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The spatial variability of soil water storage and its controlling factors during dry and wet periods on loess hillslopes

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ABSTRACT

Soil water storage (SWS), a critical parameter in hydrological processes, is an effective water source for vegetation growth in the semi-arid Loess Plateau of China. Its spatial pattern at various soil depths along transects and temporal changes in the dominant environmental factors that affect SWS are essential to ensure the sustainability of vegetation restoration efforts and achieve an accurate understanding of hydrological processes on the Loess hillslope. In this study, we investigated SWS at depths of 0–4 m at a total of 54 points on three hillslopes covered with artificial forest, natural forest and natural grass during four observation periods. The results reflected clear seasonal trends in SWS. A substantial water deficit occurred during the severe drought year of 2015. SWS at depths of 0–1 m increased and SWS at depths of 1–4 m decreased from after the rainy season of 2015 to before the rainy season of 2016 (a near-normal drought year), and SWS at depths of 0–4 m maintained its resemblance to conditions that occurred during the rainy season of 2016. These results may indicate that drought conditions affect variations in SWS. In addition, topography and vegetation type were the dominant factors controlling SWS in the different soil layers. SWS at shallow soil depths was mainly affected by topography, while SWS at deep soil depths was mainly controlled by vegetation type. During the dry season, slope aspect was the most important factor controlling SWS at shallow soil depths due to the effects of slope aspect on snowmelt and wind evaporation. On the other hand, during the wet season, the slope gradient was more important in terms of its effect on SWS than slope aspect at shallow soil depths due to the effects of slope gradient on infiltration and runoff.

1. Introduction

In semiarid areas, soil water storage (SWS) is a critical parameter in hydrological processes that is connected to precipitation, runoff and groundwater (Gao and Shao, 2012a; Li et al., 2016; Penna et al., 2013). It is a critical water resource for vegetation growth (Hu et al., 2009) and agricultural development (Li et al., 2016). Generally, a substantial portion of rainfall is intercepted by the plant canopy. The rain that reaches the soil surface forms runoff, and any remainder infiltrates into the soil. Soil water is greatly influenced by rainfall amount and intensity (Liu et al., 2015), vegetation type (Fang et al., 2016), topography (slope gradient, slope aspect, slope position, and relative elevation) (Yang et al., 2015), soil properties (bulk density, soil organic content, clay, silt and sand) (Fang et al., 2016), and other factors. Combinations of these controlling factors cause SWS to vary spatially and temporally (Li et al., 2015a, 2015b).

The spatial distribution and temporal dynamics of soil water at shallow depths on the Loess Plateau have been studied by many scholars (Huang et al., 2012; Jia et al., 2013a, 2013b; Wang et al., 2013; Zhu et al., 2014; Zhu et al., 2009). Soil water quantity has been shown to be closely related to soil depth, especially at the soil depths investigated (Jia and Shao, 2014). On the Loess Plateau, precipitation is the only source of soil water and recharge for the surface soil layers. Therefore, the soil water in deep soil layers cannot be replenished by contributions from rainfall and groundwater. In fact, the growth of perennial plants depends to a large extent on deep SWS. Perennial plants, especially introduced vegetation, cause deficits in deep SWS because they consume large amounts of soil water, exacerbating problems involving dry soil and leading to the degradation of land and vegetation cover (Fang et al., 2016; Yang et al., 2012). Deep SWS plays a relatively important role in vegetation restoration and ecosystem development (Wang et al., 2010 and 2011). However, high cost of labor and time is the limited factors making researches on deep SWS ignored. Therefore, few studies focused on spatial distribution and temporal dynamics of deep SWS which can clearly reveal the sustainability needs for vegetation restoration.

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Many studies have been carried out on the factors that affect spatial variations in SWS, such as precipitation, terrain attributes, soil properties and vegetation type. Famiglietti et al. (1998) found that precipitation variability is directly related to soil water variability. Huang et al. (2016) verified that antecedent precipitation is the main factor controlling soil water in the top layer of soils (0–10 cm). Terrain attributes are critical factors that influence soil water. Previous studies have indicated that the toes of slopes and gentle slopes contain larger amounts of soil water than the upper parts of slopes and steep slopes within shallow soil layers (Ali et al., 2010; Qiu et al., 2001; Western et al., 2004). Yang et al. (2015) found that the effects of terrain attributes on variations in soil water differ between surface soil layers and deep soil layers. Other studies have indicated that terrain attributes become increasingly important during wet periods; however, during dry periods, soil properties have a greater influence on the distribution of soil water (Grayson et al., 2002; Western et al., 1999). Vegetation type is a key factor contributing to soil water variation, especially introduced vegetation (Yang et al., 2014; Yang et al., 2012). The factors that control soil water have been investigated on scales corresponding to individual farms (Zhu and Lin, 2011), catchments (Huang et al., 2016; Huang et al., 2012; Takagi and Lin, 2012; Zhu et al., 2014), and hillslopes (Tromp-van Meerveld and Mcdonnell, 2006; Yang et al., 2015). Due to the difficulties involved in obtaining measurements from deep soil layers and the high cost of such measurements in terms of labor and time, few studies have considered the properties of deep soil layers. Instead, many studies have focused solely on the properties of surface soils (Takagi and Lin, 2012) or have neglected soil properties (Yang et al., 2015). Takagi and Lin (2012) determined the relationships between soil water in shallow (0–1.1 m) soil layers and soil-terrain attributes within a forested catchment in central Pennsylvania, USA. Yang et al. (2015) compared the correlation of the spatial patterns of soil water in the surface soil layer (0–1 m) and the deep soil layer (1–6 m) with topographic properties and vegetation attributes. Soil attributes were not considered in this study. Soil properties are critical variables that regulate soil water. Variations in soil properties depend considerably on soil depth; in particular, the properties of deep soil layers often differ substantially from those of the surface soil layer. Thus, determining the main environmental factors that consist of soil properties at various depths is necessary. It can clearly reveal effect of soil properties on SWS among several factors at wet or dry conditions. In addition, most previous studies have focused on more than one environmental factor that affects soil water, but few studies have examined the effect of multiple environmental factors on variations in SWS in different soil layers. In our study, considering multiple environmental factors consisting of soil properties at soil depths of 0–4 m can clearly determine the dominant factors controlling SWS and temporal changes in the dominant factors controlling SWS in different periods.

The study investigated the spatial distribution of SWS at four soil depths in the soil profile(0–1, 1–2, 2–3 and 3–4 m) on three hillslopes covered with artificial forest, natural forest and natural grass during dry and wet seasons. This study aimed to (1) compare SWS at various soil depths along three gradient-parallel transects on a hillslope and (2) identify the main factors affecting SWS in shallow and deep soil layers in different periods from a list of 10 environmental factors, and determine temporal changes in the dominant environmental factors that affect SWS.

2. Materials and methods

2.1. Study area

The study area is located in Caijiachuan Catchment on the Loess Plateau (110°40′-110°48′ E, 36°14′-36°18′ N). This catchment covers 39.33 km^2 and is located in Shanxi province (Fig. 1(a)). It experiences a semiarid continental climate and has received an average annual precipitation of 494.7 mm during 1985–2016. Approximately 85% of this precipitation falls during May to October. In addition, the annual precipitation varies greatly; the maximum recorded annual precipitation is 922.5 mm, whereas the minimum value is only 277.7 mm. The annual average evaporation is 1723.9 mm, more than half of which occurs from April to July (Bi et al., 2006).

The major soil type is classified as Alfisol according to the USDA classification system. The *Robinia pseudoacacia* was widely planted since implementation of the "Grain for Green" Project. Natural forest and natural grass are also dominant vegetation types on the Loess hillslope. The basic description of the experimental site is provided in Table 1.

2.2. Experimental setting and data collection

Three hillslopes covered with artificial forestland, natural forestland and natural grassland were chosen to investigate SWS variations. Three transects were located on each hillslope; these transects are labeled AF1, AF2, and AF3; NF1, NF2, and NF3; and NG1, NG2, and NG3. Within each transect, six slope positions were located at distances of 0 m, 20 m, 40 m, 60 m, 80 m and 100 m, respectively, from bottom to top along each transect. The individual stations are labeled AF11 to AF16, AF21 to AF26, AF31 to AF36, NF11 to NF16, NF21 to NF26, NF31 to NF36, NG11 to NG16, NG21 to NG26, and NG31 to NG36 (Fig. 1(b), (c) and (d)). All of the sampling sites belonging to a single transect have similar slope aspect. The experiment was carried out during two periods in 2015, May 02–12 (before the rainy season) and October 18–25 (after the rainy season) and two periods in 2016, May 04–12 and October 16–23. No precipitation fell during these periods or during the week preceding each experimental period. In this study, the period from November to April is defined as the dry season (i.e., the non-growing season), and the period from May to October was defined as the wet season (i.e., the growing season). Thus, the SWS values measured in May (before the rainy season) and October (after the rainy season) were considered to correspond to the dry season and the wet season, respectively. Soil samples were collected at depths of 0–400 cm at 20 cm intervals using an auger. Twenty soil samples were collected at each sampling site. The layer-cumulative SWS was divided into SWS0-1, SWS1-2, SWS2-3, and SWS3-4, which correspond to SWS at depths of 0–1 m, 1–2 m, 2–3 m, and 3–4 m, respectively. The layer-cumulative SWS was calculated as follows (Jia and Shao, 2013),

$$SWS = \sum \frac{10\theta_i d_i h}{\rho} \tag{1}$$

where *SWS* indicates layer-cumulative soil water storage (mm), θ_i indicates the gravimetric soil water content (%) in the soil layer, d_i indicates the soil bulk density (g/cm^3), h represents the soil layer thickness (h = 20 cm in our study). ρ is the density of water (1 g/cm^3), and i indicates the soil layer in question.

θ_i was obtained by the oven-drying method (105 °C, 24 h). During the experimental periods, the land cover type found at each site and the slope position of each site were recorded. Artificial forestland, natural forestland and natural grassland were coded as 1, 2, and 3, respectively. Slope position corresponds to the distance along the transect, as measured from the toe to the crest of each hillslope. A compass was used to determine slope gradients and the slope aspect of each site during the field investigations. Slope gradient was determined using a compass and was measured in degrees. With the compass, slope aspect was recorded in degrees clockwise from north and then transformed into its cosine. In the laboratory, soil sample was air-dried and passed through a 0.25-mm sieve after rocks and roots removed. Soil organic carbon (SOC) content was measured using the dichromate oxidation method (Feng et al., 2014). The air-dried soil sample passed through a 2 mm sieve after which clay (< 0.002 mm), silt (0.002–0.05 mm), and sand (0.05–2 mm) were measured using a Malvern Mastersizer 2000 laser diffraction device (Malvern Instruments Ltd., Malvern, UK). At each

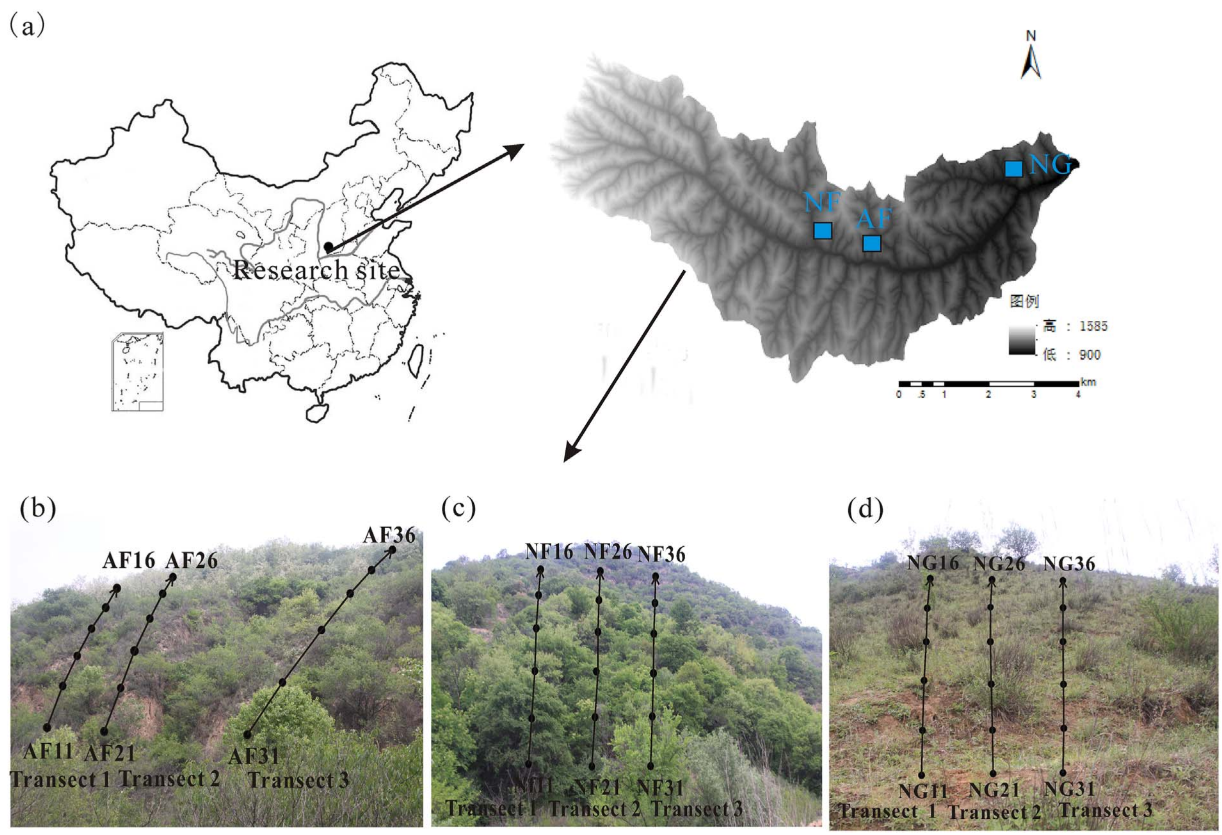

Fig. 1. Location of research sites. (a) Location of study area (Caijiachuan Catchment); (b), (c), (d) locations of experimental sites on artificial forestland, natural forestland, and natural grassland respectively.

Table 1
Basic description of experiment sites.

Site	Slope gradient (°)	Slope aspect (°)	Land coverage (%)	Main plant type	Stand density	Tree height (m)
Artificial forestland	23.7	203	70	*Robinia pseudoacacia*	2 × 2.5 m	7.9
Natural forestland	21.8	103	60	Shrub (*Rosa xanthina*, *Spiraea trilobata*, *Amygdalus davidiana* and *Ostryopsis davidiana*)	3 × 4 m	2.3
				Tree (*Acer buergerianum*, *Populus davidiana* and *Syringa reticulate*)	4 × 6 m	5.7
Natural grassland	20.2	333	85	*Carex humilis Leyss*, *Artemisia lavandulae folia* and *Bothriochloa ischcemum*	–	–

sampling site, three replicates of undisturbed soil cores were obtained by ring knife (diameter of 5 cm, length of 5 cm) at every 20 cm in the 0–100 cm soil layer to measure the bulk density (BD) and capillary porosity (CP) (Wang et al., 2008), totaling 2700 soil cores. The amount of precipitation that fell in 1985–2016 was monitored with a self-recording rain gauge.

2.3. Analytical methods

A deficit of precipitation has different impacts on soil moisture, stream flow, groundwater and reservoir storage, etc. on different time scales (Buttafuoco et al., 2015). The standardized precipitation index (SPI), which was developed by McKee et al. (1993), was used to quantify drought severity using at least 30 years of precipitation data. The SPI employs an adjusted distribution function that describes the cumulative probability of variations in the observed amount of precipitation. This function is then transformed into a standard normal quantile (SPI).

The distribution function, which describes the Gamma distribution (g(x)), was defined as (Lloyd-Hughes and Saunders, 2002)

$$\mathrm{g(x)} = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\chi^{\alpha-1}e^{-\chi/\beta} \tag{2}$$

where Γ is the gamma function, which is calculated as

$$\Gamma(\alpha) = \lim_{n\to\infty}\prod_{v=0}^{n-1}\frac{n!n^{y-1}}{y+v} \equiv \int_0^{\infty} y^{\alpha-1}e^{-y}dy \tag{3}$$

Moreover, x indicates the amount of precipitation (mm), α,β indicate the shape and scale parameters, respectively (a > 0; b > 0), which are estimated by the maximum likelihood method as

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{4}$$

$$\hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \tag{5}$$

where A is defined for n observations as

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \tag{6}$$

In addition, based on SPI values, McKee et al. proposed a seven-

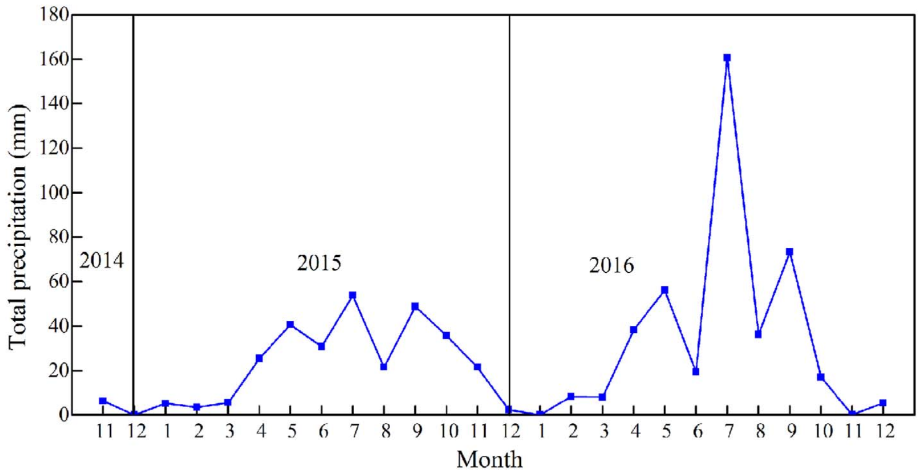

Fig. 2. Distribution of monthly precipitation from November 2014 to December 2016.

Table 2
Period types of each investigated time.

Period		SPI6	Period type	SPI12	Period type
11/01/14[a]–04/30/15	Dry season	− 0.70	Near normal	− 1.94	Severe drought
05/01/15–10/31/15	Wet season	− 1.78	Severe drought		
11/01/15–04/30/16	Dry season	0.39	Near normal	− 0.33	Near normal
05/01/16–10/31/16	Wet season	− 0.43	Near normal		

[a] represents Month/day/year.

Table 3
Length of the gradient from the DCA in dry and wet season.

Periods		Lengths of gradient			
		1	2	3	4
05/02/15	Dry season	0.078	0.037	0.019	0.000
10/18/15	Wet season	0.051	0.024	0.017	0.000
05/04/16	Dry season	0.063	0.047	0.028	0.000
10/16/16	Wet season	0.052	0.041	0.029	0.000

category classification to evaluate the seriousness of drought: SPI ≥ 2 represents extremely wet conditions, 1.50 ≤ SPI ≤ 1.99 represents severely wet conditions, 1.00 ≤ SPI ≤ 1.49 represents moderately wet conditions, − 0.99 ≤ SPI ≤ 0.99 represents near-normal conditions, − 1.49 ≤ SPI ≤ − 1.00 represents moderate drought conditions, − 1.99 ≤ SPI ≤ − 1.50 represents severe drought conditions, and SPI ≤ − 2.00 represents extreme drought conditions. This classification was used to determine the seasonal drought conditions of 2015–2016 based on precipitation data during 1985–2016 (Fig. 2). The drought conditions in different seasons varied from year to year within the study area. SPI calculated on a six-month scale, defined as SPI6, and SPI calculated using a twelve-month scale, defined as SPI12, are shown in Table 2. As shown in Table 2, the year 2015 included a severe drought; however, the drought conditions were near normal in 2016. During the wet season of 2015, a severe drought occurred. Conditions were near normal during the dry seasons of 2015 and 2016 and the wet season of 2016.

Multi-ANOVA was used to identify the effects of depth, time, vegetation, and their interaction on soil properties and SWS; the differences in SWS depletion between different vegetation types and depths were compared using one-way ANOVA. In addition, to determine the relationship between SWS and environmental factors, ordination techniques based on a linear response model or a unimodal response model were applied using CANOCO for Windows 4.5. Whether a linear or unimodal model should be used can be determined by applying detrended correspondence analysis (DCA). SWS sample data should be used in DCA if the largest gradient length is < 3.0. Linear response model redundancy analysis (RDA) was employed to describe the relationship between SWS and the environmental factors. If the largest value was > 4.0, the unimodal canonical correspondence analysis (CCA) model was applied. Table 3 shows that the lengths of the gradients were < 3.0; thus, RDA was employed to identify the environmental factors that best describe SWS. To perform the RDA analysis, two matrixes (an environmental factor matrix and an SWS matrix) are needed. Ten environmental factors were considered, slope position, slope aspect, slope gradient, vegetation type, BD0-1, CP0-1, SOC at different depths (SOC0-1 and SOC1-4), clay at different depths (clay0-1 and clay1-4), silt at different depths (silt0-1 and silt1-4), sand at different depths (sand0-1 and sand1-4). The factors that include the name of a soil property followed by "0-1" and "1-4" represent the values of the corresponding soil property at depths of 0–1 m and 1–4 m, respectively. For example, SOC0-1 indicates the SOC content at a depth of 0–1 m. And the canonical coefficients of the environmental factors for the first two axes of the RDA were divided into five categories, 0–0.1, 0.1–0.3, 0.3–0.4, 0.4–0.5 and 0.5–1. These categories indicate variables that are unrelated, weakly related, moderately related, significantly related at the 0.05 level and significantly related at the 0.01 level, respectively (Qiu et al., 2001).

3. Results

3.1. Soil as a function of soil depth

The spatial distribution of soil properties at depths of 0–4 m in artificial forestland, natural forestland and natural grassland is shown in Fig. 3. While soil properties do not vary strongly with time, they do vary with depth and vegetation type (Table 4). In general, the SOC content and sand content decreased with increasing soil depth; however, the contents of clay and silt increased with increasing soil depth in the shallow soil layer (soil depths of 0–1 m), whereas these soil properties are stable at depths > 1 m. Thus, soil properties affecting SWS can be divided into those corresponding to depths of 0–1 m and 1–4 m, for example, SOC0–1 and SOC1–4 and clay0–1 and clay1–4. Bulk density increased with increasing soil depth, while capillary porosity decreased with increasing soil depth in the soil layer (0–1 m). Of the three vegetation cover types, the highest SOC content and bulk density appeared on the hillslope covered with natural grassland. The hillslope covered by natural forest had the lowest silt content, and the highest sand content and capillary porosity. The clay content was almost the

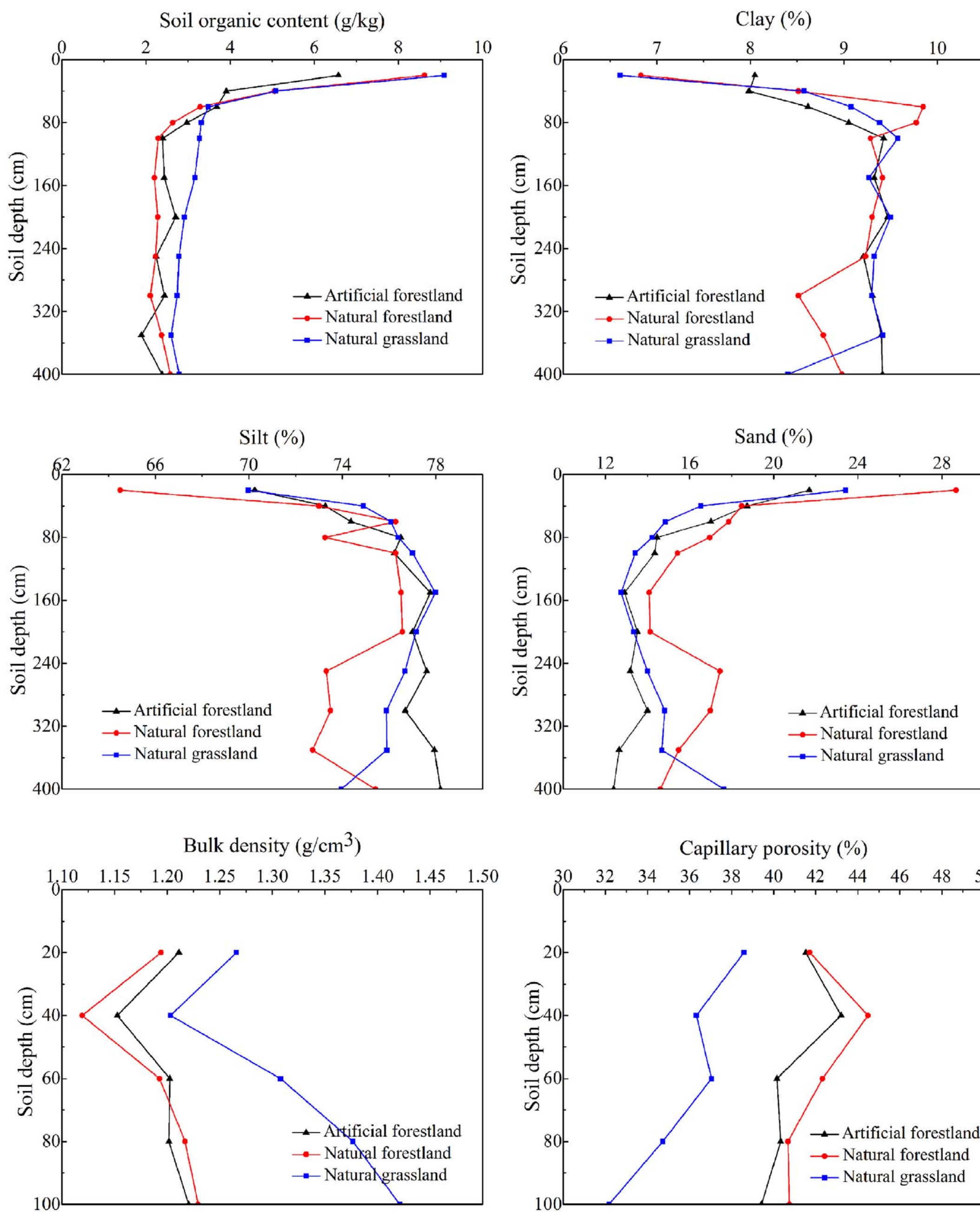

Fig. 3. Vertical distribution of soil properties within the study area.

Table 4
Significant test on soil depth, time, vegetation and their interaction with soil organic, clay, silt, sand, bulk density and capillary porosity.

Source of variation		Soil organic content		Clay		Silt		Sand			Bulk density		Capillary porosity	
	DF	F	P	F	P	F	P	F	P	DF	F	P	F	P
Soil depth	3	43.02	0.000	4.15	0.008	2.98	0.035	5.34	0.002	4	5.37	0.001	2.94	0.023
Time	3	1.59	0.055	7.44	0.000	0.55	0.578	1.73	0.182	3	1.27	0.240	1.14	0.158
Vegetation	2	6.65	0.002	9.25	0.000	3.28	0.024	5.38	0.002	2	12.68	0.000	9.26	0.000
Soil depth × Time	9	0.10	1.000	1.08	0.387	0.44	0.849	0.62	0.717	12	0.24	0.996	0.44	0.944
Soil depth × Vegetation	6	0.80	0.572	2.00	0.072	1.30	0.248	1.19	0.308	8	1.28	0.261	0.45	0.890
Time × Vegetation	6	2.49	0.028	3.56	0.003	1.25	0.287	1.57	0.165	6	0.73	0.628	1.85	0.095
Soil depth × Time × Vegetation	18	0.43	0.977	1.95	0.020	1.30	0.202	1.19	0.281	24	0.91	0.590	1.06	0.395

Table 5
Significant test on soil depth, time, vegetation and their interaction with SWS.

Source of variation	DF	F	P
Soil depth	3	11.57	0.000
Time	3	39.92	0.000
Vegetation	2	368.07	0.000
Soil depth × Time	9	3.80	0.000
Soil depth × Vegetation	6	7.67	0.000
Time × Vegetation	6	4.17	0.001
Soil depth × Time × Vegetation	18	0.32	0.997

same among the three vegetation types.

3.2. Spatial distribution of SWS

Vegetation types, soil depth and time had a significant effect on SWS (Table 5). All SWS were greater in natural grassland than those in artificial and natural forestland, and varied with soil depth, slope position, and time (Figs. 4–6). SWS displayed fluctuations that varied in degree with increasing distance up the hillslopes (Figs. 4–6). In artificial forestland, no obvious trend was found between SWS0-2 and slope positions. For example, SWS values at a distance of 80 m uphill were higher than those at a distance of 60 m. SWS0-1 displayed the largest fluctuations between slope positions, whereas SWS1-2 displayed fluctuations that were relatively small compared to those of SWS0-1. SWS2-4 decreased with increasing slope position. Within the natural forestland, no obvious decreasing trend between SWS0-4 and slope position was found. In natural grassland, SWS in the different soil layers displayed a consistent trend with slope position; SWS0-4 decreased with increasing slope position, except at a distance of 80 m from the toe of the slope, where SWS had its lowest values.

Different drought conditions can cause different spatial variations in SWS in different soil layers. In 2016, SWS0-4 displayed relatively small changes between the wet and dry seasons; however, in 2015, SWS0-4 displayed larger variations between the wet and dry seasons than in 2016. In 2015, SWS0-4 during the dry season was substantially higher than during the wet season. In addition, SWS0-1 was higher during the dry season of 2016 than during the wet season of 2015, whereas SMS1-4 decreased from the wet season of 2015 to the dry season of 2016.

Table 6 showed SWS depletion in three vegetation types. In artificial forestland and natural grassland, SWS depletion during the rainy season at soil depths of 1–2 m (38.32 mm, 43.29 mm) were significantly higher than that at soil depths of 0–1 (22.21 mm, 25.78 mm), 2–3 (20.86 mm, 34.62 mm) and 3–4 m (7.41 mm, − 0.50 mm) in severe drought year. In natural grassland, SWS depletion at soil depths of 0–1 m (37.95 mm) were significantly higher than that at soil depths of 1–2 (23.87 mm), 2–3 (24.38 mm) and 3–4 m (2.13 mm) in severe drought hydrological year. In normal hydrological year, changes in SWS were not significantly different among several soil depths. In addition, in severe drought year, natural grassland had significantly higher value of changes in SWS at soil depths of 0–1 m (37.95 mm) than artificial forestland (22.21 mm) and natural forestland (25.78 mm), but significantly lower at soil depths of 1–2 m. In normal hydrological year, water depletion occurred in artificial forestland, whereas water replenishment occurred in natural grassland.

3.3. Multivariate analysis

A statistical summary of environmental factors for the first two axes were provided by RDA. The relevant metrics include the eigenvalue (EV), the accumulated variance percentage of SWS (AVP-SW), and the

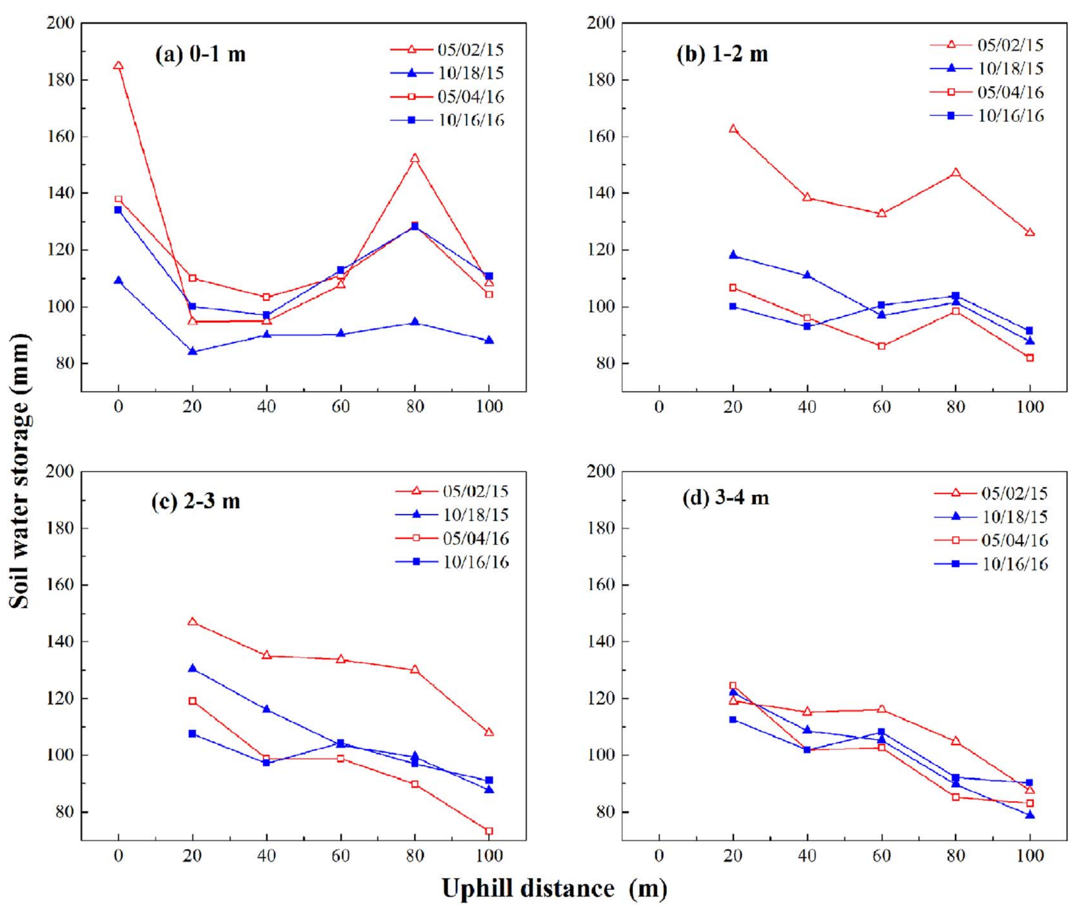

Fig. 4. Spatial distribution of SWS in artificial forestland.

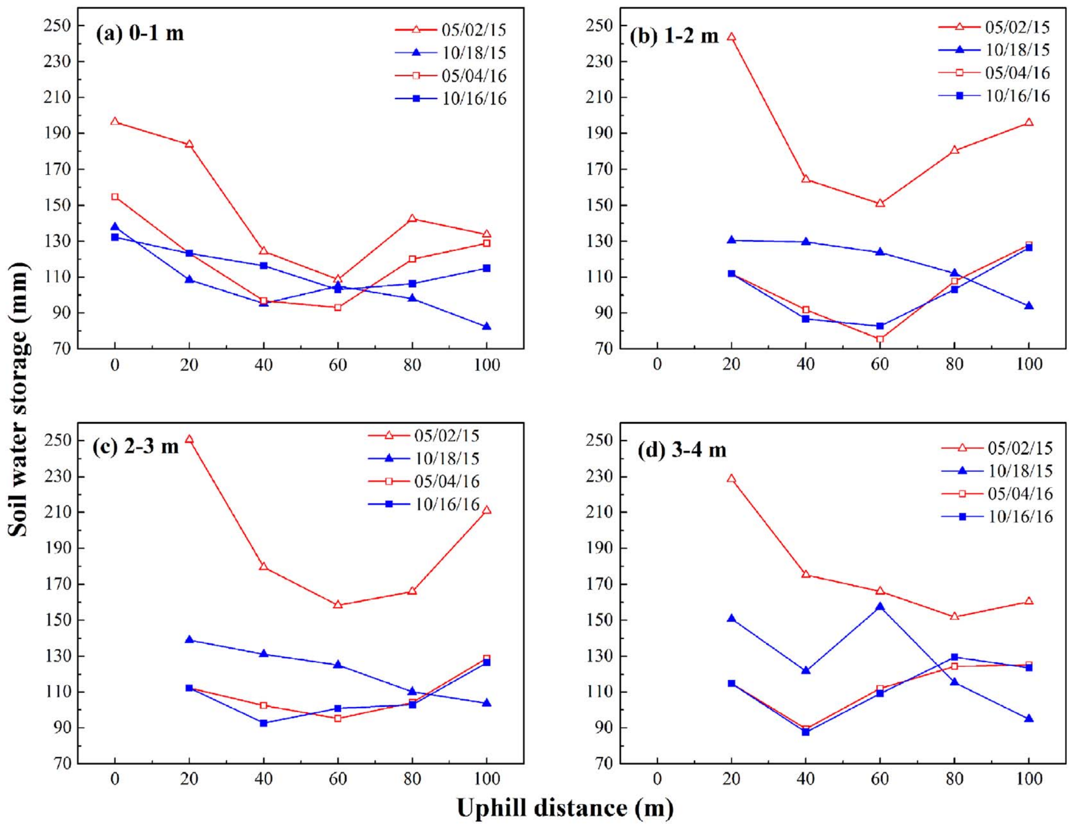

Fig. 5. Spatial distribution of SWS in natural forestland.

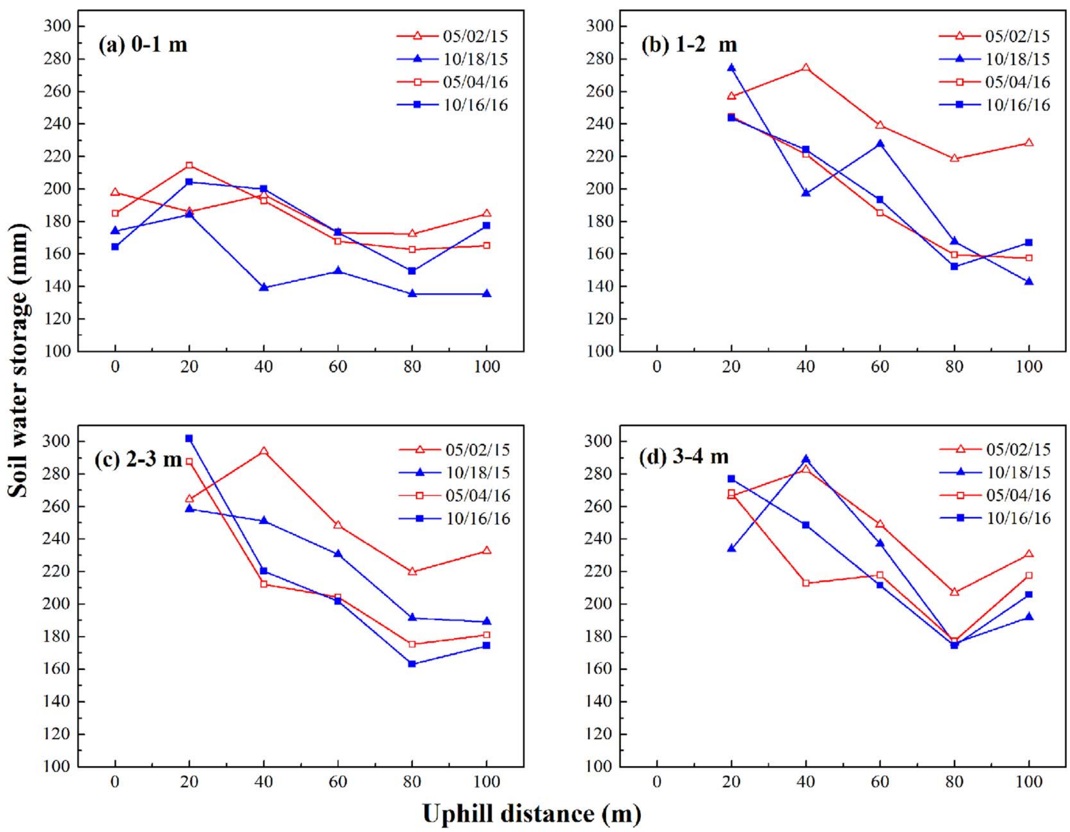

Fig. 6. Spatial distribution of SWS in natural grassland.

Table 6
SWS depletion at different soil depths in three vegetation types.

Period	Vegetation types	Changes in SWS during the rainy season			
		0–1 m	1–2 m	2–3 m	3–4 m
2015	Artificial forestland	− 22.21 ± 2.27bB	− 38.32 ± 9.19aA	− 20.86 ± 1.72bB	− 7.41 ± 6.40cA
	Natural forestland	− 25.78 ± 3.59bB	− 43.29 ± 3.83aA	− 34.62 ± 1.30abA	0.50 ± 3.87cB
	Natural grassland	− 37.95 ± 4.88aA	− 23.87 ± 1.51bB	− 24.38 ± 2.43bB	− 2.13 ± 7.98cB
2016	Artificial forestland	− 1.68 ± 4.32aA	− 3.97 ± 1.47aA	− 3.45 ± 4.67aA	− 1.52 ± 4.08aA
	Natural forestland	0.41 ± 0.43aA	− 0.80 ± 4.16aA	− 1.59 ± 0.79aA	− 0.28 ± 3.73aA
	Natural grassland	0.28 ± 4.57aA	2.32 ± 3.25aB	0.091 ± 3.38aB	4.55 ± 3.48aB

Data represent means and standard deviations (S.D.). Different uppercase letters indicate a significant difference among vegetation types by soil depth; different lowercase letters indicate significant differences among soil depths by vegetation type ($p < 0.05$).

soil water-environmental variable correlation (SWEC) (Table 7). These statistics represent the degree to which the environmental factors explain the variations in SWS for the first two axes. The environmental factors explained 80.3%, 98.5%, 82.7% and 82.7% of the variations in SWS for the first two axes. Thus, the first two axes provide a satisfactory explanation of the effect of the environmental factors on SWS. In addition, the SWEC values, which were 0.930, 1.000, 0.926 and 0.929 during the dry and wet seasons of 2015 and the dry and wet seasons of 2016, respectively, are mainly distributed along the first axis. Table 7 further indicates the canonical coefficients between each environmental factor and the variations in SWS for the two axes. Generally, the coefficients associated with the first axis were larger than those associated with the second axis, indicating the weaker role of environmental factors in the second axis. Vegetation type, slope aspect and slope gradient displayed significant correlations with the first axis in the four periods.

The ordination diagrams produced by RDA provided a detailed description of the relationship between variations in SWS and environmental factors during the different periods (Fig. 7). The first two main factors in the different periods and soil layers are shown in Table 8.The degree of correlation between the environmental factors and the depth-averaged SWS varied among the different periods. During the dry and wet seasons of 2015, similar main environmental factors affected SWS0-2. For example, during these periods, slope gradient and SOC0-1 were the main factors that affected SWS0-1, whereas slope aspect and slope gradient were the main factors that affected SWS1-2. In 2015, SWS2-4 was mainly influenced by vegetation type. The controlling factors in 2016 changed more strongly than in 2015. During the dry season of 2016, slope aspect was the main factor that controlled SWS0-3, whereas vegetation type and slope gradient were the main variables that affected SWS3-4. However, during the wet season of 2016, SOC0-1 and the slope gradient were the main factors affecting SWS0-1, and vegetation type was the critical variable controlling SWS1-4. Thus, vegetation type controlled SWS at large soil depths during the investigated periods, except for the wet season of 2016, when vegetation type controlled SWS1-4. In addition, slope position and slope gradient had a negative relationship with SWS, whereas vegetation type and slope aspect had a positive relationship with SWS. The toes of slopes and gentle slopes had higher SWS values than positions near the crests of slopes and steep slopes. Moreover, shady slopes had higher SWS values than sunny slopes, and natural grassland had higher SWS values than forestland.

The main factors affecting SWS in whole soil profiles can be extracted using forward selection and Monte Carlo tests. The results of forward selection and Monte Carlo tests of environmental factors in the different periods are shown in Table 9. They indicate that, under near-normal conditions, vegetation type was the dominant factor that controlled the spatial distribution of SWS in entire soil profiles. For example, during the dry season of 2015, and the dry and wet season of 2016, vegetation type had a significant correlation with SWS and explained 68%, 65% and 67% of the total variables selected, respectively. However, during the wet season of 2015, even though vegetation type had a significant correlation with SWS, it only explained 4% of the total variables selected. During this season, slope aspect and position explained 79% and 12%, respectively. Thus, in severe drought conditions, vegetation type played a critical role in SWS, and slope aspect and position became more dominant as controlling factors within the study site.

4. Discussion

In our study, SWS reflected different degrees of fluctuations along transects during both the growing and the non-growing seasons on three hillslopes. Relatively high SWS values were noted at the toes of slopes, indicating that more soil water was stored there compared to other parts of the hillslopes, perhaps due to the large flow accumulation area (Li et al., 2015a, 2015b). However, SWS did not show a monotonic decrease with increasing slope position. For example, the SWS values noted at a distance of 60 m uphill were lower than those measured at a distance of 80 m in artificial forestland, and the SWS values noted at a distance of 80 m uphill were lower than those measured at a distance of 100 m in natural grassland, perhaps because variations in topography consisting of landform elements and microtopography affect the spatial distribution of SMS (Li et al., 2015a, 2015b). The overall spatial patterns of SWS during the dry season bear a close resemblance to those during the wet season in the same year, consistent with the findings of Biswas and Si (2011), Gao and Shao (2012b) and Li et al. (2015a, 2015b). This resemblance may be due to soil layers with similar intrinsic soil properties, such as texture and SOC content, or the presence of soil layers at the same location with similar topography and vegetation cover that experience similar degrees of hydrological processes, such as infiltration, runoff and evapotranspiration (Li et al., 2015a, 2015b).

Vegetation also played an important role in determining the variations in SWS in the same precipitation event. Of the three vegetation types, natural grassland had significantly higher SWS values than those of artificial forestland and natural forestland, consistent with previous studies (Qiu et al., 2001; Fang et al., 2016). In natural grassland, the lowest SWS values were observed in the shallow soil layer (0–1 m), whereas the values of SWS0-1 were highest in artificial forestland. No obvious trend was observed in the SWS of natural forestland at various depths. Possible explanations for these results may be differences in the characteristics of the plants found on the three hillslopes (Jia et al., 2013a, 2013b). Root structure and vegetation cover can change evapotranspiration and storage, leading to differing spatial patterns of SWS (Zhao et al., 2010; Jia et al., 2013a, 2013b). In addition, vegetation type can also significantly control the spatial patterns of SWS (Jia and Shao, 2013). The artificial forestland was planted with *Robinia pseudoacacia,* which is a typical perennial deep-rooted tree. During the growing season, these trees likely remove large amounts of water from deep soil layers. During the entire dry season, forests mainly relied on the soil water in the 100–200 cm soil depth (Table 6). The larger

Table 7
Statistical summary and canonical coefficients of the environmental factors for the first two axes of the RDA.

Period	Axis	Statistic			Canonical coefficient													
		EV	AVP-SW	SWEC	SP	SA	SG	VT	SOC	Clay	Silt	Sand	BD0–1	CP0–1	SOC	Clay	Silt	Sand
									0–1	0–1	0–1	0–1			1–4	1–4	1–4	1–4
05/02/15	1	0.777	77.7	0.930	−0.215	0.369	−0.334	0.870**	0.235	0.027	−0.07	0.057	0.174	−0.009	0.247	−0.275	−0.374	0.371
	2	0.027	80.3	0.568	0.301	0.006	−0.003	−0.039	0.122	0.15	0.276	−0.282	−0.052	0.007	0.043	0.1008	0.034	−0.045
10/18/15	1	0.956	95.6	1.000	−0.426	0.906**	−0.469	0.872**	0.206	−0.113	0.114	−0.079	0.533**	0.030	0.062	−0.242	−0.242	0.25
	2	0.029	98.5	0.998	0.056	0.062	−0.212	−0.042	0.104	−0.045	0.275	−0.239	−0.071	0.061	−0.019	0.237	0.179	−0.193
05/04/16	1	0.813	81.3	0.926	−0.211	0.412	−0.5024**	0.831**	0.349	−0.057	0.21	−0.178	0.312	−0.18	0.202	−0.104	−0.024	0.037
	2	0.014	82.7	0.668	−0.052	0.006	0.086	−0.147	−0.293	0.068	−0.182	0.15	0.321	−0.145	−0.277	0.193	−0.025	−0.007
10/16/16	1	0.814	81.4	0.929	−0.162	0.440	−0.498	0.840**	0.393	−0.025	0.227	−0.2	0.323	−0.162	0.244	−0.087	−0.033	0.042
	2	0.013	82.7	0.655	−0.129	−0.064	0.072	−0.027	−0.047	−0.132	−0.206	0.214	0.242	−0.115	−0.312	0.139	0.211	−0.207

EV: eigenvalue; AVP-SW: accumulated variance percentage of soil water; SWEC: soil water-environmental variable correlation.
* and ** represent variables that are significantly related at the 0.05 and 0.01 level, respectively.

amounts of water intercepted by forest canopies lead to decreases in the infiltration of precipitation and make it difficult for soil water to infiltrate into deep soil layers. Thus, SWS0-1 was higher than SWS in the deeper soil layers. The natural grassland had many fine roots which were distributed throughout the shallow soil layer. Different from forests, natural grass mainly extracted soil water at soil depths of 0–1 m (Table 6). The relatively low surface SWS in the natural grassland was caused by relatively high evapotranspiration and the uptake of water by roots. And water depletion in natural grassland was significantly lower than that in artificial and natural forestland except for at the soil depths of 0–1 m in severe drought year of 2015. In near-normal drought year of 2016, water replenishment occurred in natural grassland, whereas, water depletion occurred in artificial and natural forestland. Thus, natural grassland may be the optimum of vegetative cover.

In addition, the spatial variation in SWS was greatly affected by variations in climatic factors. Precipitation is the only source of recharge to SWS on the Loess Plateau; thus, precipitation is closely related to spatial and seasonal variations in SWS (Wei et al., 2009; Zhang et al., 2016). Meanwhile, the evapotranspiration from soil and plants during the wet (growing) season was significantly different from that during the dry (non-growing) season. This difference may affect the spatial variations in SWS, perhaps even aggravating water deficits. In 2015, SWS0-4 during the wet season was relatively lower than that during the dry season, which indicates that pronounced water deficits occurred during this year of severe drought. The water deficit mainly resulted from a shortage in recharge due to precipitation, large amounts of evaporation and water uptake by the roots of plants (Jia et al., 2013a, 2013b). However, in 2016, SWS0-4 during the wet season was nearly equal to that during the dry season because higher amounts of precipitation can replenish water lost to evaporation and the uptake of water by plant roots. In addition, from after the rainy season in 2015 to before the rainy season in 2016, SWS0-1 increased, while SMS1-4 decreased. This observation indicates that small amounts of precipitation (79.1 mm) and snowmelt can only recharge soil water at shallow depths. However, water consumption occurred in the deep soil layer, even outside of the growing season. In the future, long-term monitoring of soil water should be performed to convincingly describe the dynamics of SWS in a greater number of different periods and at various depths.

SWS is a critical variable in determining vertical water and energy fluxes (Brocca et al., 2009; Heathman et al., 2012; Li et al., 2015a, 2015b). In addition, SWS varies along hillslopes due to the redistribution of precipitation and runoff. Thus, understanding the controlling factors of SWS in shallow and deep soil layers along hillslopes and temporal changes in controlling factors during the dry season and wet season is important. The results of this study indicate that the main factors affecting SWS in shallow and deep soil layers changed over time; the main factors also varied between periods. The two primary factors affecting SWS in both the dry and wet seasons of 2015 were similar in the same soil layer. For example, SOC0-1 and slope gradient were the main factors controlling SWS0-1, whereas slope aspect and gradient were the main factors controlling SWS1-2; vegetation type was the most influential variable affecting SWS2-4. This result may have occurred because the large amounts of SOC found in the surface soil can retain soil water under moderate drought conditions, thus preventing a more severe drought. Moreover, topography (slope gradient and aspect) played important roles in determining the SWS of shallow soil layers, consistent with the results of previous studies (Takagi and Lin, 2012; Yang et al., 2015), however, in deep soil layers, root water uptake was the main factor causing variations in SWS, which corresponds with the findings of (Ferreira et al., 2007; Yang et al., 2015). However, the importance of the main factors varied. For example, during the dry season of 2015, SOC0-1 and slope aspect were the most important factors affecting soil layers at depths of 0–1 m and 1–2 m, respectively. However, slope gradient was the most important factor affecting SWS0-2 during the wet season of 2015, perhaps because the slope gradient has a

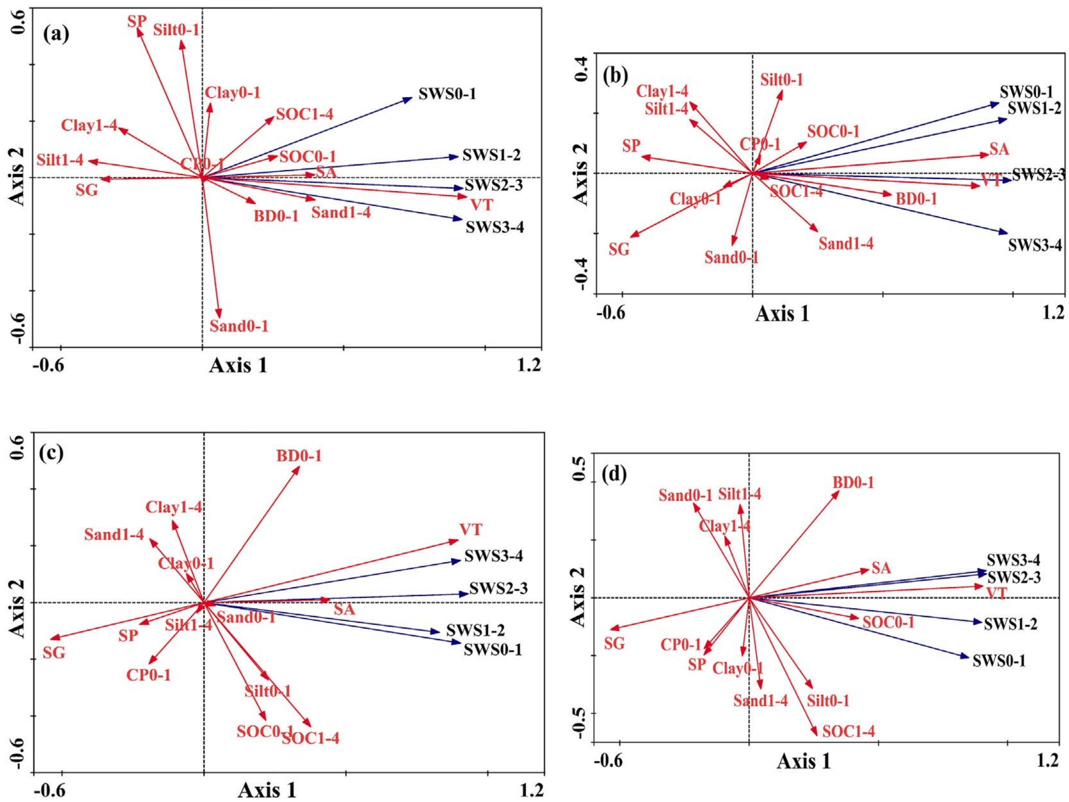

Fig. 7. Ordination biplots obtained using detrended correspondence analysis showing the relationship between depth-averaged soil water content and environmental factors at different times; (a) 05/04/15; (b) 10/18/15; (c) 05/02/16; (d) 10/16/16; the blue lines with arrows denote the SWS in different soil layers, whereas the red lines with arrows denote the environmental factors; the angles between the blue lines with arrows and the red lines with arrows denote the correlations between SWS in different layers and the environmental factors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 8
The first two main factors in different soil layers during different periods.

Periods	Soil layer (m)			
	0–1	1–2	2–3	3–4
05/02/15	SOC0-1, SG	SA, SG	VT, SA	Sand1-4, VT
10/18/15	SG, SOC0-1	SG, SA	SP, VT	SP, BD0-1
05/04/16	SA, Sand0-1	SA, Sand0-1	SA, SG	VT, SG
10/16/16	SOC0-1, SG	SOC0-1, VT	VT, SG	VT, SG

SP: slope position; SA: slope aspect; VT: vegetation type; SG: slope gradient; BD: bulk density; SOC0-1: layer-averaged soil organic carbon content at depths of 0–1 m.

significant influence on infiltration and runoff during the wet season. During the dry season of 2016, slope aspect was the main factor regulating SWS0-3, and deep SWS was also controlled by vegetation type. Precipitation infiltrated during the dry season of 2016 (Fig. 2). Moreover, snowmelt during this period, when soil water can be recharged, tends to migrate downslope due to topography (Williams et al., 2009), and slope aspect was the factor that exerted the greatest control on the rate of snowmelt. Within the study area, the speed of the northwest wind, which controls soil moisture (Cho and Choi, 2014) and prevails during the dry season, leads directly to the influence of slope aspect on SWS. During the wet season of 2016, SOC0-1 and slope gradient were the main factors affecting SWS0-1, and SOC0-1 and vegetation type were the main factors affecting SWS1-2; however, the main factors that drove changes in SWS2-4 were vegetation type and slope gradient. The differences in the factors controlling SWS in the various soil layers may occur because the organic carbon content of the shallow soil layers can have an important effect on soil porosity and saturated soil water content during the wet season; however, during the wet season, when rapid plant growth occurs, the vegetation can draw water from SWS1-4, that is, from larger soil layers, than during other periods. It may occur because relatively large amounts of precipitation provide water that is available to the leading roots of plants, which can draw from soil water in shallow and deep soil layers. Vegetation type was a relatively important factor in affecting the SWS in the vertical profile during each investigated period, which was the most important factor under near-normal drought conditions (e.g., the dry season of 2015 and the dry and wet seasons of 2016); however, slope aspect and position were more influential under severe drought conditions (e.g., the wet season of 2015) than vegetation type (Table 9) because precipitation can infiltrate into the surface soil under drought conditions, whereas SWS is greatly affected by slope aspect and position, and deep SWS cannot be replenished to permit the uptake of water by roots, contributing to the lower variations in SWS caused by vegetation type.

The environmental factors varied among the different periods. The environmental factors reflected greater changes during a relatively wet year (a near-normal year) than during a year that featured a severe drought. The main factors during the wet season of a near-normal year differed from the most influential factors during the dry season. However, during severe drought years, the main factors in the wet and dry seasons appear to be more stable than under near-normal conditions in the same soil layer. The explanation may be that the effects of precipitation that falls during the dry and wet seasons of near-normal years cause the roles of terrain attributes, vegetation type and soil properties in controlling soil water to change. However, the amount of precipitation that falls in severe drought years is relatively low and hardly affects the other controlling factors.

5. Conclusion

The seasonal patterns of SWS in different slope positions and vegetation types were investigated at sites on the Loess Plateau, and the

Table 9
Forward selection and Monte Carlo tests of environmental factors for different time periods.

Environmental factor	05/02/15			10/18/15			05/04/16			10/16/16		
	p	F	RCR	p	F	RCR	p	F	RCR	p	F	RCR
SP	0.24	1.68	1	0.002**	15.29	12	0.184	5.06	4	–	–	–
SA	–	–	–	0.002**	43.91	79	–	–	–	–	–	–
SG	–	–	–	0.522	0.99	1	0.024*	6.21	4	0.034*	6.05	4
VT	0.002**	84.68	68	0.002**	7.3	4	0.002**	75.03	65	0.002**	79.68	67
SOC0-1	0.178	1.56	1	0.2	1.74	1	0.036*	4.29	2	0.002**	7.02	5
Clay0-1	–	–	–	–	–	–	0.746	0.24	1	–	–	–
Silt0-1	0.194	1.66	1	–	–	–	0.138	5.09	4	0.156	5.14	3
Sand0-1	–	–	–	–	–	–	–	–	–	–	–	–
BD0-1	0.084	2.11	3	–	–	–	0.268	1.34	1	–	–	–
CP0-1	–	–		0.358	1.18	1	–	–	–	–	–	–
SOC1-4	0.068	2.62	1	0.24	7.23	1	0.514	3.67	2	0.128	1.81	1
Clay1-4	–	–	–	0.072	3.25	1	0.238	1.81	1	0.05	3.73	2
Silt1-4	–	–	–		–	–	0.008**	3.79	2	0.316	0.89	1
Sand1-4	0.002**	8.23	8	–	–	–	–	–	–	–	–	–
Total	–	–	81	–	–	100	–	–	84	–	–	83

CP: Capillary porosity; F indicates the F-ratio; RCR indicates the variance explained by the variables selected.
* represents $p < 0.05$.
** represents $p < 0.01$.

relationships between SWS and 10 environmental variables were assessed for different periods. The results indicated that the toes of slopes displayed relatively high SWS, even though SWS did not display a monotonic decrease with increasing slope position due to topographic variations. Vegetation type affected SWS in different soil layers such that the lowest SWS was observed in shallow (0–1 m) soil layers in natural grassland due to relatively high soil evapotranspiration, but SWS0-1 was highest in forestland because the soil water in deep soil layers was depleted by the uptake of water by roots. Due to a lack of precipitation, severe water deficits occurred in the severe drought year of 2015, while a little of water recharge amounts occurred during the near-normal drought year of 2016. In addition, topographic characteristics (slope gradient and aspect) were the main factors controlling SWS0-2. During the wet season, slope gradient was more important than slope aspect in terms of its effect on SWS. The opposite was noted during the dry season. In severe drought conditions (e.g., the wet season of 2015), slope aspect and position became more dominant as controlling factors than vegetation type, while in near-normal drought conditions (e.g., the dry season of 2015 and the dry and wet seasons of 2016), vegetation type played most critical role in SWS.

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