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Variability and pattern of surface moisture on a small-scale hillslope in Liudaogou catchment on the northern Loess Plateau of China☆

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ABSTRACT

The variability and structure of surface soil moisture along a hillslope is still poorly understood on the northern Loess Plateau of China. In this study, a field experiment was conducted on a small-scale hillslope in Liudaogou catchment and aimed to characterize the pattern of upper 15 cm soil moisture. During the experimental period, mean soil moisture on the hillslope was dominated by an antecedent rainfall event. The values of mean moisture were positively proportional to the antecedent precipitation amount and then decreased during the next dry-down period. The variance of surface moisture decreased with increasing mean moisture. The spatial patterns of surface moisture could be separated into four groups by the structures of surface moisture along the hillslope during the experimental period. Rainfall property and soil response to rainfall jointly exerted some control on the spatial patterns of surface moisture. Gradient, soil bulk density, and surface rock fragment content contributed little to the patterns of surface moisture along the hillslope.

1. Introduction

Surface soil moisture plays a crucial role in the interaction between land surface and atmosphere as well as in hydrological and ecological processes (Grayson et al., 1997; Betts et al., 1999; Peters-Lidard et al., 2001; Ma et al., 2004). First, it exerts a major control on the partitioning of net radiation into latent heat and sensible heat and rainfall into runoff and infiltration (Findell and Eltahir, 1997; Famiglietti et al., 1998; Bronstert and Bárdossy, 1999). As a significant portion of the land water cycle, soil moisture provides an important source of water for the formation of clouds and precipitation over land, especially over semiarid and arid areas. Additionally, like water reservoirs, surface soil moisture impacts land surface temperature and climate systems (Sun and Pinker, 2004). Given the important of surface soil moisture to the land surface system, quantification of its pattern and variability has received more and more attention in recent years.

The variability and pattern of surface moisture in time and space is influenced by many factors. Gradient and orientation have important effects on the distribution of surface soil moisture on a hillslope (Nyberg, 1996). The pattern of soil moisture exhibits a high degree of organization during the wet period owing to surface and subsurface lateral redistribution of water, but there is little spatial organization during the dry period (Western et al., 1999). A field experiment was conducted on a 200 m hillslope, and the results indicated that surface 0–5 cm soil moisture was controlled by soil heterogeneity, topography, and mean soil moisture content as soil dried gradually after a rainfall event (Famiglietti et al., 1998). By using noise-forced diffusive precipitation model and the WRG (Waymire, Gupta and Rodriguez-Iturbe) model, it was found that rainfall exerts extensive effects on surface moisture especially during storms, and that soil texture was more important than rainfall in quantifying this influence (Yoo et al., 1998). A study of the spatial structure of surface water fluxes using a spatially distributed water and energy balance model has shown that the temporal behavior of surface soil moisture exhibits three distinct regimes during dry-down (Peters-Lidard et al., 2001). Other factors such as soil configuration (Júnior et al., 2005), macroporosity (Famiglietti et al., 1998), vegetation (Petrone et al., 2004; Pariente, 2002), and land use (Fu et al., 2003) all exert impacts on the variance and distribution of surface moisture along a hillslope. As a result, soil moisture patterns are still poorly understood.

The northern Loess Plateau of China is facing severe soil and water loss, and vegetation and ecosystem degradations owing to intense soil erosion and highly frequent human activity (Tang et al., 1993). Complicated terrains and soil types, irregular rainfall between seasons and years, and excessive storms, make for great fluctuation of surface moisture levels in this region. In most studies, soil moisture is mainly

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determined by passive and active microwave remote sensing or aircraft data over a large area (Islam and Li, 1999; Mahrt et al., 2001; Leconte et al., 2004; Zribi et al., 2005). However, this method does not work well for the complicated terrains and land uses on the China Loess Plateau. Few soil moisture field experiments have been performed so there is a lack of relevant information. Therefore, the purpose of the present study is to perform a field experiment in a small catchment in the northern Loess Plateau of China in order to characterize the pattern and variability of surface soil moisture along a small-scale hillslope.

2. Study area

The study was conducted on a hillslope in Liudaogou catchment (38°46′–38°51′ N, 110°21′–110°23′ E), Shenmu county, the northern Loess Plateau of China (Fig. 1). The altitude and area of the catchment are 1081–1274 m and 6.89 km^2, respectively. The mean annual temperature and total precipitation for the catchment are 8.4 °C and 408 mm, respectively. Of the total precipitation, 81% falls in three months, June to August, each year. Local soil is aeolian loess. The compositions of soil particles are 45.4–50.9% of sand, 30.1–44.5% of silt, and 11.2–14.3% of clay, respectively (USDA soil classification system). Soil erosion modulus for the catchment is 15,040 t km^{-2} a^{-1}, and soil and water loss areas account for 79% of the total. Severe soil erosion further causes a fragmentized landform, and eroded ravines occur widely. Field survey has shown that the density of ravines ($>$100 m) reaches 6.45 km km^{-2}, and the proportion of the ravine area to the total area is 38%. The terrain of the catchment is hilly and gully highland. The living vegetation in the catchment is mainly drought shrub-clustered grassland.

In the study area, the soil is rich with soluble Ca and Mg carbonates. Under local environmental and climate conditions, the carbonates can easily move downwards during the wet periods and deposit in deeper soil layers during the drought periods, forming into petrocalcic horizons or conglomerations in the long term of soil genesis. With the loss of top soil, the petrocalcic horizons or conglomerations are exposed to the air and then break down into rock fragments due to external forces.

3. Materials and methods

3.1. Soil sampling

The field experiment was conducted on a 37 m hillslope. The hillslope was once used for cultivating *Panicum miliaceum* (L.) but had been deserted for four years. Its orientation is north to east for 5°. Soil on the hillslope is consistent with the description in Section 2. Moreover, the soil contains some rock fragments in surface layer. Soil sampling sites were set at a 1 m interval along the hillslope transect, and the total number of sampling sites was 37 (Fig. 2). From 10 June to 10 September 2005, surface 0–15 cm moisture contents of the sites were measured at an interval of 10 days by a Trime-EZ (IMKO GmbH) soil moisture meter.

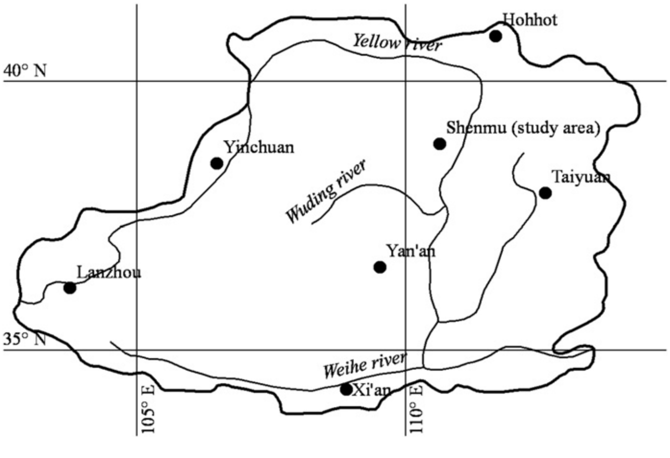

Fig. 1. Location of Liudaogou catchment, Shenmu county, on the Loess Plateau of China.

3.2. Measuring method

During soil moisture measurements, three points were selected randomly within a 10 cm radius around the sampling sites. The mean value of three points was taken as the soil moisture content of the sampling site. If it rained then soil moisture measurements were made as soon as the rainfall ended. Rock fragment cover at the measuring sites was obtained from images of 1 m square at each sampling site. The gradients of sampling sites were obtained by compass. In order to eliminate the effects of rock fragments on sampling and measuring, the Trime-EZ probe was operated carefully to avoid touching the rock fragments. In the study area, the rock fragment covers (the proportions of rock fragment areas to the total) were relatively low (mean rock fragment cover was 3.8%, and never exceeded 8%), and did not greatly impact soil sampling and moisture measurements.

4. Results and analyses

4.1. Variability of mean surface soil moisture in time

From 10 June to 10 September 2005, the surface 0–15 cm soil moisture contents (volumetric percentage) of sampling sites were measured and mean surface moisture contents were calculated (method described in Section 3.2). Fig. 3 shows the temporal variability of mean surface moisture and precipitation during the experimental period. In the figure, there are two peaks for surface soil moistures on 20 July and 17 August, respectively during the experimental period. Before the sampling dates, the two heaviest rainfalls of 67.1 mm on 19 July and 23.4 mm on 16 August, respectively, occurred. Clearly, higher soil moisture corresponded with heavier rainfalls. Surface moisture content increased after each rainfall event, and then decreased in the following days without rainfall until the next rainfall event. Fig. 4 shows the relationship between mean surface moisture contents and antecedent precipitation amount. Generally, mean moisture contents were positively related to antecedent precipitation. The mean surface moisture contents on the hillslope increased with increasing precipitation.

Surface moisture is to a large extent affected by the latest rainfall event and the precipitation amount. This result is reasonable for the study area. The northern Loess Plateau is well known for rare precipitation and high soil evaporation. As a result, evaporation is much higher than precipitation and soil water is often in shortage during most of the year. Because of deep water tables, the soil water supply mainly depends on natural rainfalls, i.e., soil moisture is highly rainfall-dependent. When it rains, soil wets easily and soil moisture increases rapidly. Soil moisture decreases quickly with intensive surface evaporation. Our data readily show soil moisture decreasing. This is normal for surface soil moisture being impacted by evaporation. Rainfall occurrence and precipitation amount control the temporal variance of surface soil moisture on the small-scale hillslope.

During each measurement time, we obtained mean and variance of soil moisure for the hillslope. Fig. 5 shows the mean and variance of soil moisure on the hillslope. Variance is negatively related to mean soil moisture. The higher the mean moisture content the smaller the variance of soil moisture content along the hillslope. This result implies, that as the mean surface soil moisture increases the difference in surface soil moisture for the sampling sites is small on the hillslope. Consequently, the spatial variability of surface moisture for the soil sampling sites is smallest when the soil is wet. In contrast, as the mean

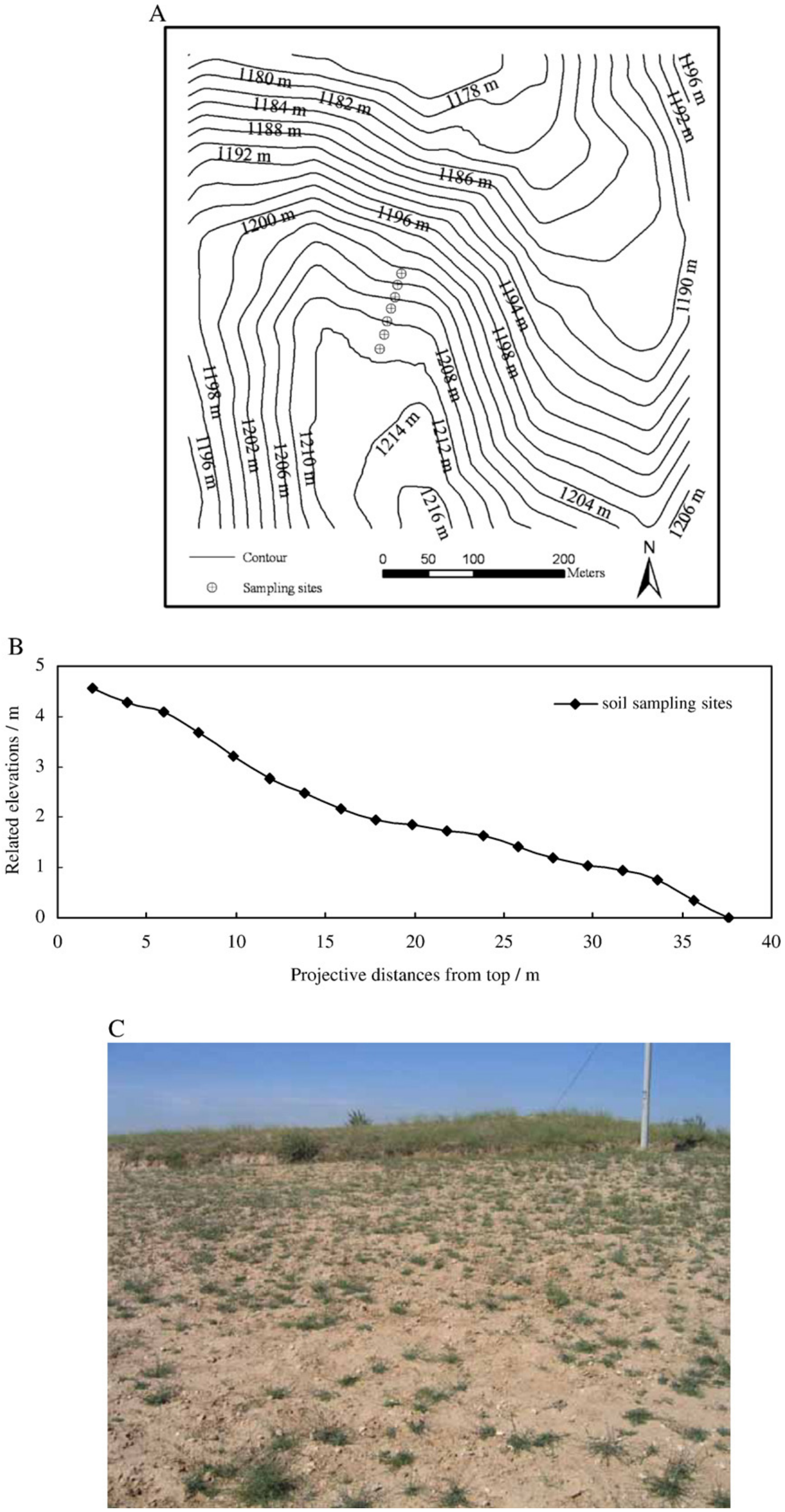

Fig. 2. A. Study area and soil sampling sites. B. Study hillslope profile. C. Surface feature of study hillslope. This picture shows the surface features in the study hillslope. There are amounts of rock fragments covering soil surface. The vegetation is rare and monotonous in the hillslope. The type of local soil is aeolian loess.

moisture content decreases, the variation of surface moisture content along hillslope profile increases, resulting in large spatial variability of surface moisture. This result is not consistent with findings reported by other researchers (Famiglietti et al., 1998). Their study shows that the spatial variability of soil moisture contents along a hillslope increases with the mean soil moisture content, because soil heterogeneity including macroporosity and clay particles exert major impacts on infiltration and runoff during heavy rainfalls or storms.

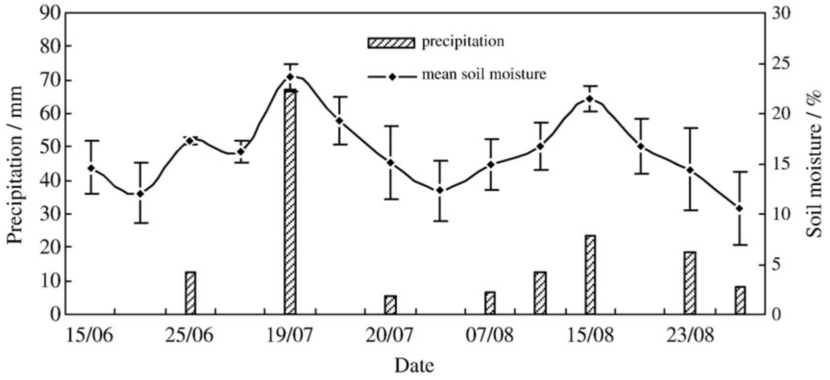

Fig. 3. Precipitation and mean soil moisture during experimental period.

Our results differ. There are some reasons supporting our result. First, rainfall properties in this region are important. The distribution of rainfalls between seasons and years is irregular and heavy rainfalls or storms mainly fall between June and August (accounting for 81% of the total). Second, soil properties are important. Local soil is loam with a relatively large infiltration capacity. Both rainfall and soil properties could provide the following two outcomes: 1) during storms or heavy rainfalls (rainfall intensity exceeding soil infiltration rate), rainfall could infiltrate thoroughly in different positions of the hillslope, and the non-infiltrated rainfall would form into runoff for the lower positions of the hillslope. In this case, surface soil is thoroughly wetted, resulting in high soil moisture content along the hillslope. There are only small differences in soil moisture content between the soil sampling sites, i.e., little variability along the hillslope profile during wet periods; 2) during small rainfalls (rainfall intensity less than infiltration rate) or no rainfall, surface soil moisture is strongly influenced by soil heterogeneity along the hillslope. The heterogeneity as soil texture and configuration along the hillslope as significant effects on infiltration and evaporation impact soil moisture distribution. For example, during dry-down following small rainfalls soil texture, especially clay content, has an important effect on soil evaporation behavior and infiltration which causes large fluctuations of surface soil moistures along the hillslope. Moreover, other factors such as micro-landform, gradient, and vegetation also strengthen this difference. Hence, surface soil moisture presents large spatial variability during these drier periods.

4.2. Structure of surface soil moisture along the hillslope transect

For a thorough understanding of the spatial variability of surface moisture, the patterns of surface moisture distribution are provided in Fig. 6. In Fig. 6, the patterns differ from each other during the experimental period. Based on the differences in spatial structures, the spatial patterns of surface moisture can be separated into four different groups as shown in Fig. 6A, B, C, and D. Similarly, the experimental period can be divided into four corresponding stages: from 10 June to 20 June, 21 June to 5 July, 6 July to 17 August, and 18 August to 10 September, respectively. During the first stage (from 10 June to 20 June, Fig. 6A), there are lower moisture zones at the top, middle, and bottom of the hillslope. During the next stage (from 21 June to 5 July, Fig. 6B), few differences in surface moisture occur on the hillslope except for a lower moisture zone at the top of the hillslope. During the third stage (from 6 July to 17 August, Fig. 6C), the distribution pattern of surface moisture is similar to that of the first stage. During the last stage (from 18 August to 10 September, Fig. 6D), the changes of surface moisture contents are irregular along the hillslope, and a marked feature is that there is a zone of lower soil moisture at the mid-hillslope. Fig. 7 shows precipitation depths during the four stages. Considering the rainfall data shown in Fig. 7, we name the four stages as the drought season, the coming rainy season, the rainy season, and the ending rainy season, respectively. During the drought season, there is little or no rainfall and soil moistures are small (about 12%). During the rainy season, there are heavy rainfalls (67.1 mm on 19 July and 23.4 mm on 16 August, respectively), and soil moistures are large (about 18%). As for the coming rainy season and the ending rainy season, there are a few smaller rainfalls and soil moistures fluctuate quite a bit. Of the total precipitation during the experimental time, the precipitation during the rainy season accounts for 74.5%.

We have classified the patterns of soil moisture along the hillslope into four groups based on the spatial structures during the experiment period (Fig. 6). However, the consistency of the distribution patterns

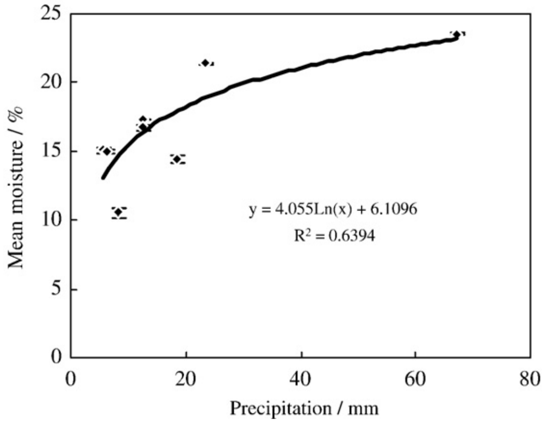

Fig. 4. Mean moisture versus precipitation.

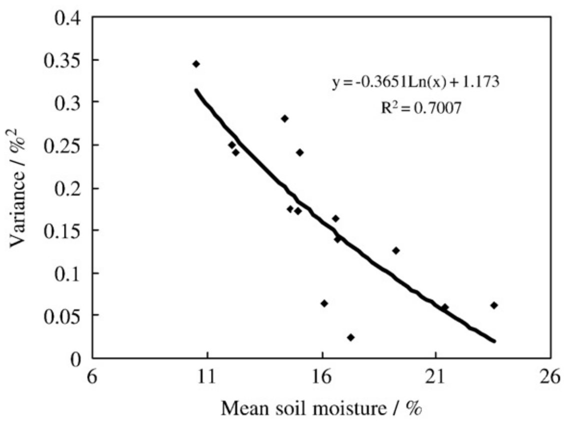

Fig. 5. Variance versus mean moisture.

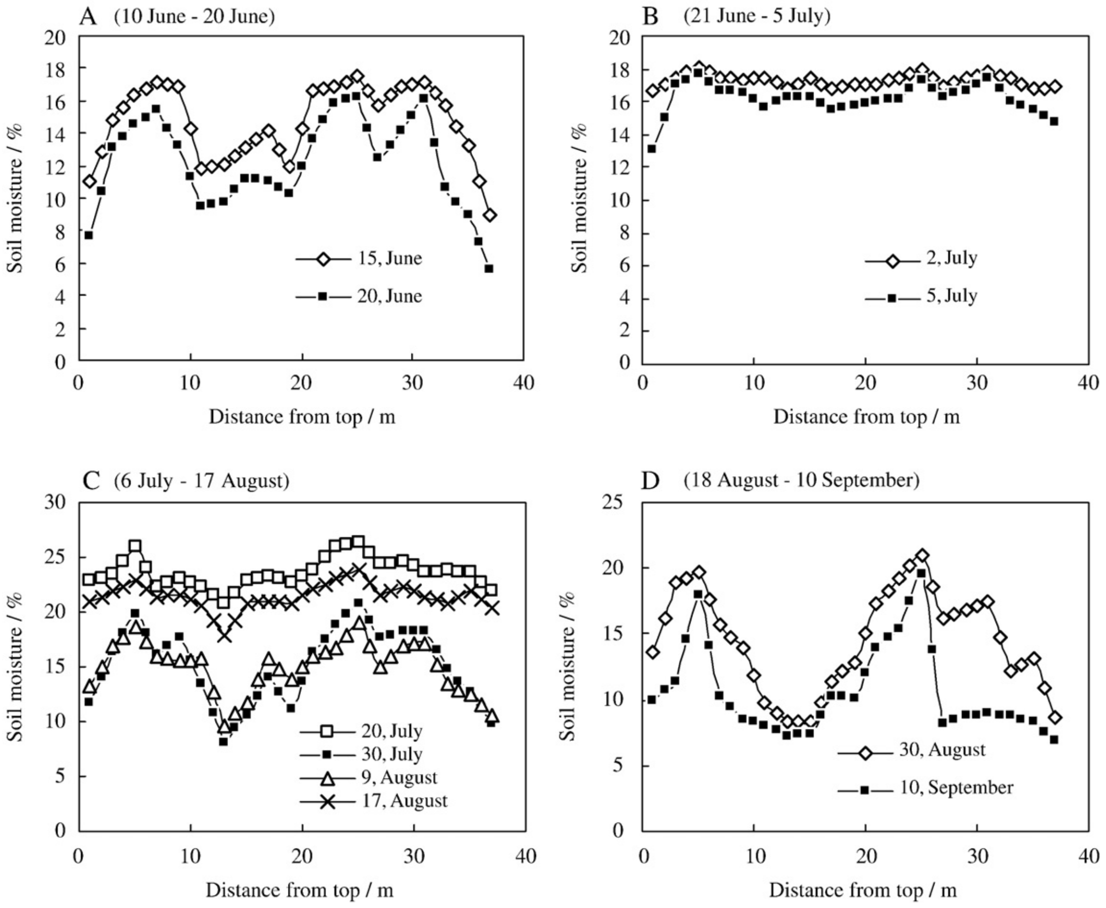

Fig. 6. Patterns of surface moisture along the hillslope at four stages.

within each group was not tested. In other words, we did not know whether the structure within each stage was stable or if the spatial distribution of soil moisture had periodicity. In order to quantify the spatial structures, an autocorrelation function (ACF) for time series analysis (TSA) was used, and results are provided in Fig. 8. The process of TSA was to transform moisture data in order to create a time series so as to ensure transformed data normality with mean and standard error close to 1 and 0, respectively, and then to get the coefficient of each point by the autocorrelation function. Fig. 8 shows the time stability for the structure of surface moisture along the hillslope. In the figure, the maximum positive correlation coefficient occurs at the final point indicating that the spatial structures of surface moisture are spatially constant and the patterns of surface moisture content along the hillslope are periodically present. If the maximal positive correlation coefficient occurs at any position before the final point, it shows that the distribution pattern change and are without periodicity.

The TSA shows that the spatial patterns of surface moistures are changeless during the drought season (from 10 June to 20 June) and the rainy season (from 6 July to 17 August). In other words, the spatial structures of soil moistures content are periodic on the hillslope profile during the stages. However, during the coming rainy season (from 21 June to 5 July) and the ending rainy season (from 18 August to 10 September) the spatial structures are modified. Consequently, the patterns of soil moistures did change.

Based on TSA (Fig. 8) and rainfall properties (Fig. 7), we named the drought season and the rainy season as stable periods and the coming and the ending rainy seasons as transitional periods. During the stable periods, the spatial pattern of soil moisture was fixed and the only difference was the value of mean moisture. However, during the transitional periods the spatial pattern changed and was unsteady. The different spatial patterns during the experimental period can be linked to rainfall types at different stages and the responses of soil properties to rainfall. There are three cases. (1) During heavy rainfalls or storms (rainfall intensity is much more than the infiltration rate), mean surface soil moisture is large due to rainfall infiltration, which causes the impacts of other factors such as soil heterogeneity to be concealed; the spatial patterns of surface moistures are dominated by rainfall. (2) During small rainfalls (intensity is less than the infiltration rate) or no rainfall, the influence of soil heterogeneity is dominant. (3) When heavier rainfalls are followed by minor rainfalls or the reverse case, the spatial patterns of surface soil moisture are influenced by both rainfall and soil heterogeneity. In this case, the

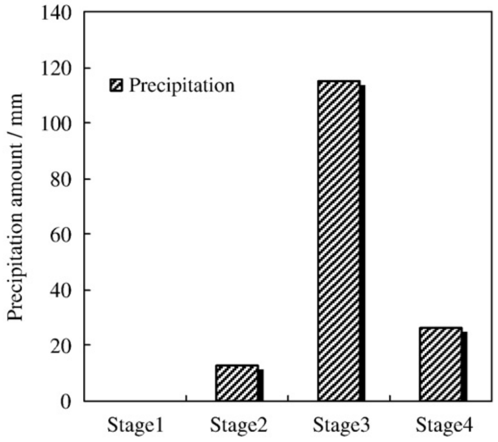

Fig. 7. Precipitations at different stages.

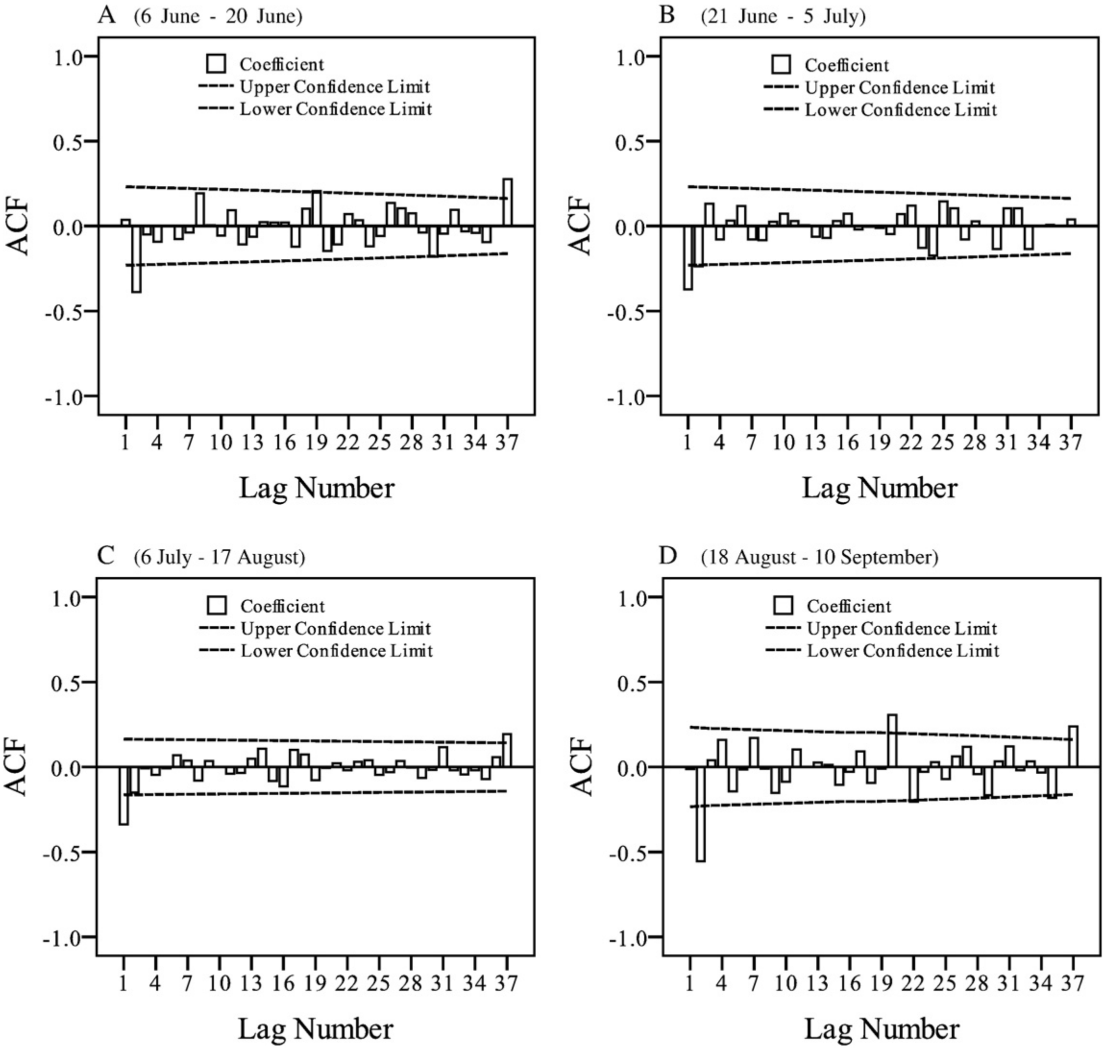

Fig. 8. Time stabilities of surface moisture structures based on auto correlations function (ACF) at four stages.

pattern is first shaped by rainfall but will later be modified by soil heterogeneity in the next dry-down. If the dominated factor is singular like rainfall or soil heterogeneity, the pattern will maintain its initial status and have time stability. Otherwise, the pattern will be modified as being affected by two or more factors. In our experiment, the stable periods were cases 1 and 2 and the transitional period was case 3. Moreover, it can be seen from Fig. 6 that surface moisture has a length scale of about 10 m. At every 10 m, the soil moisture content experiences a relatively wet spot (Fig. 6A and C). This temporal persistence suggests a permanent aspect of the hillslope (soil heterogeneity and vegetation).

4.3. Factors affecting the variability of surface soil moisture

The variability of surface soil moisture is influenced not only by a single factor but by many factors jointly which causes the variability of

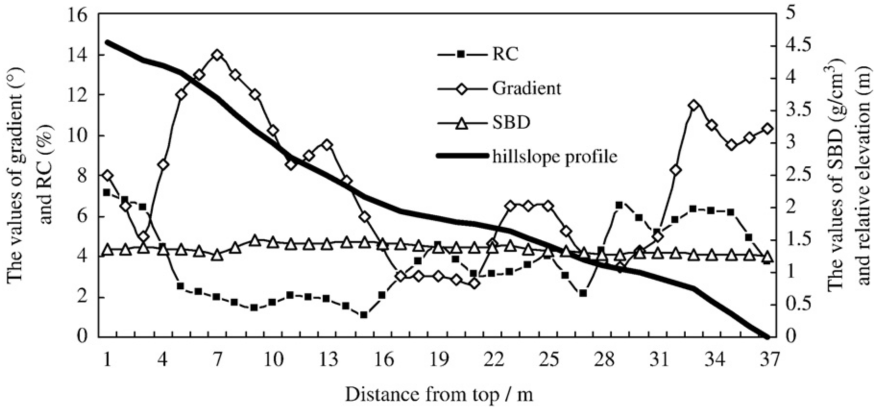

Fig. 9. Changes of RC, SBD, gradient along the hillslope and the hillsope profile.

Table 1
Correlation matrix

	MSM2	MSM3	MSM4	RC	Gradient	SBD
MSM1	0.788	0.833	0.732	−0.111	−0.096	−0.032
MSM2		0.647	0.557	−0.233	0.057	0.009
MSM3			0.883	0.09	−0.146	−0.159
MSM4				0.134	−0.129	−0.131
RC					−0.201	−0.547
Gradient						−0.115

surface moisture to be complicated. It is difficult for a comprehensive understanding of the behavior of surface moisture. In previous related studies, many parameters such as terrain, soil properties, land use, and surface features are used to characterize the variability. In this paper only precipitation depth, soil bulk density, gradient, and surface features (referring to rock fragment cover) were collected. The reason is that the soil on the hillslope is poorly-structured aeolian sandy soil. Its organic matter content is very low and has little change. Furthermore, the vegetation on the hillslope was monotonous and lacked development due to the small rainfall. Consequently, vegetation cover was considerably low along the hillslope. The rock fragment cover was collected because rock fragments were often found in the study area and had an important influence on runoff and infiltration (Poesen and Lavee, 1994; Fiès et al., 2002; Mandal et al., 2005). The rock fragment cover, gradients, and soil bulk densities for soil sampling sites are shown in Fig. 9. In general, the mid-hillslope was flatter than the upper and lower hillslope. This can also be seen from the hillslope profile in the figure. The soil bulk density had little variance for the sampling sites on the hillslope.

To determine the factors that dominate the variability of surface moisture, a factor analysis method was used and the results are shown in Table 1. In Table 1, we show four factors: mean soil moisture (MSM), rock fragment cover (RC, the proportion of rock fragment area to the total for the sampling site), soil bulk density (SBD), and gradient. MSM is the mean value of soil moisture content for each sampling site along the hillslope during each stage. The MSM for the four stages are distinguished as MSM1, MSM2, MSM3, and MSM4, respectively. From Table 1, it can be seen that the correlations between MSM1, MSM2, MSM3, and MSM4 are relatively large (correlation coefficients $R^2 > 0.55$). This indicates that the former mean surface moisture contents have important impact on the next moisture content. However, the effects of RC, gradient, and SBD on surface moisture are weak. These weak effects on surface moisture variability can be ascribed to two reasons. First, when surface moisture content is high, the effects are concealed by high soil moisture content, because the higher mean soil moisture content reduces the variance (variance = standard deviation / mean). Second, when mean surface moisture is low, each factor has an important effect on the mean surface moisture, but the integrated effects are uncertain, because the factors are interdependent. Some are negative and others positive. It is difficult to distinguish the effect of each factor on surface moisture. As for the rainfall, it is almost the same for the different positions of the hillslope owing to the small-scale of the hillslope (only 37 m long). In this sense, the rainfall is uniform and independent for every sampling site. Hence, former soil moisture has an important effect on the latter. As for other factors, they are changed continuously along the hillslope. Their effects are limited, and to a great extent are rainfall-dependent. All of these lead to their weak effects on soil moisture along the hillslope.

5. Conclusions

The field experiment was conducted to investigate the variability and pattern of surface 0–15 cm soil moisture along a small-scale hillslope in the northern Loess Plateau from 10 June to 10 September 2005. The results indicted that (1) the effects of rock fragments, gradients, and soil bulk density at the sampling sites on the variability of surface moisture were weak; (2) antecedent rainfall events dominated mean surface moisture on the hillslope. Mean surface moisture content increased with antecedent precipitation amount. The variability of surface soil moisture decreased with increasing mean soil moisture during the experiment period; (3) the spatial patterns of surface moisture content distribution along the hillslope could be divided into four groups, and the pattern of surface moisture distribution was dominated by rainfall properties and the soil response to rainfall.

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References

Betts, A.K., Ball, J.H., Beljaars, A.C.M., Miller, M.J., Viterbo, P.A., 1999. The land surface-atmosphere interaction: a review based on observational and global modeling perspectives. Journal of Geophysical Research 103 (D3), 7209–7226.

Bronstert, A., Bárdossy, A., 1999. The role of spatial variability of soil moisture for modeling surface runoff generation at the small catchment scale. Hydrology and Earth System Sciences 3 (4), 95–104.

Famiglietti, J.S., Rudnicki, J.W., Rodell, M., 1998. Variability in surface moisture content along a hillslope transect: rattlesnake hill, Texas. Journal of Hydrology 210, 259–281.

Fiès, J.C., Delouvigny, N., Chanzy, A., 2002. The role of stones in soil water retention. European Journal of Soil Science 53, 95–104.

Findell, K.L., Eltahir, E.A.B., 1997. An analysis of the soil moisture-rainfall feedback, based on direct observations from Illinois. Water Resources Research 33 (4), 725–735.

Fu, B.J., Wang, J., Chen, L.D., Qiu, Y., 2003. The effects of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. Catena 54, 197–213.

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

Islam, S., Li, J., 1999. On the estimation of soil moisture profile and surface fluxes partitioning from sequential assimilation of surface layer soil moisture. Journal of Hydrology 220, 86–103.

Júnior, V.V., Carvalho, M.P., Dafonte, J., Freddi, O.S., 2005. Spatial variability of soil water content and mechanical resistance of Brazilian ferralsol. Soil and Tillage Research 85, 166–177.

Leconte, R., Brissette, F., Galarneau, M., Rousselle, J., 2004. Mapping near-surface soil moisture with RADARSAT-a synthetic aperture radar data. Water Resources Research 40, 1029–1038.

Ma, K.M., Fu, B.J., Liu, S.L., Guan, W.B., Liu, G.H., Lü, Y.H., Anand, M., 2004. Multiple-scale soil moisture distribution and its implications for ecosystem restoration in an arid river valley, China. Land Degradation and Development 15, 75–78.

Mahrt, L., Vickers, D., Sun, J.L., 2001. Spatial variations of surface moisture flux from aircraft data. Advances in Water Resources 24, 1133–1141.

Mandal, U.K., Rao, K.V., Mishra, P.K., Vittal, K.P.R., Sharma, K.L., Narsimlu, B., Venkanna, K., 2005. Soil infiltration, runoff and sediment yield from a shallow soil with varied stone cover and intensity of rain. European Journal of Soil Science 56, 435–443.

Nyberg, L., 1996. Spatial variability of water content in the covered catchment at Gardsjon, Sweden. Hydrological Processes 10, 89–103.

Pariente, S., 2002. Spatial patterns of soil moisture as affected by shrubs in different climatic conditions. Environmental Monitoring and Assessment 73, 237–251.

Peters-Lidard, C.D., Pan, F., Wood, E.F., 2001. A re-examination of modeled and measured soil moisture spatial variability and its implications for land surface modeling. Advances in Water Resources 24, 1069–1083.

Petrone, R.M., Price, J.S., Carey, S.K., 2004. Statistical characterization of the spatial variability of soil moisture in a cutover peatland. Hydrological Processes 18, 41–52.

Poesen, J., Lavee, H., 1994. Rock fragments in top soils: significance and processes. Catena 23, 1–28.

Sun, D.L., Pinker, R.T., 2004. Case study of soil moisture effect on land surface temperature retrieval. IEEE Geoscience and Remote Sensing Letters 1 (2), 127–130.

Tang, K.L., Hou, Q.C., Wang, B.K., Zhang, P.C., 1993. The environment background and administration way of wind-water crisscross region and Shenmu experimental area on the Loess Plateau. In: Liu, Y.M., Wang, J.W. (Eds.), Memoir of Northwestern Institute of Soil and Water Conservation, Academia Sinica and Ministry of water resources. Shaanxi Scientific and Technological Press, Xi'an, pp. 2–15.

Western, A.W., Grayson, R.B., Blöschl, G., Willgoose, G.R., 1999. Observed spatial organization of soil moisture and its relation to terrain indices. Water Resources Research 35 (3), 797–810.

Yoo, C., Valdes, J.B., North, G.R., 1998. Evaluation of the impact of rainfall on soil moisture variability. Advances in Water Resources 21, 375–384.

Zribi, M., Baghdadi, N., Holah, N., Fafin, O., 2005. New methodology for soil surface moisture estimation and its application to ENVISAT-ASAR multi-incidence data inversion. Remote Sensing of Environment 96, 485–496.