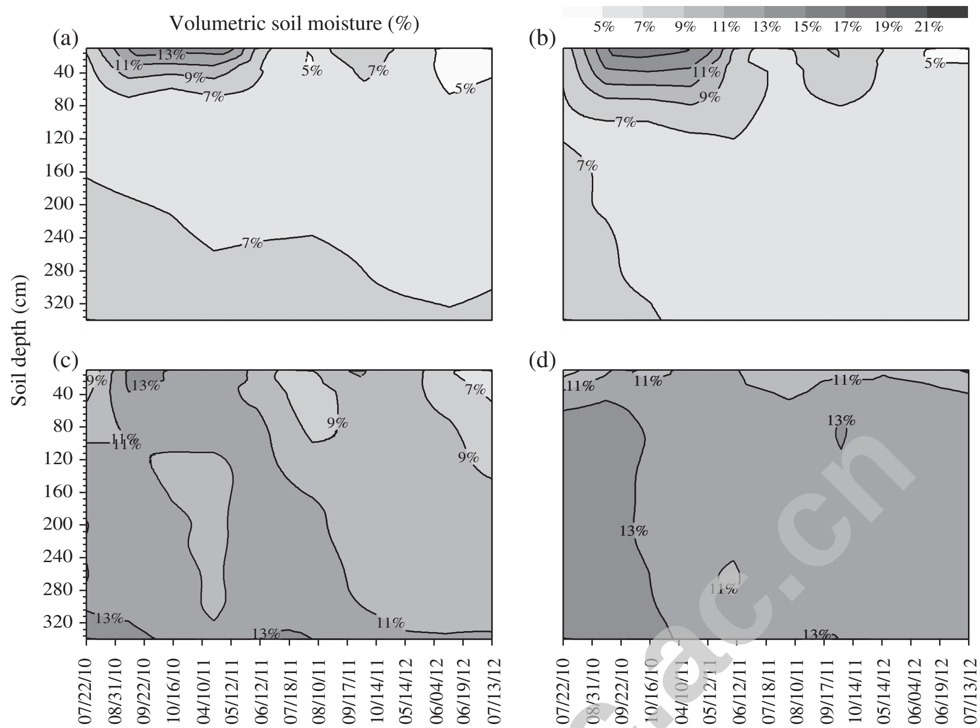

Fig. 2. The vertical distribution and temporal dynamics of soil moisture for plots under (a) KOP (Korshinsk peashrub), (b) ALF (purple alfalfa), (c) NAF (natural fallow), and (d) MIL (millet).

Table 1
Variation coefficients (CV) and Pearson correlation of time series for soil moisture (%, V/V) in KOP (Korshinsk peashrub) plot.

Depth (cm)	10	20	30	40	50	60	70	80	90	100	120	140	160	180	200	220	240	260	280	300	320	340
Mean (%)	9.25	7.44	7.37	7.14	6.69	6.35	5.96	5.79	5.70	5.85	5.93	6.12	6.12	6.45	6.64	6.85	6.91	7.18	7.37	7.45	7.60	8.00
CV	0.67	0.54	0.44	0.35	0.29	0.21	0.14	0.08	0.07	0.07	0.06	0.07	0.07	0.06	0.06	0.07	0.06	0.07	0.07	0.07	0.07	0.09
10		0.98**	0.93**	0.85**	0.72**	0.65**	0.60*	0.48	0.19	0.19	0.18	−0.01	−0.03	−0.05	0.17	0.11	0.15	0.21	0.33	0.25	0.39	0.47
20			0.98**	0.91**	0.80**	0.73**	0.69**	0.56*	0.24	0.25	0.24	0.08	−0.01	0.02	0.23	0.17	0.19	0.28	0.39	0.29	0.43	0.52*
30				0.97**	0.89**	0.84**	0.78**	0.62*	0.26	0.25	0.23	0.09	−0.01	0.03	0.24	0.16	0.19	0.28	0.40	0.30	0.42	0.52*
40					0.96**	0.92**	0.83**	0.62*	0.23	0.16	0.16	0.00	−0.07	−0.01	0.16	0.09	0.13	0.21	0.32	0.24	0.33	0.43
50						0.98**	0.86**	0.68**	0.27	0.15	0.13	−0.02	−0.06	−0.01	0.13	0.04	0.12	0.19	0.29	0.25	0.28	0.38
60							0.90**	0.72**	0.31	0.18	0.18	0.01	−0.03	0.02	0.13	0.03	0.13	0.19	0.31	0.29	0.30	0.38
70								0.89**	0.57*	0.41	0.39	0.19	0.13	0.23	0.28	0.28	0.31	0.37	0.47	0.47	0.47	0.52*
80									0.76**	0.69**	0.64*	0.49	0.43	0.45	0.54*	0.47	0.50	0.59*	0.65**	0.68**	0.63*	0.67**
90										0.88**	0.87**	0.73**	0.80**	0.81**	0.79**	0.81**	0.82**	0.82**	0.84**	0.91**	0.85**	0.81**
100											0.93**	0.93**	0.88**	0.89**	0.92**	0.89**	0.89**	0.91**	0.86**	0.88**	0.88**	0.84**
120												0.86**	0.82**	0.90**	0.87**	0.88**	0.87**	0.94**	0.87**	0.92**	0.90**	0.86**
140													0.85**	0.86**	0.91**	0.84**	0.81**	0.86**	0.83**	0.79**	0.79**	0.76**
160														0.84**	0.94**	0.83**	0.89**	0.81**	0.78**	0.84**	0.81**	0.74**
180															0.83**	0.95**	0.89**	0.89**	0.77**	0.81**	0.81**	0.74**
200																0.88**	0.90**	0.89**	0.86**	0.86**	0.88**	0.85**
220																	0.94**	0.92**	0.82**	0.85**	0.88**	0.82**
240																		0.93**	0.87**	0.93**	0.94**	0.87**
260																			0.91**	0.94**	0.93**	0.93**
280																				0.94**	0.94**	0.93**
300																					0.96**	0.94**
320																						0.97**

* and ** Stand for significance level less than 0.05 and 0.01, respectively.

The correlation between depth-averaged soil moisture and its corresponding variance depended on the date of observation and type of revegetation. For example, the correlations in KOP determined on six dates (22 September and 16 October 2010; 10 April, 12 May, and 18 July 2011; and 14 May 2012) were significantly positive ($p < 0.01$). The significant correlations were positive on most occasions in all plots. This result indicated that the variance of soil moisture tended to increase with increasing soil moisture. Significantly positive correlations observed between temporal-averaged soil moistures and the corresponding variances were mainly at depths within 100 cm (Table 2). Such positive correlations appeared at ten depths in NAF but at only two depths in MIL.

Table 2
Variation coefficient (CV) and Pearson correlation of time series for soil moisture (%, V/V) in ALF (purple alfalfa) plot.

Depth (cm)	10	20	30	40	50	60	70	80	90	100	120	140	160	180	200	220	240	260	280	300	320	340
Mean (%)	10.11	8.32	8.83	8.71	8.43	8.01	7.43	6.79	6.63	6.45	6.58	6.49	6.45	6.54	6.51	6.57	6.59	6.64	6.59	6.69	6.91	6.90
CV	0.59	0.50	0.44	0.39	0.34	0.29	0.23	0.18	0.13	0.10	0.08	0.06	0.07	0.06	0.04	0.06	0.07	0.05	0.07	0.06	0.07	0.06
10		0.98**	0.95**	0.92**	0.87**	0.80**	0.81**	0.73**	0.62*	0.47	0.19	0.06	0.04	−0.11	−0.21	−0.07	−0.03	0.27	−0.06	0.06	0.23	0.13
20			0.98**	0.96**	0.92**	0.86**	0.87**	0.76**	0.64*	0.47	0.21	0.12	0.08	−0.06	−0.16	0.00	0.05	0.32	0.00	0.13	0.29	0.16
30				0.99**	0.97**	0.91**	0.91**	0.78**	0.65**	0.46	0.25	0.18	0.15	−0.01	−0.11	0.07	0.11	0.36	0.09	0.20	0.35	0.22
40					0.99**	0.95**	0.95**	0.82**	0.69**	0.48	0.26	0.19	0.14	−0.02	−0.11	0.05	0.10	0.31	0.08	0.19	0.33	0.20
50						0.99**	0.98**	0.86**	0.72**	0.51	0.31	0.22	0.16	0.02	−0.09	0.05	0.12	0.30	0.11	0.23	0.35	0.23
60							0.99**	0.91**	0.78**	0.57*	0.37	0.25	0.17	0.03	−0.08	0.02	0.11	0.24	0.10	0.21	0.31	0.21
70								0.94**	0.82**	0.63*	0.39	0.25	0.17	0.03	−0.07	0.01	0.11	0.23	0.08	0.19	0.29	0.18
80									0.96**	0.83**	0.56*	0.34	0.24	0.12	0.02	0.00	0.17	0.18	0.10	0.22	0.29	0.21
90										0.93**	0.71**	0.48	0.36	0.29	0.19	0.11	0.30	0.23	0.17	0.30	0.35	0.29
100											0.81**	0.58*	0.47	0.44	0.37	0.23	0.39	0.29	0.25	0.35	0.38	0.35
120												0.90**	0.84**	0.81**	0.73**	0.65**	0.73**	0.65**	0.66**	0.69**	0.69**	0.72**
140													0.93**	0.94**	0.89**	0.88**	0.90**	0.82**	0.79**	0.831**	0.83**	0.832**
160														0.93**	0.88**	0.90**	0.913**	0.80**	0.89**	0.86**	0.90**	0.92**
180															0.93**	0.90**	0.93**	0.74**	0.85**	0.90**	0.84**	0.85**
200																0.92**	0.91**	0.73**	0.83**	0.79**	0.79**	0.82**
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280																				0.91**	0.92**	0.92**
300																					0.94**	0.91**
320																						0.97**

* and ** Stand for significance level less than 0.05 and 0.01, respectively.

Table 3
Variation coefficient (CV) and Pearson correlation of time series for soil moisture (%, V/V) in NAF (natural fallow) plot.

Depth (cm)	10	20	30	40	50	60	70	80	90	100	120	140	160	180	200	220	240	260	280	300	320	340
Mean (%)	10.43	9.43	9.91	10.05	9.93	9.99	10.14	10.11	10.13	10.22	10.21	10.32	10.62	11.13	11.00	10.96	11.17	11.37	11.31	11.19	11.82	12.45
CV	0.46	0.33	0.26	0.23	0.20	0.19	0.18	0.15	0.14	0.13	0.12	0.12	0.12	0.10	0.12	0.10	0.11	0.10	0.10	0.09	0.08	0.11
10		0.91**	0.74**	0.67**	0.56*	0.50	0.31	0.26	0.14	0.02	−0.13	−0.14	−0.17	0.08	−0.14	−0.12	−0.11	−0.08	−0.03	−0.08	0.04	−0.14
20			0.94**	0.90**	0.83**	0.78**	0.64*	0.56*	0.41	0.31	0.11	0.07	0.04	0.17	0.12	0.07	0.08	0.13	0.18	0.11	0.18	0.04
30				0.98**	0.94**	0.91**	0.83**	0.74**	0.60*	0.53*	0.31	0.25	0.21	0.24	0.33	0.22	0.24	0.30	0.35	0.27	0.27	0.19
40					0.98**	0.95**	0.89**	0.80**	0.65**	0.58*	0.32	0.24	0.21	0.18	0.32	0.20	0.23	0.27	0.32	0.24	0.24	0.16
50						0.99**	0.94**	0.89**	0.75**	0.67**	0.42	0.33	0.30	0.21	0.37	0.28	0.31	0.32	0.35	0.29	0.29	0.22
60							0.96**	0.93**	0.81**	0.73**	0.51	0.42	0.40	0.27	0.43	0.36	0.40	0.38	0.40	0.35	0.35	0.28
70								0.93**	0.83**	0.79**	.575*	0.48	0.45	0.22	0.50	0.37	0.42	0.41	0.43	0.38	0.33	0.33
80									0.95**	0.88**	.691**	0.56*	0.52*	0.29	0.51	0.42	0.49	0.44	0.40	0.35	0.34	0.32
90										.96**	0.814**	0.69**	0.61*	0.40	0.61*	0.49	0.56*	0.52*	0.47	0.41	0.35	0.38
100											0.838**	0.73**	0.65**	0.44	0.68**	0.51	0.57*	0.55*	0.53*	0.46	0.32	0.42
120												0.95**	0.91**	0.754**	0.88**	0.82**	0.85**	0.85**	0.78**	0.74**	0.68**	0.78**
140													0.97**	0.87**	0.94**	0.93**	0.95**	0.93**	0.89**	0.89**	0.81**	0.87**
160														0.85**	0.92**	0.94**	0.95**	0.93**	0.87**	0.89**	0.85**	0.89**
180															0.83**	0.92**	0.88**	0.91**	0.90**	0.89**	0.88**	0.89**
200																0.91**	0.90**	0.97**	0.95**	0.92**	0.80**	0.88**
220																	0.97**	0.97**	0.94**	0.96**	0.95**	0.95**
240																		0.93**	0.90**	0.94**	0.91**	0.89**
260																			0.97**	0.96**	0.91**	0.95**
280																				0.97**	0.89**	0.94**
300																					0.93**	0.94**
320																						0.92**

* and ** Stand for significance level less than 0.05 and 0.01, respectively.

4. Discussion

4.1. Dialectical analysis of the effects of vegetational restoration

Vegetational restoration can substantially promote the prevention of soil erosion (Deng et al., 2012). It is considered that the severe erosion status of Loess Plateau has changed into slight erosion since vegetational restoration associated with Grain for Green project is implemented (Sun et al., 2014). Four runoff plots in our study had adopted revegetation measures for seven years prior to 2010. During the experimental period, erosion from runoff in response to rainstorms occurred only in MIL. The control of soil erosion on the loessial slope benefited from revegetation. The hydrological conditions in the profile, however, may be negatively affected in semiarid regions (Cao et al., 2009; Yang et al., 2012b). Neal et al. (2012) reported that some perennial and annual forage created soil-moisture deficits when insufficiently irrigated. Cultivated vegetation on the Loess Plateau has overexploited the soil water stored in the deep profile (Wang et al., 2008; Wang et al., 2009) and has caused a potential threat to the survival of the vegetation and the sustainable use of the land (Chen et al., 2008; Jun et al., 2008).

Such phenomena attracted the attention of local researchers. Soil water storage within 0–100 cm decreased 49.4, 32.4, and

Table 4
Variation coefficient (CV) and Pearson correlation of time series for soil moisture (%, V/V) in MIL (millet) plot.

Depth (cm)	10	20	30	40	50	60	70	80	90	100	120	140	160	180	200	220	240	260	280	300	320	340
Mean (%)	10.27	10.32	11.60	12.00	12.25	12.39	12.61	12.89	12.91	12.73	12.43	12.49	12.67	12.56	12.31	12.29	12.40	12.40	12.28	12.42	12.65	13.01
CV	0.39	0.22	0.09	0.09	0.09	0.08	0.09	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.07	0.09	0.08	0.09	0.10	0.09	0.09	0.07
10		0.95**	0.74**	0.60*	0.56*	0.52*	0.53*	0.51	0.48	0.45	0.45	0.44	0.42	0.41	0.47	0.46	0.44	0.42	0.44	0.43	0.47	0.47
20			0.91**	0.81**	0.78**	0.75**	0.76**	0.75**	0.73**	0.70**	0.70**	0.70**	0.67**	0.67**	0.71**	0.71**	0.69**	0.67**	0.69**	0.69**	0.71**	0.71**
30				0.97**	0.95**	0.94**	0.93**	0.94**	0.93**	0.91**	0.91**	0.90**	0.89**	0.89**	0.91**	0.91**	0.909**	0.89**	0.90**	0.90**	0.92**	0.92**
40					0.99**	0.99**	0.97**	0.98**	0.97**	0.96**	0.96**	0.95**	0.94**	0.94**	0.95**	0.94**	0.953**	0.94**	0.93**	0.94**	0.95**	0.96**
50						0.98**	0.98**	0.99**	0.98**	0.97**	0.96**	0.95**	0.94**	0.94**	0.95**	0.94**	0.95**	0.94**	0.92**	0.94**	0.94**	0.96**
60							0.99**	0.99**	0.99**	0.98**	0.97**	0.97**	0.97**	0.97**	0.97**	0.96**	0.98**	0.97**	0.96**	0.97**	0.97**	0.98**
70								0.99**	0.99**	0.99**	0.98**	0.98**	0.97**	0.97**	0.97**	0.97**	0.97**	0.96**	0.95**	0.97**	0.95**	0.97**
80									0.99**	0.99**	0.97**	0.97**	0.96**	0.96**	0.97**	0.97**	0.97**	0.96**	0.95**	0.96**	0.96**	0.98**
90										0.99**	0.99**	0.99**	0.98**	0.98**	0.98**	0.984**	0.99**	0.98**	0.97**	0.98**	0.97**	0.98**
100											0.99**	0.99**	0.99**	0.98**	0.98**	0.983**	0.98**	0.99**	0.97**	0.98**	0.97**	0.99**
120												0.99**	0.99**	0.99**	0.99**	0.992**	0.99**	0.994**	0.99**	0.99**	0.98**	0.99**
140													0.99**	0.99**	0.99**	0.99**	0.99**	0.99**	0.99**	0.99**	0.97**	0.99**
160														0.995**	0.99**	0.99**	0.99**	0.99**	0.99**	0.99**	0.96**	0.99**
180															0.99**	0.99**	0.99**	0.99**	0.99**	0.99**	0.98**	0.99**
200																0.99**	0.99**	0.99**	0.99**	0.99**	0.98**	0.99**
220																	0.99**	0.99**	0.99**	0.99**	0.98**	0.99**
240																		0.99**	0.99**	0.99**	0.99**	0.99**
260																			0.99**	0.99**	0.98**	0.99**
280																				0.99**	0.99**	0.99**
300																					0.983**	0.99**
320																						0.99**

* and ** Stand for significance level less than 0.05 and 0.01, respectively.

Table 5
The linear correlation of depth-averaged soil moisture (x) with its corresponding variance (y) over time.

Date	KOP			ALF			NAF			MIL		
	Linear equation	R^2	*P*-value	Linear equation	R^2	*P*-value	Linear equation	R^2	*P*-value	Linear equation	R^2	*P*-value
2010/7/22	$y = 0.279 + 0.094x$	0.13	0.06	$y = 3.096 - 0.324x$	0.03	0.569	$y = 2.476 + 0.075x$	0.04	0.72	$y = 23.379 - 1.56x$	0.55	**<0.001**
2010/8/31	$y = 0.288 + 0.137x$	0.02	0.42	$y = -3.514 + 0.589x$	0.42	**0.001**	$y = -0.709 + 0.316x$	0.03	0.56	$y = 5.892 - 0.221x$	0.03	0.22
2010/9/22	$y = -1.065 + 0.28x$	0.79	**<0.001**	$y = -3.736 + 0.677x$	0.73	**<0.001**	$y = -1.907 + 0.47x$	0.2	**0.02**	$y = -22.766 + 1.963x$	0.55	**<0.001**
2010/10/16	$y = -3.778 + 0.65x$	0.62	**<0.001**	$y = -4.254 + 0.779x$	0.31	**0.004**	$y = -56.732 + 5.549x$	0.04	0.19	$y = 13.108 - 0.798x$	0.20	**0.02**
2011/4/10	$y = -3.529 + 0.711x$	0.59	**<0.001**	$y = -3.485 + 0.582x$	0.72	**<0.001**	$y = -4.093 + 0.674x$	0.01	0.37	$y = -7.85 + 0.934x$	0.05	0.17
2011/5/12	$y = -10.148 + 1.572x$	0.53	**<0.001**	$y = -3.079 + 0.53x$	0.74	**<0.001**	$y = -15.276 + 1.603x$	0.27	**0.01**	$y = -21.079 + 1.908x$	0.48	**<0.001**
2011/6/12	$y = 1.387 - 0.071x$	0.02	0.43	$y = 3.023 + -0.337x$	0.11	0.073	$y = 0.752 + 0.092x$	0.02	0.42			
2011/7/18	$y = -0.578 + 0.219x$	0.33	**<0.001**	$y = 0.16 + 0.074x$	0.04	0.736	$y = -11.665 + 1.443x$	0.39	**<0.001**	$y = 38.439 - 3.257x$	0.32	**<0.001**
2011/8/10	$y = 2.31 - 0.249x$	0.12	0.06	$y = -0.264 + 0.138x$	0.02	0.444	$y = 1.121 + 0.164x$	0.04	0.73	$y = 4.451 - 0.199x$	0.14	0.05
2011/9/17	$y = 0.05 + 0.159x$	0.05	0.16	$y = -2.554 + 0.449x$	0.73	**<0.001**	$y = 2.407 - 0.005x$	0.05	0.97	$y = 3.471 - 0.103x$	0.05	0.77
2011/10/14	$y = 1.154 - 0.053x$	0.04	0.61	$y = -1.845 + 0.406x$	0.08	0.113	$y = -2.806 + 0.519x$	0.09	0.09	$y = 9.088 - 0.536x$	0.10	0.08
2012/5/14	$y = -4.113 + 0.801x$	0.55	**<0.001**	$y = -7.843 + 1.35x$	0.91	**<0.001**	$y = -8.933 + 1.101x$	0.47	**<0.001**	$y = -33.623 + 3.103x$	0.24	**0.01**
2012/6/4	$y = 0.438 + 0.022x$	0.04	0.7	$y = -0.178 + 0.101x$	0.03	0.222	$y = 2.479 - 0.058x$	0.05	0.81	$y = 0.568 + 0.131x$	0.04	0.67
2012/6/19	$y = 0.757 - 0.017x$	0.04	0.69	$y = 0.613 + -0.039x$	0.03	0.53	$y = 1.201 + 0.148x$	0.11	0.07	$y = 4.002 - 0.177x$	0.00	0.35
2012/7/13	$y = 5.561 - 0.703x$	0.2	0.02	$y = -5.143 + 1.02x$	0.41	**0.001**	$y = 4.797 - 0.274x$	0.01	0.38	$y = 10.699 - 0.613x$	0.01	0.28

KOP, ALF, NAF and MIL stand for the revegetation types of Korshinsk peashrub, purple alfalfa, natural fallow and millet, respectively. R^2 stands for the determination coefficient of the corresponding linear equation. The bold *P*-values are significant at levels of 0.01 or 0.05.

14.9 mm in KOP, ALF, and NAF, respectively, relative to MIL in the experimental period 2010–2011 (Jia and Shao, 2013). Evaporation was mainly responsible for the loss of water in MIL. The consumption of water by the vegetation in KOP, ALF, and NAF was thus the dominant factor in the decrease of soil water storage. The consumption of water by vegetation, along with the water deficit induced by increasing potential evapotranspiration, affected the entire profiles in KOP and ALF (Fig. 2). Moreover, such an influence likely extended below the depths we investigated. For example, the depletion of water by Korshinsk peashrubs and purple alfalfa, cultivated for 31 and 7 years, respectively, may reach 22.4 and 15.5 m, respectively, in Suide, a county approximately 214 km from Shenmu (Wang et al., 2009). Jun et al. (2014) reported the maximum depth of water absorption by alfalfa in four plots in the watershed was 330 cm in the second year and 420 cm in the third year. Moisture generally decreased along the soil profile in NAF. Yang et al. (2012b) reported a decreasing trend of soil moisture along the profile of fallow farmland, where soil moisture was similar to that in the corresponding layer of native grassland. In our study, the decrease in soil moisture in NAF should not be considered as degradation, especially in contrast to the moisture status in KOP and ALF. The native vegetation in NAF appeared able to successfully control erosion from runoff. We thus deduced that natural fallow may be the best form of revegetation for the semiarid regions of the Loess Plateau from the point of view of the productivity and sustainability of the ecosystem. Other aspects also support this conclusion (Jin et al., 2014; Wang et al., 2012a), although recommended measures to reduce soil-moisture deficit were not confined to natural fallow (Jun et al., 2014; Yang et al., 2012b).

4.2. Patterns of variability induced by dried soil layers

Spatiotemporal variation is a common feature of soil moisture. The mechanisms influencing such variation should be less complicated at the plot scale than at a larger scale (Zhu and Lin, 2011). This study has highlighted the temporal variability of soil moisture in deep profiles on the basis of small experimental plots with very similar conditions other than type of vegetation. As expected and

Table 6
The linear correlations of temporal-averaged soil moisture (x) with its variance (y) over different depths.

Depth	KOP			ALF			NAF			MIL		
	Linear equation	R^2	*P*-value	Linear equation	R^2	*P*-value	Linear equation	R^2	*P*-value	Linear equation	R^2	*P*-value
10	$y = -3.134 + 0.953x$	0.34	**0.01**	$y = -3.134 + 0.953x$	0.34	**0.013**	$y = -0.224 + 0.481x$	0.64	**<0.001**	$y = 5.668 + 0.129x$	0.07	0.73
20	$y = 0.592 + 0.136x$	0.09	0.15	$y = 0.592 + 0.136x$	0.09	0.149	$y = -2.129 + 0.619x$	0.34	**0.01**	$y = 1.644 + 0.009x$	0.08	0.9
30	$y = -0.457 + 0.233x$	0.25	**0.03**	$y = -0.457 + 0.233x$	0.25	**0.034**	$y = -3.307 + 0.667x$	0.81	**<0.001**	$y = -1.094 + 0.337x$	0.10	0.13
40	$y = 0.612 + 0.106x$	0.04	0.51	$y = 0.612 + 0.106x$	0.04	0.508	$y = -2.077 + 0.422x$	0.3	**0.02**	$y = -1.795 + 0.388x$	0.12	0.11
50	$y = -0.69 + 0.277x$	0.32	**0.02**	$y = -0.69 + 0.277x$	0.32	**0.016**	$y = -1.279 + 0.295x$	0.43	**<0.001**	$y = -0.77 + 0.265x$	0.11	0.12
60	$y = -2.853 + 0.691x$	0.6	**<0.001**	$y = -2.853 + 0.691x$	0.6	**<0.001**	$y = -1.111 + 0.277x$	0.29	**0.02**	$y = -1.168 + 0.327x$	0.12	0.11
70	$y = -7.086 + 1.457x$	0.66	**<0.001**	$y = -7.086 + 1.457x$	0.66	**<0.001**	$y = -1.34 + 0.294x$	0.41	**0.01**	$y = -94.96 + 10.383x$	0.32	**0.02**
80	$y = -4.984 + 1.046x$	0.44	**<0.001**	$y = -4.984 + 1.046x$	0.44	**0.004**	$y = -1.987 + 0.416x$	0.44	**<0.001**	$y = -1.598 + 0.347x$	0.25	**0.03**
90	$y = -1.999 + 0.485x$	0.28	**0.03**	$y = -1.999 + 0.485x$	0.28	**0.025**	$y = -3.835 + 0.716x$	0.62	**<0.001**	$y = -1.923 + 0.416x$	0.15	0.08
100	$y = -0.644 + 0.235x$	0.14	0.09	$y = -0.644 + 0.235x$	0.14	0.093	$y = -1.911 + 0.385x$	0.59	**<0.001**	$y = -0.742 + 0.363x$	0.07	0.18
120	$y = -0.902 + 0.258x$	0.35	**0.01**	$y = -0.902 + 0.258x$	0.35	**0.012**	$y = -3.208 + 0.596x$	0.09	0.14	$y = -1.02 + 0.418x$	0.06	0.2
140	$y = 0.974 - 0.056x$	0.06	0.66	$y = 0.974 + -0.056x$	0.06	0.658	$y = 0.503 - 0.021x$	0.07	0.86	$y = 1.797 + 0.011x$	0.08	0.93
160	$y = 0.351 + 0.042x$	0.07	0.76	$y = 0.351 + 0.042x$	0.07	0.763	$y = -4.559 + 0.794x$	0.05	0.21	$y = -2.168 + 0.396x$	0.23	0.04
180	$y = -0.595 + 0.214x$	0.01	0.32	$y = -0.595 + 0.214x$	0.01	0.318	$y = 0.735 - 0.05x$	0.06	0.69	$y = -5.656 + 0.972x$	0.03	0.25
200	$y = 0.063 + 0.095x$	0.05	0.57	$y = 0.063 + 0.095x$	0.05	0.574	$y = 1.429 - 0.124x$	0.05	0.6	$y = -10.634 + 1.243x$	0.35	**0.01**
220	$y = -0.055 + 0.123x$	0.01	0.38	$y = -0.055 + 0.123x$	0.01	0.384	$y = -0.698 + 0.164x$	0.12	0.12	$y = 0.681 + 0.155x$	0.02	0.42
240	$y = -0.673 + 0.195x$	0.03	0.24	$y = -0.673 + 0.195x$	0.03	0.244	$y = -1.697 + 0.359x$	0.25	**0.03**	$y = 2.006 + 0.033x$	0.07	0.78
260	$y = -0.926 + 0.263x$	0.01	0.31	$y = -0.926 + 0.263x$	0.01	0.312	$y = -0.068 + 0.102x$	0.04	0.5	$y = -7.643 + 0.965x$	0.22	0.05
280	$y = -3.489 + 0.635x$	0.34	**0.01**	$y = -3.489 + 0.635x$	0.34	**0.014**	$y = -0.139 + 0.154x$	0.07	0.74	$y = 2.093 - 0.005x$	0.08	0.97
300	$y = -1.953 + 0.37x$	0.35	**0.01**	$y = -1.953 + 0.37x$	0.35	**0.012**	$y = -3.492 + 0.617x$	0.03	0.25	$y = 4.44 - 0.188x$	0.04	0.22
320	$y = -0.204 + 0.124x$	0.05	0.6	$y = -0.204 + 0.124x$	0.05	0.6	$y = -1.513 + 0.33x$	0.03	0.44	$y = 10.991 - 0.603x$	0.03	0.43
340	$y = -0.386 + 0.148x$	0.09	0.14	$y = -0.386 + 0.148x$	0.09	0.145	$y = -0.709 + 0.186x$	0.06	0.64	$y = -16.604 + 1.651x$	0.14	0.1

KOP, ALF, NAF and MIL stand for the revegetation types of Korshinsk peashrub, purple alfalfa, natural fallow and millet, respectively. R^2 stands for the determination coefficient of the corresponding linear equation. The bold *P*-values are significant at levels of 0.01 or 0.05.

previously studied, vertical variation of soil moisture tended to be higher near the soil surface as a result of the frequent exchange of water and energy (Jia and Shao, 2013). The order of CV magnitude for the four plots changed with depth in the shallow layers, most likely due to the dominant contribution of the vegetation in the deeper profiles. The four types of vegetation differed greatly in their ability to consume soil water, especially in the deep layers. The deep layers, however, had a low variability of soil moisture. The deep layers in MIL were considered to be undisturbed by plants and climatic factors. The development of roots by the various plants in NAF (Jia and Shao, 2013), combined with changing soil porosity, prevented a stable CV. Allowing for these, we deduced that in KOP and ALF, a hydrological phenomenon – dried soil layers – may have formed below the depths of 70 and 90 cm, respectively. The continuously increasing dry state of the deep soil in both plots supported such a deduction.

The upper and lower soil layers in KOP and ALF had different patterns of variation in the correlation coefficients for the time series of soil moisture. The correlation in the upper layers was lower as the distance between two observational depths increased. The significant correlations in the lower layers seemed to not degrade with vertical distance. Such a result is reasonable under the assumption that dried soil layers had formed. Dried soil layers usually form below the depth of soil affected by the infiltration of rainwater (Jun et al., 2008; Wang et al., 2008, 2010). The hydrological connection in the soil profile is prevented once dried soil layers appear (Chen et al., 2008). A stable dry state thus continues in the deep soil and seems to be unalterable. Accordingly, the correlation of time series of soil moisture between upper and lower layers was not significant.

Dried soil layers can be directly identified by their low levels of soil moisture. Wang et al. (2000) suggested the stable field capacity to be the upper limit of soil–water content for the dried soil layers. Specifically, the upper limit has been set at 60% of field capacity, determined by a laboratory centrifugal test (Wang et al., 2010, 2012b), and is mainly controlled by soil texture. In our experiments, the stable field capacities approximated a constant value of 12% (volumetric), which was converted from its gravimetric value (Jia et al., 2013) combined with the average bulk density. Fig. 2 indicated that the lower layers in KOP and ALF had soil moistures less than 12%. Dried soil layers thus clearly appeared in the KOP and ALF plots. With data from 2009 for the same plots, Fu et al. (2013) reported that dried soil layers appeared at depths of 100–260 cm in KOP and 100–360 cm in ALF. The different depths of formation of dried soil layers were based on approximate values of the depth of rain infiltration. Interestingly, the information deduced from the CVs and correlation coefficients of the soil profiles provided new evidence for the dried soil layers in the plots.

The time series of soil moisture in the surface soil layers had significant correlations with those at different depths in the four plots: within 70 cm in KOP, within 90 cm in ALF, within 50 cm in NAF, and within 70 cm in MIL. The maximum depths of correlation were inconsistent, suggesting that the feasibility and accuracy of predicting soil moisture using time series (Zou et al., 2010) would be affected if the vegetational type was overlooked. The estimation of soil moisture at particular depths based on the significance of correlation coefficients of time series, however, is beyond the scope of this study.

4.3. Influence of soil moisture on its variability

The correlation of soil-moisture variability with the mean values depended to a large extent on the rainfalls of the investigated area. Famiglietti et al. (1998) reported that the variability of the surface-moisture content decreased along a hillslope transect with decreasing mean soil moisture as the hillslope dried following rains. The variability of the soil-moisture content might be maximal following a storm due to high heterogeneity; soil heterogeneity decreased after a long drought when the soil-moisture variability might be minimal (Reynolds, 1970). These findings indicated that high variability was related to high soil moisture, and decreasing variability was often followed by reductions in soil moisture. In our study, the positive correlations between the variances of soil moisture and the corresponding mean values were not always significant, which could be ascribed to the influence of vegetational type and observational depth and date. For example, depth-averaged soil moistures in KOP and ALF correlated significantly to their variances in September and October 2010 and April and May 2011. The soils in KOP and ALF on the corresponding dates were relatively wet, thus the correlations were significant.

The soils in NAF and MIL in October 2010 and April 2011 were relatively dry due to the low cover of vegetation, and the correlations were not significant. Other dates when soils were under similar moisture conditions did not produce consistent results; the soils were most likely affected by the changing moisture status under the influence of the vegetation. Also, the combined effects of vegetation and soil depth complicated the correlation between mean soil moisture and its variance.

4.4. Controlling factors of deep soil moisture for loessial soil

The loessial soil layers on the Loess Plateau differ greatly in depth, ranging from 15 to 50 m in regions west of the Liupan Mountain (Zhu, 1985) and varying from 50 to 100 m in most parts of the Loess Plateau (Mu et al., 2003). Additionally, the maximal depth of loessial soil can reach 505 m in Jingbian County of Gansu Province (Lei, 2006). Water is stored down soil profiles in the pores between soil particles. The calculated amounts of soil–water storage would be influenced by the investigated depths (Arya et al., 1983; Jun et al., 2014; Warren et al., 2005). Moreover, the heterogeneity of soil texture and structure within the subjectively investigated soil layers also influence the distribution of soil water (Saxton and Rawls, 2006; Wang et al., 2009). Soil water is mainly recharged by precipitation. The deep soil moisture is determined to a great extent by the infiltration depth. The differences in annual rainfall and various infiltration depths are thus also controlling factors of deep soil moisture. Coal and oil have been discovered in this region since the 1990s. After large-scale exploration, mined-out regions appeared on the Loess Plateau that may have influenced deep soil moisture. In conclusion, anthropogenic causes and natural factors such as climate, topography and soil properties are considered to be associated with the deep soil moisture of loessial soil, which changed with space and time and were not confined to the vegetational types we tested in this study.

5. Conclusions

Vegetational type had a profound effect on the dynamics of deep soil moisture. In addition to the ever-increasing potential evapotranspiration, the consumption of water by plants contributed greatly to the degradation of the status of soil moisture in our experimental plots and complicated the temporal variability of deep soil moisture. Korshinsk peashrub and purple alfalfa even induced the formation of dried soil layers. As a type of revegetative measure, fallow may be the best choice for maintaining good hydrological states of the soil.

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