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Spatial variations and impact factors of soil water content in typical natural and artificial grasslands: a case study in the Loess Plateau of China

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Abstract

Purpose Soil water overconsumption is threatening the sustainability of regional vegetation rehabilitation in the Loess Plateau of China. In this study, two typical natural and artificial grasslands under different precipitation regimes were selected and the spatial variations in and the factors that impact the soil water content were investigated to provide support for vegetation restoration and sustainability management in the Loess Plateau.

Materials and methods Soil samples were collected in May and September. *Medicago sativa* L. and *Stipa bungeana* Trin. were selected as representatives of natural and artificial grasslands, respectively. Soil measurements were conducted at the beginning and end of the rainy seasons at soil depths of 0 to 3 m in 0.2-m increments, and 147 undisturbed and 2205 disturbed soil samples were collected at 27 sampling sites with different precipitation gradients across the Loess Plateau. The plant height, the field capacity, the saturated hydraulic conductivity, the bulk density, and the slope gradient were considered as impact factors. Statistic methods included one-way ANOVA, correlation tests, significance tests, and redundancy analyses.

Results and discussion Spatial variation trends indicated that the mean soil water content increased as the multi-year mean precipitation increased, and the soil water content was higher in the natural grassland of *Stipa bungeana* Trin. than in the artificial grassland of *Medicago sativa* L. in the same precipitation gradient zone. Vertical spatial variation trends indicated that the soil water content was higher in most surface layers than in the deep layer and lower at the end of the rainy season than at the beginning of the rainy season, when the mean annual precipitation was less than 510 mm. The soil water content of the *Stipa bungeana* Trin. grassland was significantly correlated with precipitation and plant height, whereas the soil water content of the *Medicago sativa* L. grassland only exhibited a significant correlation with precipitation. Thus, grasses with fine palatability, good adaptability, and low water consumption should be cultivated in the Loess Plateau.

Conclusions The decreased soil water content is more obvious in the soil layers with active vegetation roots. In the areas with multi-year precipitation at 370–440 mm, natural grasslands are more suitable for restoration and these areas should be treated as key areas for vegetation restoration. With regard to the spatial distribution of vegetation restoration, the economic and ecological benefits must be balanced so that the ratio of artificial vegetation and natural restoration can be optimized to realize the continued sustainability of vegetation restorations.

Keywords Grasslands · Loess Plateau · Regional scale · Soil water content

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1 Introduction

Drylands occupy 41 % of the global land area and are home to more than two billion people (Moussa et al. 2006). With climate change, global drylands are facing severe challenges because of water shortages (D'Odorico et al. 2007; Franz et al. 2012; Manzoni et al. 2013) and the relationships between the soil water content and vegetation in arid and semi-arid areas, such as the savannas of Africa, the North American monsoon region, and the Loess Plateau of China, have become hot topics in ecohydrology (Rodríguez-Iturbe and Porporato 2004; Caylor et al. 2006; Tromp-van Meerveld and McDonnell 2006; Vivoni et al. 2007; Vivoni et al. 2009; Legates et al. 2010; Wang et al. 2013). Grassland is a typical type of vegetation in semiarid areas and is among the largest ecosystems in the world, with woody savannahs, savannahs, and non-woody grasslands occupying 22.1 % of the global land area (excluding Greenland and Antarctica) (White et al. 2000; Huang et al. 2005). Water directly controls the dynamics of grassland ecosystems, and grasses modulate several hydrological processes and the rate of the water cycle (D'Odorico et al. 2010). In addition, variations in the soil water content under different types of grasslands impact the quality and quantity of pasturage and food supplies; thus, these relationships are directly coupled to human livelihood in water-limited regions (D'Odorico and Porporato 2006; Franz et al. 2012; Lu et al. 2014a).

The Loess Plateau of China is an important region for studying ecohydrology (D'Odorico et al. 2007; Fu et al. 2011). This region is the world's most typical loess area and accounts for 6.54 % of China's land area. The reckless pursuit of economic growth and grain yield in the middle of the last century destroyed nearly all of the natural vegetation in this region, and the severe environmental deterioration in this region threatens the local human populations (Liu et al. 2008; Feng et al. 2016). Grasslands are widely distributed on the Loess Plateau and occupied nearly 1/3 of the total area even before the *Grain for Green Project* (Zhang 2007). The grasslands in the Loess Plateau are composed of artificial and natural grasslands. By comparison, artificial grasslands have better economic benefits than natural grasslands. However, after implementing artificial grasslands, grassland production decreases over time while the water consumption and demand remain constant (Li 2002). The overconsumption of soil water by grass roots results in dry soil layers that cannot recover in the short term in many areas of the Loess Plateau (Ning et al. 2013). In recent years, researchers have conducted a series of studies focusing on these phenomena and problems in the Loess Plateau (Liu et al. 2016). The results have shown that grasslands are an important component of the vegetation in the Loess Plateau and that the conversion of croplands to grasslands is the most effective method for restoring the ecosystem in this region; however, the main factors to consider can vary at different scales (Li and Shao 2006; Yao et al. 2012a; Yao et al. 2012b). Current studies of soil water content variations mainly emphasize comparisons of grasslands with other types of lands, and experimental research has mainly focused on the dynamics that occur at the slope and watershed scale and have used remote sensing and large-scale models.

According to 283 articles from the China National Knowledge Infrastructure (CNKI) or published by ScienceDirect and Springer from 1988 to 2015, the largest artificial grassland consists of *Medicago sativa* L., and the natural grassland with the largest distribution consists of *Stipa bungeana* Trin. (Wang et al. 2011b). However, 67.39 % of studies on the relationships between grasslands and soil water content have been performed using sample plots or transects, and only a few studies have been performed on a large scale, such as at the belt transect or regional scales (Lv et al. 2012; Lu et al. 2015). Studies conducted in other regions of China indicate that the main environmental factors that impact soil water content may change between different moisture periods and with soil depth; for example, the main factors defining the first axis are different for humid and dry periods, and the effects of relative elevation and slope aspect increase and decrease, respectively, as the soil water content decreases (Zhu et al. 2014; Huang et al. 2016). In addition, the studies that compare soil water contents from areas with different precipitation gradients and different types of grasslands have only focused on a few sampling depths and times (Fu et al. 2003; Foley et al. 2005; Schymanski et al. 2009; Gao et al. 2011; Liu et al. 2012; Montenegro and Ragab 2012; Wang et al. 2012; Yao et al. 2012a). In most studies comparing regional soil water content variations, samples were only collected once, and the sampling points for determining the deep soil water content were usually too shallow. In addition, the number of comparative studies focusing on deep soil layers that have been conducted within the same year is insufficient (Yao et al. 2005b; Wang et al. 2011a; Wang et al. 2014a). Our study examined the soil moisture profile at a depth of 0–3 m across different precipitation gradients at the beginning and end of the rainy season and considered the impacts of grass growth on changes in the soil water content.

Based on the work of previous studies, *Medicago sativa* L. and *Stipa bungeana* Trin. growing under different precipitation gradients were selected to represent natural and artificial grasslands, respectively, and samples were collected twice, once at the beginning and once at the end of the rainy season. This paper aimed to (1) compare the spatial variations of the soil water content beneath *Medicago sativa* L. and *Stipa bungeana* Trin. at different soil depths and in different precipitation zones of the Loess Plateau; (2) analyze the impacts of environmental factors on the variability of soil water contents under two types of grasslands; and (3) provide suggestions for the ecological restoration of grasslands in the Loess Plateau of China.

2 Materials and methods

2.1 Description of the sites

The research areas were located in the north-central Loess Plateau of China (34.1°–41.1° N, 107.2°–111.2° E) (Fig. 1). The studied areas have a typical continental monsoon climate, and the mean annual precipitation calculated over many years ranges from 300 to 600 mm. The precipitation in a given year is unevenly timed, and more than 60 % falls during the months of July to September. During these months, frequent heavy rainfall occurs that results in soil and water losses. The mean annual temperature calculated over many years ranges from 8 to 11 °C. The amount of precipitation that occurred during the sampling year (2014) is slightly higher than the annual mean precipitation. The vegetation zones include typical grassland and forest steppe zones. Common herbaceous plants include *Medicago sativa* L., *Stipa bungeana* Trin., *Artemisia sacrorum*, *Artemisia capillaris*, *Bothriochloa ischaemum*, and *Lespedeza davurica* (Yang and Shao 2000).

2.2 Experiment design and data analysis methods

2.2.1 Experiment design

Geological information was obtained using a hand-held Garmin GPS (version eTrex 30, Garmin electric business management Co., Ltd., Shanghai, China). Slope gradient and aspect were determined using a geological compass, and precipitation was determined by interpolating data collected at 62

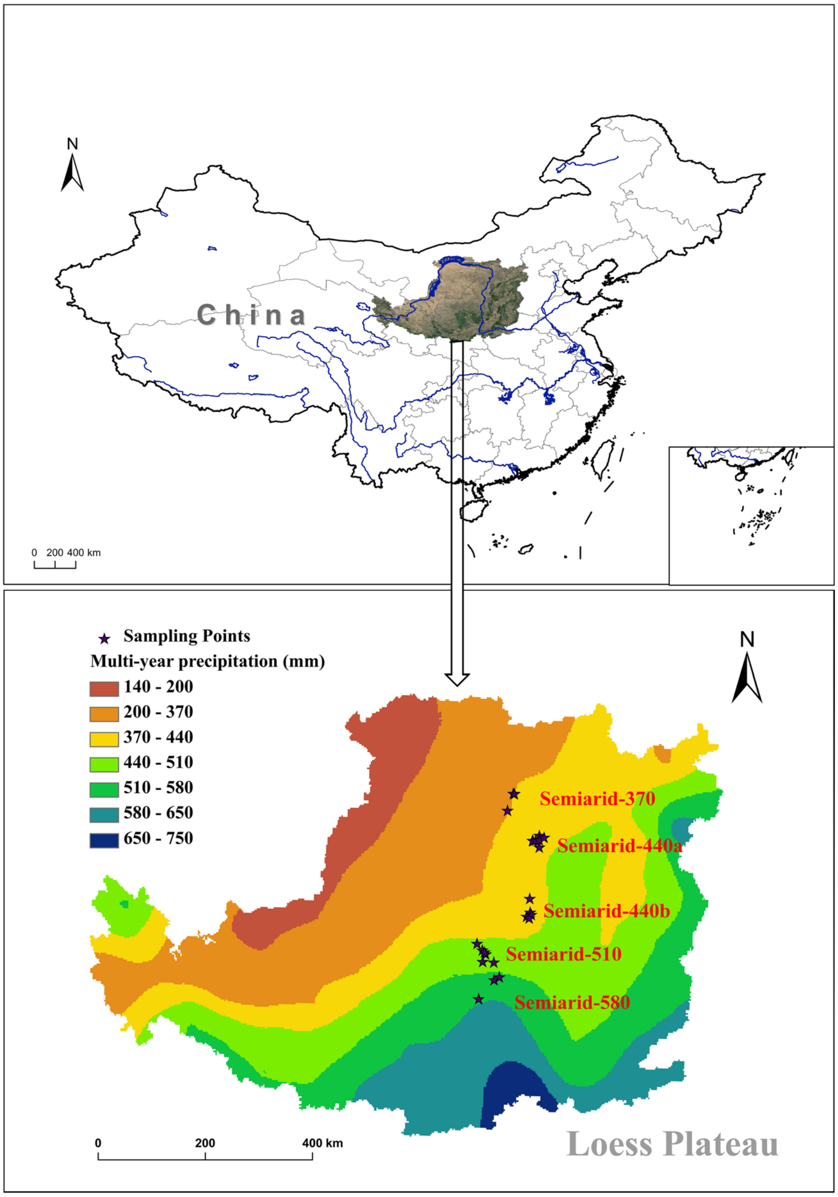


Fig. 1 Map of the sampling area

Loess Plateau meteorological monitoring stations by the China Meteorological Administration.

During the sampling year, the amount of precipitation was slightly higher than the mean annual precipitation. The study area was divided into zones based on the mean annual precipitation at intervals of 70 mm, which resulted in the following four precipitation zones: 300–370, 370–440, 440–510, and 510–580 mm. Because the 370–440-mm zone spans a large latitude range, two sampling areas were selected for sampling. One representative sampling area was selected in each of the other precipitation gradients. Therefore, five sampling areas were designated from north to south: Semiarid-370, Semiarid-440a, Semiarid-440b, Semiarid-510, and Semiarid-580 (Fig. 1). The sampling areas were located at an altitude of 917–1505 m in gully terrain. The soils were mainly composed of loessial soil and yellow sand soil. Because the soil water content was lower on the sunny slopes than on the shady slopes and was lower in uphill areas than in downhill areas, the sampling sites were all located at the top or uphill areas on sunny slopes or semi-sunny slopes between 0° and 30°. The dominant species were apparent, and little human and animal destruction were observed. The land had been converted back to grassland from cropland approximately 15 years before the study. Specific information on each sample site is shown in the Electronic Supplementary Material.

Sampling was performed in May (beginning of the rainy season) and September (end of the rainy season) in 2014. Grasslands with *Medicago sativa* L. (MS) were chosen to represent the artificial grassland, and grasslands with *Stipa bungeana* Trin. (SB) were chosen to represent the natural grassland. According to the actual grassland distributions, 2–4 sampling plots with the same vegetation were chosen for each sampling zone and the total number of sampling points was 49. In May, the number of sampling points was 27, and in September, the number of sampling points was 22 because five sampling points were destroyed during the rainy season. Soil water content measurements were performed using the classic drying method. A soil auger with a diameter of 5 cm was used to obtain soil samples at depths of 0–3 m. Samples were collected at intervals of 20 cm for the 0- to 3-m layer and repeated randomly three times at each sampling point. Overall, 2205 disturbed soil samples were collected. The soil samples were sealed in aluminum boxes and transported back to the lab for measurements. The soil samples were heated to 105 °C and dried to a constant weight to determine the soil water content.

For each sampling plot, the soil saturated hydraulic conductivity, bulk density, and field moisture capacity were measured three times for the top layers of the soil. The core cutter method was used to determine the soil physical properties, and 147 undisturbed soil samples were collected from the 49 sampling points. The area of the surveyed vegetation quadrat was 2 m × 2 m, and 20 dominant species were randomly measured inside the quadrat. The average height was calculated to represent the mean plant height, and the coverage was obtained visually.

2.2.2 Data analysis

The statistical analysis of the data included the maximum, minimum, mean, standard deviation, and coefficient of variation of the soil water contents beneath the different types of grasslands in the different sampling areas. Variations in the soil water content for different areas and different species were analyzed using one-way analysis of variance (ANOVA), and the least squares difference method (LSD) was utilized to verify the results. Correlations between the soil water content and the influential factors were verified by Pearson's contingency coefficient (2-tailed; significant at $P < 0.05$; very significant at $P < 0.01$). By combining the linear constraint sorting redundancy analysis (RDA), the correlations between the different grassland types and the soil water contents were compared.

The mean soil water content for each sampling point was calculated using Eq. (1) as follows:

$$\mathrm{SW}C_m = \frac{1}{i}\sum_{i=1}^{i} \mathrm{SM}C_i \tag{1}$$

where m represents the serial number of each site and i represents the layer number of soils collected along the perpendicular direction at point m. The soil water content SWC_m for each layer was obtained by averaging the repeatedly measured values (Sun et al. 2014; Yang et al. 2012).

The mean soil water content for the sampling area was calculated using Eq. (2):

$$\mathrm{SW}C_n = \frac{1}{n}\sum\nolimits_{n=1}^{n} \mathrm{SM}C_{m,} \tag{2}$$

where n represents the number of sampling points in the sampling area (Sun et al. 2014).

The change in the soil water content between the beginning and end of the rainy season was calculated using Eq. (3):

$$\mathrm{Variation}n_m = \mathrm{SW}C_{m\text{-}b}\text{-}\mathrm{SW}C_{m\text{-}e'} \tag{3}$$

where $\mathrm{SWC}_{m\text{-}b}$ represents the value at the beginning of the rainy season at point m and $\mathrm{SWC}_{m\text{-}e}$ represents the value at the end of the rainy season at point m.

The rate at which the soil water content changed from the beginning to the end of the rainy season was calculated using Eq. (4):

$$C.R._m = \mathrm{Variation}n_m \Big/ \mathrm{SW}C_{m\text{-}b'} \tag{4}$$

where C.R. represents the rate of change and the other letters are as described in Eq. (3).

Data pretreatment was performed using Excel 2007. One-way ANOVA and correlation and significance tests were conducted using SPSS 19.0. RDA was performed using Canoco for Windows 4.5. The figures were plotted using ArcGIS 9.3 and Origin 8.5.

3 Results

3.1 Spatial variations of the average soil water content under different precipitation gradients

The mean soil water contents for the different areas planted with MS and SB (Fig. 2, Table 1) were calculated using the data obtained from field sampling at the beginning (May) and the end (September) of the rainy season and Eqs. (1) and (2). Figure 2 and Table 1 show that the spatial variation follows the same trend as the precipitation and increased with increasing precipitation. Semiarid-440a and Semiarid-440b are located far apart, although they are in the same precipitation gradient zone. The multi-year mean precipitation in Semiarid-440a is slightly higher than that in Semiarid-440b, whereas the soil water content in Semiarid-440a is slightly lower than that in Semiarid-440b. The differences in the soil water contents between Semiarid-440a and Semiarid-440b are not significant. A comparison of the soil water contents within Semiarid-440a, Semiarid-440b, and Semiarid 510 shows that the soil water content is higher for the natural SB grassland than for the artificial MS grassland (Fig. 2) in the same precipitation gradient zone. However, the changes in soil water content with precipitation are smaller for SB than for MS. For example, the multi-year mean precipitation increases by 11.8 % from Semiarid-440a to Semiarid-510; however, the soil water content for SB only increases by 23.1 %, and the soil water content for MS only increases by 59.8 %. These results indicate that the change of the soil water content under the artificial grasslands is more obvious than the change in the soil water content under natural grasslands relative to precipitation. In addition, a comparison of the soil water content between MS and SB under the different precipitation gradients reveals that greater amounts of precipitation lead to smaller differences in the soil water content (Fig. 2). For the Semiarid-370, Semiarid-440a, Semiarid-440b, and Semiarid-510 areas, the average soil water content is significantly lower at the end of the rainy season than at the beginning of the rainy season in the natural and artificial grasslands (Table 1), and the average soil water content is significantly higher at the end of the rainy season than at the beginning of the rainy season in Semiarid-580. The reduction in the soil water content is lower in the natural grasslands than in the artificial grasslands under all of the precipitation gradients (Fig. 2). With increases in both the multi-year mean precipitation and precipitation in a given sampling year, the soil water consumption in the artificial grassland increases. A similar trend is observed in the natural grassland, although this result is not significant (Fig. 2).

The differences in the soil water contents at the different sampling points between the end and beginning of the rainy season (Fig. 3) can be calculated using the data collected at the beginning (May) and the end (September) of the rainy season and using Eqs. (3) and (4). Figure 3 shows that for most of the sampling points, the soil water content remains high at the end of the rainy season when the sampling points show high soil water contents at the beginning of the rainy season and this change is more significant with lower multi-year precipitation (Fig. 3).

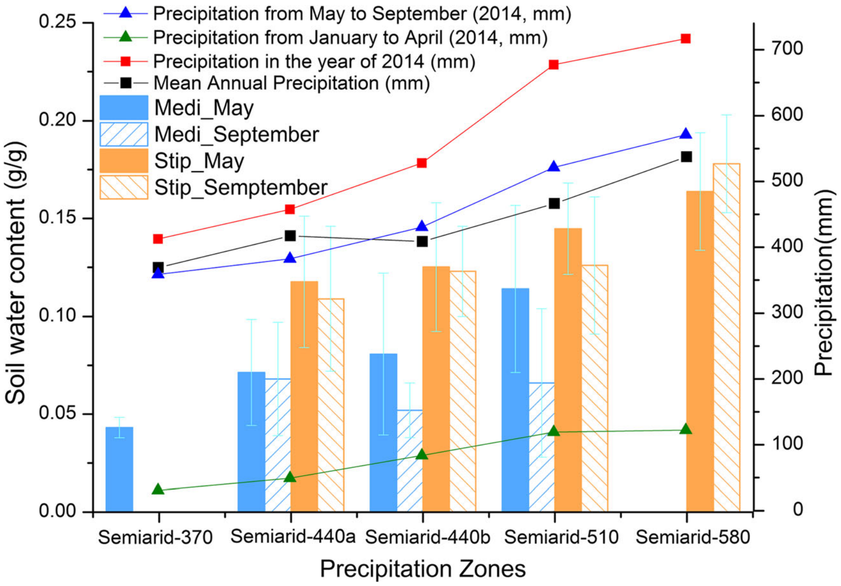


Fig. 2 Precipitation and changes in the soil water content at the beginning (May) and the end (September) of the rainy season for the different types of grasslands in the different areas (*error bars* represent the means standard errors of the soil water contents for each sampling area). Notes: Medi indicates the soil water content under *Medicago sativa* L., and Stip indicates the soil water content under *Stipa bungeana* Trin

Table 1 Soil water content at the beginning (May) and end (September) of the rainy season in the different investigated areas

Month	Zones	*Medicago sativa L.*					*Stipa bungeana Trin.*				
		Mean (g/g)	Max (g/g)	Min (g/g)	SD	CV (%)	Mean (g/g)	Max (g/g)	Min (g/g)	SD	CV (%)
May	Semiarid-370	0.043a	0.145	0.005	0.005	13.8					
	Semiarid-440a	0.071bA	0.127	0.027	0.027	38.1	0.118dB	0.180	0.065	0.034	28.5
	Semiarid-440b	0.081bA	0.141	0.041	0.041	51.2	0.125dB	0.191	0.047	0.033	26.7
	Semiarid-510	0.114cA	0.191	0.043	0.043	37.4	0.145eB	0.187	0.071	0.023	16.2
	Semiarid-580						0.164f	0.217	0.088	0.030	18.4
Sep.	Semiarid-440a	0.068aA	0.181	0.022	0.029	44.6	0.109cB	0.181	0.047	0.037	34.2
	Semiarid-440b	0.052bA	0.137	0.029	0.014	25.2	0.123cdB	0.188	0.023	0.023	20.9
	Semiarid-510	0.066aA	0.125	0.032	0.038	54.2	0.126dB	0.187	0.068	0.035	27.5
	Semiarid-580						0.178e	0.244	0.123	0.025	14.2

The same lowercase letters in the same columns indicate that the differences are not significant at the 0.05 level. Similarly, the same uppercase letters in the same rows indicate that the differences are not significant at the 0.05 level (one-way ANOVA, LSD test, 0.05: *SD* represents standard deviation; *CV* represents coefficient of variation; *Sep.* represents September)

3.2 Vertical spatial variations of the soil water content under different precipitation gradients

The overall vertical distribution of the soil water content in different areas (Fig. 4) can be calculated using Eq. (1). Figure 4 shows a significant difference in the soil water content for different precipitation gradients. Overall, the soil water content is higher for the top layer than for the deep layers. The mean soil water content in May gradually and evidently decreased from the 0–2-m layer to the 2–3-m layer by 58.1 % (Semiarid-370), 7.3 % (Semiarid-440a), 1.0 % (Semiarid-440b), 0.9 % (Semiarid-510), and 4.2 % (Semiarid-580) (LSD, 0.05). In addition, the soil water content is lower at the end than at the beginning of the rainy season in most layers, except for the 0–2-m layer in Semiarid-580 (Fig. 4).

The soil water content of the top soil layer does not show a pronounced difference between MS (artificial grassland) and SB (natural grassland) (Fig. 5). However, with increasing soil depth, the soil water content for MS increases and then decreases, and the soil water content for SB does not show large variations with increasing soil depth. In addition, with increasing soil depth, the differences in the soil water contents between the two types of grasslands gradually increase (Fig. 5). The differences in the soil water contents between the artificial and natural grasslands are 0.042 g/g in Semiarid-440a, 0.035 g/g in

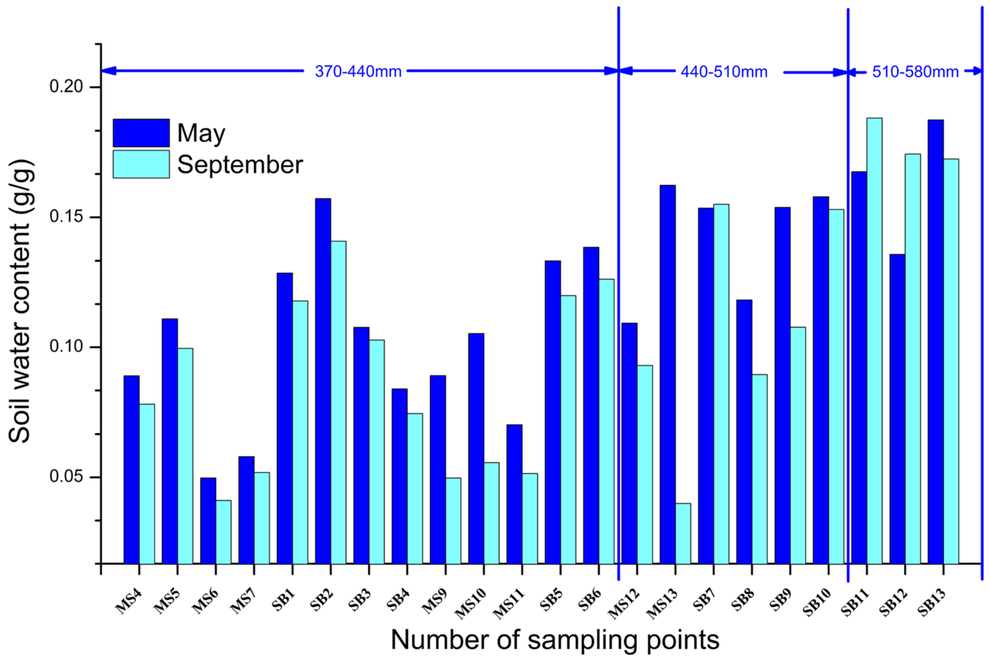


Fig. 3 Mean soil water contents for the sampling points at the beginning (May) and end (September) of the rainy season. Notes: Medi indicates the soil water content under *Medicago sativa* L., and Stip indicates the soil water content under Stipa bungeana Trin. The *blue numbers* above the columns are the multi-year average precipitation

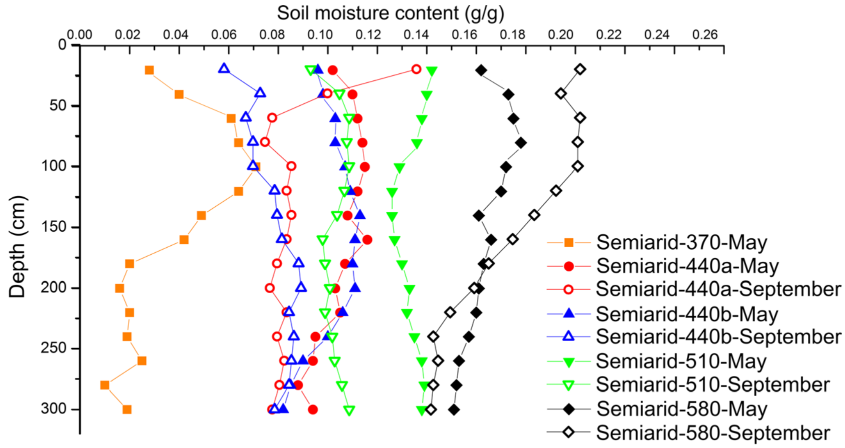


Fig. 4 Vertical distribution of the soil water content under the different precipitation gradients

Semiarid-440b, and 0.027 g/g in Semiarid-510, and the differences in the soil water contents between the two types of grasslands increased by 1.7 % (Semiarid-440a), 128.0 % (Semiarid-440b), and 125.0 % (Semiarid-510). These changes are more obvious in the 0–2-m layer (Fig. 5).

Figure 6 shows that the water contents of the soils above 40 cm for the two types of grasslands change rapidly and shows no obvious patterns; thus, the water contents are presumably influenced by external environmental factors. However, the soil water content below 40 cm during the rainy season is reduced and exhibits apparent differences, with the reduced soil water content gradually decreasing with increasing soil depth in the Semiarid-440a and Semiarid-440b areas, which have less precipitation, and increasing with increasing soil depth in Semiarid-510, which is a precipitation-rich area (Fig. 6a). The reduction in the soil water content for SB grasslands decreases as the multi-year mean precipitation increases, and this reduction is markedly smaller than that of the MS grasslands. The reduction of the soil water content decreases and then increases before finally decreasing again from the top soil layer to a depth of 3 m under SB (Fig. 6b).

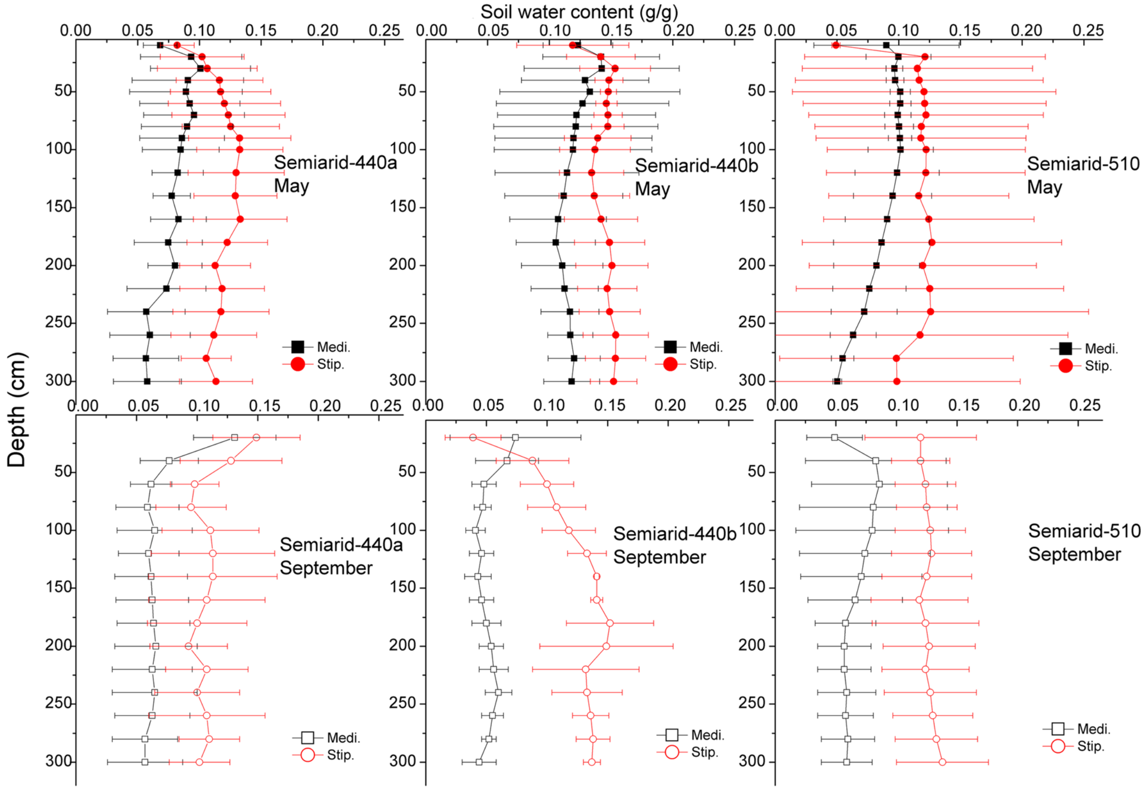
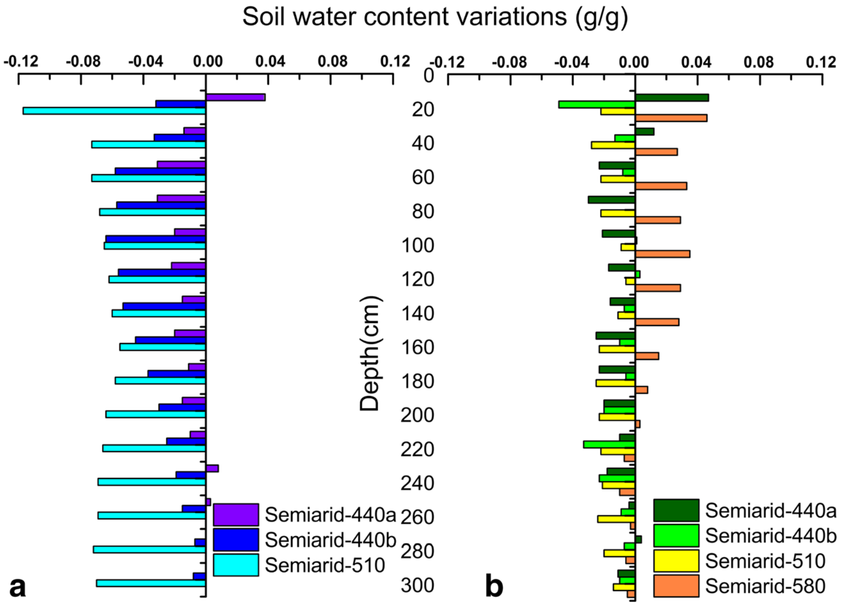


Fig. 5 Soil water content distribution under the natural (Stip.) and artificial (Medi.) grasslands under the different precipitation gradients (*error bars* show the standard errors of the soil water contents at the same depths in the same area). Notes: Medi indicates the soil water content under *Medicago sativa* L., and Stip indicates the soil water content under *Stipa bungeana* Trin

Fig. 6 Variations in the soil water contents under *Medicago sativa* L. (**a**) and *Stipa bungeana* Trin. (**b**) grasslands at different depths and across different areas between the beginning and end of the rainy season



For different soil depths, the correlations between the soil water contents at the beginning and end of the rainy season are different (Table 2). The correlation coefficient for the soil water contents in the 0–20-cm topsoil layer at the beginning and end of the rainy season is the smallest. However, for the soils below 40 cm, there appears to be a strong correlation between the soil water contents at the beginning and end of the rainy season (Pearson's correlation, $P < 0.01$, Table 2). This relationship is more significant in the 0–2 m layer under the SB grassland and in the 2–3 m layer under the MS grassland (Table 2). Overall, the correlation coefficient for the soil water content of the artificial grassland at the beginning and end of the rainy season is the smallest.

Table 2 Correlation coefficients of the soil water contents at different depths at the beginning and end of the rainy season ($N = 22$)

Stipa bungeana Trin.				Depth				
	20 cm	40 cm	60 cm	80 cm	100 cm	120 cm	140 cm	160 cm
Pearson's correlation	0.560*	0.726**	0.699**	0.758**	0.780**	0.692**	0.481**	0.605*
Sig. (2-tailed)	0.046	0.005	0.008	0.003	0.002	0.009	0.096	0.028
	180 cm	200 cm	220 cm	240 cm	260 cm	280 cm	300 cm	Average
Pearson's correlation	0.694**	0.705**	0.524	0.439	0.269	0.453	0.430	0.644*
Sig. (2-tailed)	0.008	0.007	0.066	0.134	0.374	0.012	0.142	0.017
Medicago sativa L.				Depth				
	20 cm	40 cm	60 cm	80 cm	100 cm	120 cm	140 cm	160 cm
Pearson's correlation	−0.096	0.077	0.133	0.087	−0.057	−0.036	−0.023	0.206
Sig. (2-tailed)	0.805	0.844	0.732	0.823	0.884	0.926	0.954	0.595
	180 cm	200 cm	220 cm	240 cm	260 cm	280 cm	300 cm	Average
Pearson's correlation	0.316	0.249	0.432	0.376	0.477	0.441	0.450	0.179
Sig. (2-tailed)	0.407	0.519	0.245	0.318	0.194	0.234	0.224	0.645
Both together				Depth				
	20 cm	40 cm	60 cm	80 cm	100 cm	120 cm	140 cm	160 cm
Pearson correlation	0.349	0.589**	0.581**	0.637**	0.610**	0.630**	0.610**	0.721**
Sig. (2-tailed)	0.111	0.004	0.005	0.001	0.003	0.002	0.003	0.000
	180 cm	200 cm	220 cm	240 cm	260 cm	280 cm	300 cm	Average
Pearson correlation	0.774**	0.768**	0.747**	0.702**	0.684**	0.764**	0.765**	0.641**
Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

3.3 Factors influencing temporal and spatial variations in the soil water content

Based on the data collected at the beginning and end of the rainy season, the correlations between the soil water content and the factors of precipitation, slope, soil bulk density, field moisture capacity, saturated hydraulic conductivity, and mean plant height were subjected to a 2-tailed test using Pearson’s contingency coefficient (Table 3). Table 3 shows that the soil water content is significantly correlated with precipitation, bulk density, and field moisture capacity. Of these factors, the overall soil water content of the SB grassland exhibits a very significant correlation with precipitation and a significant correlation with mean plant height. However, the soil water content of the MS grassland exhibited no significant correlation with mean plant height (Table 3).

The data gradient (Fig. 7) was determined from the RDA of the soil water contents at different soil depths, from the environmental factor data collected at the beginning and end of the rainy season, and using detrended correspondence analysis (DCA), which was performed to verify the species data (length of gradient <3). Figure 7 shows that precipitation levels and soil properties are the main factors that affect soil water content when the effects of vegetation are removed; however, the impacts of slope are not significant. Precipitation has a greater influence on the soil water content in shallow layers, whereas soil properties have a greater influence on the soil water contents in deeper layers (Fig. 7a). However, when the impacts of vegetation are considered, this relationship changes. The type of grassland influences the soil water content at depths below 1 m, and the average height of the grassland has a greater influence at depths of 0–1 m. In addition, the impact of the grassland type and height is even greater than that of the precipitation and soil properties, whereas the impact of slope becomes weaker when vegetation is considered (Fig. 7b).

The variation and rate of variation of the soil water content at the end and beginning of the rainy season can be calculated using Eqs. (3) and (4), and the correlations of these values with the influencing factors were obtained from correlation analyses (Table 4). Table 4 shows that the variations and rates of variation of the soil water content for the 2 types of grasslands under different precipitation gradients exhibit marked differences in their correlations with soil depth, multi-year

Table 3 Correlations between the soil water contents and the influencing factors

	MAP	Pre-2014	Pre-Apr.	Pre-Sep.	Gradient	Height	BD	FC	SHC
Medicago sativa L. (*N* = 23)									
SWC	0.625*	0.657*	0.640*	0.644*	0.401	−0.393	−0.686**	0.622*	−0.418
Pre-2014	0.841**								
Pre-Apr.	0.813**	0.979**							
Pre-Sep.	0.825**	0.998**	0.978**						
Gradient	0.519	0.590*	0.765**	0.592*					
Height	−0.320	−0.218	−0.204	−0.180	−0.437				
BD	−0.791**	−0.746**	−0.802**	−0.738**	−0.562*	0.129			
FC	0.844**	0.636*	0.673**	0.628*	0.498	−0.084	−0.889**		
SHC	−0.739**	−0.526	−0.584*	−0.527	−0.547*	−0.008	0.811**	−0.924**	
Stipa bungeana Trin. (*N* = 26)									
SWC	0.716**	0.634*	0.618*	0.639*	0.106	−0.579*	−0.239	0.564*	0.331
Pre-2014	0.890**								
Pre-Apr.	0.830**	0.986**							
Pre-Sep.	0.905**	0.995**	0.971**						
Gradient	0.065	0.481	0.585*	0.457					
Height	−0.656*	−0.703**	−0.729**	−0.641*	−0.217				
BD	−0.342	−0.476	−0.450	−0.509	−0.470	−0.007			
FC	0.466	0.586*	0.595*	0.544	0.335	−0.609*	−0.557*		
SHC	0.665*	0.444	0.349	0.457	−0.313	−0.333	−0.360**	0.364	

N represents the number of usable samples, *SWC* represents the soil water content, *BD* represents the bulk density, *FC* represents the field capacity, *SHC* represents the saturated hydraulic conductivity, *MAP* represents mean annual precipitation, *Pre-2014* represents the precipitation in the sampling year, *Pre-Apr* represents the precipitation from January to April in the sampling year, and *Pre-Sep* represents the precipitation from May to September in the sampling year

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

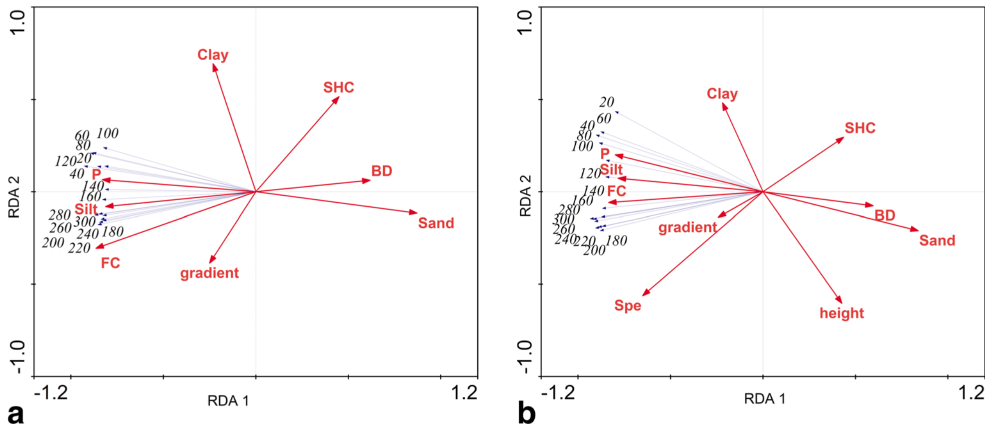


Fig. 7 Redundancy analysis (RDA) of the factors influencing the soil water content when grass is included (**b**) and when grass is not included (**a**). Notes: *BD* represents the bulk density, *FC* represents the field capacity, *SHC* represents the saturated hydraulic conductivity, *gradient* represents the slope, *Spe* represents the species of grass, *height* represents the average height of grass in the plot, *Sand*, *Silt* and *Clay* represent the sand, silt and clay contents, respectively

mean precipitation, soil water content at the beginning of the rainy season, mean plant height, and bulk density of the soil top layer. The variation and rate of variation of the soil water content for the MS grassland at the beginning and end of the rainy season show significant correlations with soil depth, multi-year mean precipitation, soil top layer bulk density, and soil water content at the beginning of the rainy season. For the SB grassland, the variation and rate of variation of the soil water content at the beginning and end of the rainy season do not show obvious correlations with soil depth, multi-year mean precipitation, and soil water content at the beginning of the rainy season; however, significant correlations are observed with the bulk density of the top soil layer, mean plant height, and vegetation coverage (Table 4).

4 Discussion

4.1 Spatial variation of soil water at the regional scale

The soil water content of the top soil layer is primarily influenced by infiltration and evaporation, which are influenced by terrain conditions such as the slope location and gradient, and climate conditions such as seasonal rainfall (Yang et al. 2012).

Table 4 Correlation analysis between the variations and rates of variation of the soil water contents and the influencing factors during the rainy season

Factors	*Medicago sativa* L.				*Stipa bungeana* Trin.			
	Var.	*P* value	C.R.	*P* value	Var.	*P* value	C.R.	*P* value
N/SD	135/0.038		135/0.240		195/0.021		195/0.180	
Depth	−0.288**	0.001	−0.319**	0.000	−0.086	0.230	−0.092	0.199
BD	−0.261**	0.002	−0.263**	0.002	0.216**	0.002	0.256**	0.000
Cover	−0.192*	0.026	−0.142	0.101	0.305**	0.000	0.198**	0.006
Height	−0.056	0.516	0.004	0.966	0.223**	0.002	0.251**	0.000
SWC-May	0.797**	0.000	0.519**	0.000	−0.005	0.947	−0.353*	0.000
Precipitation	0.295**	0.001	0.118	0.174	0.059	0.413	−0.110	0.124
Pre-2014	0.588**	0.000	0.397**	0.000	−0.027	0.707	−0.200**	0.005
Pre-Apr.	0.572**	0.000	0.411**	0.000	−0.069	0.336	−0.241**	0.001
Pre-Sep.	0.584**	0.000	0.396**	0.000	−0.019	0.787	−0.193**	0.007

Var. represents the variation, *C.R.* represents the change rate, *SD* represents the standard deviation, *N* represents the effective number of samples, *BD* represents the bulk density, *Cover* represents the vegetation coverage, and *SWC-May* represents the soil water content at the beginning of the rainy season, *MAP* represents mean annual precipitation, *Pre-2014* represents precipitation in the sampling year, *Pre-Apr* represents precipitation from January to April in the sampling year, *Pre-Sep* represents precipitation from May to September in the sampling year

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

With increasing soil depth, the effect of evaporation on the soil water content decreases, and the effect of transpiration by vegetation increases (Rosenbaum et al. 2012; Yang et al. 2014). In this study, the evapotranspiration of soil water from the top soil layer is significant; the evaporation of soil water decreases and the soil water content increases with increasing depth (Fig. 2). Because of the limited precipitation infiltration depth and the stability of the water consumption by the vegetation roots, the soil water content decreases with further increases in soil depth. The soil water content clearly differs at different depths and in different precipitation areas, and the depth variations corresponding to each type of vegetation are consistent (Table 1, Fig. 4 and Fig. 5). In Semiarid-510, the soil water content increases, decreases and then increases again with depth, and these contents are significantly higher than those in Semiarid-370, Semiarid-440a, Semiarid-440b, and Semiarid-580. Moreover, the precipitation in this area allowed the soil water contents in the shallow layers to meet the demands of the grasses for water; therefore, the soil water content at depths of more than 2 m began to recover to the original values. The variation of the soil water contents in the top soil layers is large and becomes constant with increasing soil depth, and the effects of topography on the soil water content also vary with increasing soil depth (Huang et al. 2013; Qiu et al. 2001; Sun et al. 2014). For example, a study of a hummocky landscape in Canada indicated that the effects of topography on the soil water content increase and then decrease with increasing depth (Hu and Si 2014).

According to regional studies of the soil water content of the Loess Plateau, Semiarid-370 belongs to an imbalanced compensation soil moisture zone, Semiarid-440a belongs to a low-consumption soil moisture zone, Semiarid-440b and Semiarid-510 belong to a periodic deficiency soil moisture zone, and Semiarid-580 belongs to a balanced compensation soil moisture zone (Yang et al. 1994). With increases in the multi-year mean precipitation, the effect of land use type on the soil water content becomes more pronounced in the semi-humid and humid areas (Wang et al. 2011a). The correlation coefficients reveal that variations in the soil water content at the beginning of the rainy season are small in areas with low multi-year mean precipitation. With increases in the multi-year mean precipitation, the coefficient of variation for the MS grassland first increases and then decreases, whereas the coefficient of variation for the SB grassland increases and then decreases before subsequently increasing again (Table 1). At the end of the rainy season, considerable amounts of evaporation and transpiration result in consistently low soil water contents in the areas with light precipitation (Table 1). In the areas with abundant precipitation caused by physiological characteristics, such as the water demands of vegetation and differences among plants, varying effects on the soil water content gradually emerge. Semiarid-440a and Semiarid-440b are located in the same precipitation gradient zone. Although these areas are located far apart, the precipitation and soil water contents in these areas are not obviously different. The regional soil water content markedly increases as the multi-year mean precipitation and the precipitation during the sampling year increase (Fig. 2, Table 1). The soil water content under MS is more strongly correlated with the precipitation during the sampling year, while the soil water content under SB is more strongly correlated with mean annual precipitation. During the sampling year, the soil water content distribution is impacted more by the precipitation that occurs on the sampling days (from May to September) than by the precipitation that occurs before the sampling days (from January to April), and the rate of change of the soil water content between the beginning and end of the rainy season is impacted more by the precipitation that occurs before the sampling days (Table 3, Table 4).

4.2 Changes in soil water content during the rainy season

A slight variation in the vertical distribution of soil water moisture is present because the temperature at the beginning of the rainy season remains low and the growth of vegetation is slow. The status of the soil water content may be representative of the relatively stable state of the Loess Plateau (Chen et al. 2007). Topography affects the soil water content at the beginning of the rainy season only in the top soil layer (0–20 cm) and affects the entire soil profile at the end of the rainy season (Wang et al. 2014a). Studies have found that the rainy season helps increase the overall soil water contents in slopes. However, if the soil water content is high at the beginning of the rainy season, it will remain relatively high at the end of the rainy season, and the relative spatial distribution pattern of the soil water content does not change with the slope. In addition, the spatial distribution pattern of the soil water content is more stable in the deep soil than in the top layers of soil and shows temporal stability (Yao et al. 2012b).

In contrast to findings by previous researchers, the soil water content at the end of the rainy season is less than that at the beginning, except in Semiarid-580. The likely explanations for this result are numerous. First, the balance between precipitation and water uptake may change with the increasing precipitation. In our study, soil water from precipitation can meet the consumption of natural grassland when the mean annual precipitation is greater than 510 mm. If precipitation increases constantly, which occurs in some humid areas, this relationship may change again. Second, extreme precipitation occurred in the study areas in 2013, and long continuous precipitation resulted in much higher soil water contents at the beginning of the 2014 rainy season than in previous years (Huang et al. 2014a; Huang et al. 2014b; Yan 2014). Third, in the available studies, sampling was mainly performed in June and October (Yao et al. 2012b). At the beginning of June, vegetation grows rapidly in the study area, and water consumption is therefore high. Because the temperature decreases, the growth of vegetation slows in October, and consequently, precipitation has a much larger compensation effect on the soil water content. However, in the present study, sampling was performed in May, which is the start of the growing season and corresponds with a period of low water consumption. At the end of the rainy season, sampling was performed in September, which is a period of high water consumption. Therefore, the results of this study are different from those of previous studies. The changes in the soil water content over the entire growing season can be described by combining the results of previous studies with the results of our study. Such a combination shows that the soil water content begins to decrease as grass begins to grow (May), and the speed of this decrease becomes more rapid with the acceleration of grass growth (June to September). Next, the soil water content gradually recovers as the grass begins to wither (October) during normal years in the Loess Plateau.

A study conducted on the Chinese Loess Plateau shows that land use may also affect the infiltrability of soil and that the soil hydraulic conductivity is higher in the SB field than in the MS field (Hu et al. 2009). Existing studies have shown that an infiltration depth of 1–2 m for annual precipitation is typical in semiarid areas (Ferriera et al. 2007; Wang et al. 2013; Yang et al. 2014). In our study, the soil water content under SB is higher than under MS, and the differences between them are greater below a depth of 2 m than at a depth of 0–2 m. Thus, the higher soil water contents under SB potentially occurred due to the higher infiltrability and lower consumption at the depth of 0–2 m, while the soil water content changes below 2 m are potentially impacted more by plant consumption.

4.3 Factors that influence soil water content variations

Variations in soil water contents are influenced by many factors and show scale effects. Researchers have argued that the drying of the soil in the Loess Plateau is caused by climate warming (Yang et al. 1999; Wang et al. 2011b), whereas others attribute this effect to unreasonable vegetation restoration (Li and Shao 2001). Studies in other countries have yielded different conclusions, which suggests that the effects of various types of land use on the soil water content are not important (Venkatesh et al. 2011). Small-scale studies have confirmed that the effect of precipitation on the soil water content is negligible compared with the effect of vegetation. In addition, the reduction of the soil water content is often small when the decrease of precipitation is large (Yao et al. 2012a). However, at the regional scale, precipitation is mainly responsible for soil water content variations. Although the degree of the correlation between soil water content and precipitation is different for different types of grasslands, the investigated correlations are all significant (Table 3). The soil physical indices, such as bulk density and the saturated hydraulic conductivity, and the soil ecological indices, such as plant height, are significantly correlated with precipitation; however, the correlation of these indices with the soil water content exhibits significant differences at different soil depths in the two types of grassland (Table 3, Fig. 7). The linear gradient RDA reveals that the correlation between the soil moisture and multi-year precipitation levels is weak in certain layers, such as the 40–160 cm soil layer under MS and the 20–120 cm soil layer under SB. However, the soil moisture and multi-year precipitation levels show a strong negative correlation with plant height, which indicates that deeper soil depths are responsible for more water consumption by plant roots. Thus, the effects of the slope gradient on the soil water content are masked by precipitation and vegetation factors. However, a strong correlation is always exhibited between the field moisture capacity and the soil water content (Fig. 7). Therefore, in the large-scale vegetation restoration process for the Loess Plateau, the effects of topographical factors are not evident at the regional scale; however, precipitation and vegetation type are equally important factors worthy of serious consideration.

4.4 Ecological restoration for grasslands

The historical data and a report by the Intergovernmental Panel on Climate Change (IPCC) show that the mean precipitation will decrease in the future in dry areas at mid-latitudes and that extreme precipitation events will become more violent and frequent (Pachauri and Reisinger 2007; Shen and Wang 2013; Stocker et al. 2013; Sun et al. 2013). These changes will considerably affect the growth of vegetation in the Loess Plateau (Lü et al. 2014; Feng et al. 2015; Yao et al. 2005a). Reasonable designs for future Loess Plateau eco-construction represent a crucial element for addressing climate and environmental changes (Yao et al. 2005b; Xin et al. 2007; E et al. 2011; Vose et al. 2011; Wang et al. 2011b; Li et al. 2012; Lu et al. 2014b; Qin et al. 2014; Wang et al. 2014b).

MS is a high-quality forage crop that has high productivity and strong adaptability. This species grows best in northeastern China, which contains more than 78 % of the country's artificial pasture area. However, because of its high productivity and high water consumption, the potential for the sustainable growth of MS under the limited precipitation conditions that occur in the Loess Plateau is poor (Cheng et al. 2011). Water cannot infiltrate below a depth of 2 m during the growth period of perennial soybeans in artificial grasslands, which leads to the formation of a dry layer due to the consumption of water by vegetation (Dietz and Fattorini 2002). Based on the actual conditions, soybean vegetation can be properly cultivated to yield economic benefits. However, the cultivation and time scales must be controlled because this vegetation is usually rotated to gramineous plants in less than 7 years (Li

2002; Zhao et al. 2004; Li et al. 2006; Jia et al. 2009; Cheng et al. 2011). Direct abandonment in areas with extremely scarce water will reduce vegetation coverage within a certain period of time and potentially accelerate water and soil loss. Therefore, human interventions must be implemented to prevent such losses. Because areas with extremely low water availability are mostly pastoral areas, pasture rotation should be implemented. In the selection of artificial grass types, it is appropriate to decrease the amounts of high water-consuming crops, such as MS, in favor of grasses with fine palatability, good adaptability, and low water consumption.

5 Conclusions

The soil water contents in the grasslands in the sampling areas largely vary in the horizontal and vertical directions. In the horizontal direction, the soil water content markedly increases with increasing multi-year mean precipitation at the beginning of the rainy season, and this trend becomes less pronounced at the end of the rainy season. Relative to the soil water content in the natural grassland at the beginning of the rainy season (May), the percentages of the soil water contents of the artificial grasslands are 63.2 (Semiarid-440a), 69.7 (Semiarid-440b), and 81.3 (Semiarid-510) and decrease to 59.0 (Semiarid-440a), 39.3 (Semiarid-440b) and 51.5 (Semiarid-510) at the ending of the rainy season (September). MS consumes more water and is more adaptable than SM to variations in precipitation and initial soil water content. In the vertical direction, the soil water contents are 58.1 % (Semiarid-370), 7.3 % (Semiarid-440a), 1.0 % (Semiarid-440b), 0.9 % (Semiarid-510), and 4.2 % (Semiarid-580) higher in the 0–2 m soil layer than in the 2–3 m layer. The difference between the soil water contents in the two types of grasslands increases with increasing soil depth at the beginning of the rainy season. However, this difference is not significantly correlated with soil depth at the end of the rainy season. For soils deeper than 40 cm, a significant correlation is observed between the soil water content at the end and beginning of the rainy season. MS absorbs and uses more soil water from the deep soil layers than SB.

Precipitation and grassland type are the main factors responsible for the significant variations of the soil water contents observed between the different areas at the regional scale. However, the contributing topographical factors in previous studies considering smaller scales do not exhibit obvious effects at the regional scale. The sensitivity of artificial grasslands to precipitation and soil water content is higher than that of natural grasslands. In areas with multi-year precipitation of 370–440 mm, natural grass is more suitable for restoration, and such areas should be treated as key areas for vegetation restoration. Therefore, under the background of future climate change in the Loess Plateau, vegetation restoration plans must consider the ecological, economic, and societal benefits and attempt to find a balance among these factors to implement sustainable environmental development that can support human populations.

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