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Soil water content and temporal stability in an arid area with natural and planted grasslands

Ze Huang[1,2*] | **Hai-Tao Miao**[2*] | **Yu Liu**[1,2] | **Fu-Ping Tian**[3] | **Honghua He**[2] | **Weibo Shen**[2] | **Manuel López-Vicente**[4] | **Gao-Lin Wu**[1,2,3]

[1] Breeding Base for State Key Laboratory of Land Degradation and Ecological Restoration in Northwest China, Key Laboratory for Restoration and Reconstruction of Degraded Ecosystem in Northwest China of Ministry of Education, Ningxia University, Yinchuan, China

[2] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, China

[3] Lanzhou Institute of Husbandry and Pharmaceutical Sciences, Chinese Academy of Agricultural Sciences, Lanzhou, China

[4] Department of Soil and Water, Experimental Station of Aula Dei, Estación Experimental de Aula Dei-Consejo Superior de Investigaciones Científicas, Zaragoza, Spain

Correspondence
Gao-Lin Wu, State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, Shaanxi 712100, P.R. China.
Email: gaolinwu@gmail.com; wugaolin@nwsuaf.edu.cn

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Abstract

Soil water content (SWC) is a key factor for successful vegetation restoration in arid and semiarid regions, and vegetation has significant influences on the spatial patterns and temporal dynamics of SWC. The aim of this study was to investigate the temporal stability of SWC under different restored grasslands in an arid hilly area of Central China. SWC was measured in the 0- to 300-cm soil profile in the natural grassland (*Stipa capillata*) and three typical planted grasslands (*Medicago sativa*, *Agropyron cristatum*, and *Caragana korshinskii*) over two growing seasons (from June to October 2015 and 2016) under natural rainfall conditions. The results showed that the mean SWC in the natural grassland was approximately 30% higher than those in the planted grasslands. The SWC consumption of the planted legume grasslands in the deepest soil layers (below 200 cm) was higher than that of the natural grassland, owing to the deep root system of the legumes. Both natural and planted grasslands had low SWC temporal stability in the top soil layers (0–50 cm), whereas more stable conditions were gradually observed with increasing the soil depth. The mean value of the mean relative differences of SWC in natural grassland (ca. 15%) was lower than that in the planted grasslands (*A. cristatum* grasslands) and much lower than that in the scrubland, highlighting the stronger temporal stability of SWC in the natural grassland. In conclusion, natural grassland could maintain higher and stable SWC and is recommended to be used for achieving sustainable vegetation restoration in arid and semiarid regions.

KEYWORDS
arid areas, gramineous grassland, legume grassland, root, soil water storage, temporal stability

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[*] These authors contributed equally to this work.

1 | INTRODUCTION

Land degradation is a serious ecological problem in arid and semiarid regions (Gisladottir & Stocking, 2005). Soil erosion, cultivation of marginal lands, and destruction of native vegetation are three of the major causes of land degradation (Lei, Yu, Zhuang, & Zhang, 2016). In the last decades, a great deal of efforts has been made in restoring vegetation to control land degradation and improve the ecological environment in China (Chen, Huang, Gong, Fu, & Huang, 2007; Chen, Shao, & Li, 2008). Grasslands are one of the largest ecosystems in the world and play an important role in vegetation restoration (Zhang, Zhao, Liu, Fang, & Feng, 2016). Besides, recent studies have suggested that grasslands have higher values of soil water content (SWC), whereas scrublands and forests present drier conditions at deeper soil layers in dry lands (Wang, Wang, Fu, Yang, & Li, 2017). Precipitation is the sole source of soil water replenishment in arid and semiarid regions; improper planting patterns can aggravate water scarcity and strongly influence the growth and natural succession of vegetation (Porporato, D'odorico, Laio, Ridolfi, & Rodriguez-Iturbe, 2002; Wilcox & Newman, 2005; Shangguan & Zheng, 2006; Chen et al., 2008; Feng et al., 2016). Restoration with improper vegetation species would accelerate the consumption of soil water, especially in arid and semiarid regions where precipitation is generally much less than evapotranspiration (Cheng, Huang, Shao, & Warrington, 2009). Jia, Shao, Zhu, and Luo (2017) reported that planted vegetation can aggravate soil desiccation, which threatens the success of vegetation restoration. Hence, the choice of appropriate species is a key aspect in grassland restoration plans.

The dynamics of SWC have an important effect on vegetation restoration (Wang, Wedin, Franz, & Hiller, 2015), whereas the distribution and density of plants also influence the spatial variation of SWC (van Wesemael, Cammeraat, Mulligan, & Burke, 2003; Zucco, Brocca, Moramarco, & Morbidelli, 2014). The available SWC and its distribution are affected by the interaction between the environment and plants (Wilcox & Newman, 2005). Therefore, it is crucial to understand the spatial patterns of SWC and the temporal stability of these patterns after vegetation restoration (Zhang et al., 2016). The proper practice for vegetation restoration appears as an open question that must be based on the state of the local ecological conditions.

More than 30 years ago, Vachaud, Silans, Balabanis, and Vauclin (1985) first indicated that the rank of SWC changed slightly over time. Recently, many studies have found that the spatial patterns of SWC are stable in the medium and long term for a specific site, land use, and soil and vegetation management practices (Ben-Salem, Álvarez, & López-Vicente, 2018; Hu, Shao, Han, Reichardt, & Tan, 2010; López-Vicente, Quijano, & Navas, 2015; Zhang & Shao, 2017; Zucco et al., 2014). For instance, Xu et al. (2017) indicated that the spatial patterns of SWC in Chinese land terraces had a strong temporal stability during the rainy season. Zhao, Jia, Zhu, and Shao (2017) recommended the use of plant species that have stronger stability and cause higher SWC for vegetation restoration. Therefore, understanding the temporal and spatial distributions of SWC is very important for successful vegetation restoration (Mcvicar et al., 2010). Wang, Fu, Gao, Liu, and Zhou (2013) highlighted that the studies on the temporal and spatial variations of SWC in different grassland types are the basis of grassland restoration and rehabilitation in arid and semiarid areas. Vegetation directly affects soil water inputs through precipitation partitioning by plant canopies (Marin, Bouten, & Sevink, 2000). In addition, shallow-rooted plant species only influence soil water dynamics in the shallow soil layers, whereas species with deep roots take up water from deeper soil layers when water is depleted in the shallow soil layers (Schwinning & Sala, 2004). Therefore, transpiration is usually higher in plant communities with deep roots (Moran et al., 2009; Porporato, Laio, Ridolfi, & Rodriguez-Iturbe, 2001).

To achieve sustainable restoration in arid and semiarid environments, it is important to understand the relationship between vegetation patterns and SWC dynamics. Although many studies have analysed the responses of soil water with different vegetation types to rainfall in arid areas (e.g., Chen et al., 2007; Wang et al., 2013), the stability of the patterns of SWC with different plant species in grasslands under natural rainfall conditions warrants further study. In this study, we first investigated the effects of three typical grassland species and one scrub species on the vertical and temporal dynamics of SWC in the 0- to 300-cm soil profile in an arid region (on the Chinese Loess Plateau). Second, the potential factors influencing the temporal stability of SWC were evaluated. The results of this study can provide an empirical basis for designing proper grassland restoration plans in arid and semiarid regions.

2 | STUDY AREA, METHODS, DATA, AND ANALYSIS

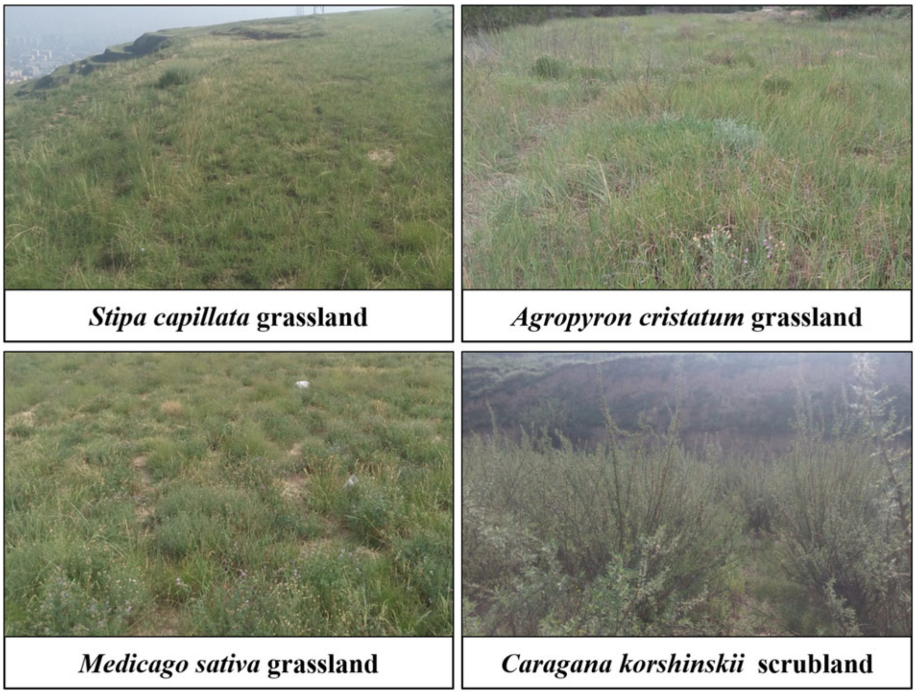
2.1 | Study area

This study was conducted at the Key Field Observation Station of the Ecological Environment of the Chinese Ministry of Agriculture (36°01′ N; 103°45′E). This site is located on the Loess Plateau at an elevation of 1,823 m asl and is part of the arid hilly and gully region. The mean annual temperature is 9.3°C, with a minimum of −23.1°C recorded in January and a maximum of 39.1°C registered in July. The annual mean precipitation is 324.5 mm with a humid period between July and September. The annual evaporation is approximately 1,450.0 mm. The mean annual frost-free period lasts approximately between 135 and 167 days.

The major soil type in the study area is loessial soil, and the field capacity of the soil ranges between 19% and 23%. The groundwater level is deeper than the root system of the vegetation, and thus rainfall is the sole source of soil water replenishment. There is no water percolating in the study area. The topography is flat, and no surface run-off was observed. As reported by Bhark and Small (2003), canopy interception loss is not obvious in grasslands, and it is consumed through evaporation. Therefore, we considered that precipitation, plant consumption, and evapotranspiration were the main factors influencing SWC (Chen et al., 2008). The natural grassland (NG) ecosystem in this area is dominated by *Stipa capillata* Linn. Since 2002, the abandoned land has been primarily planted with three species, that is, *Caragana korshinskii* Kom., *Medicago sativa* L., and *Agropyron cristatum* L.

2.2 | Field experiment and data analysis

On the basis of the common species in the study area, three typical planted species and one NG were selected, and the characteristics of the soil water variation were investigated under natural rainfall conditions (Figure 1). The planted species were *M. sativa*, *A. cristatum*, and



Stipa capillata grassland

Agropyron cristatum grassland

Medicago sativa grassland

Caragana korshinskii scrubland

FIGURE 1 Pictures of the studied *Stipa capillata*, *Agropyron cristatum*, and *Medicago sativa* grasslands and *Caragana korshinskii* scrubland

C. korshinskii, and the plantation was completed in 2002. The dominant species of the NG was *S. capillata*. *M. sativa* and *C. korshinskii* are leguminous species, whereas *A. cristatum* and *S. capillata* are gramineous species. The planted grassland (PG) and NG are close together in the study area, so the differences in precipitation and other hydro-climatological factors can be ignored.

The experiment was carried out from June to October 2015 and from April to October 2016. SWC was measured by using the soil-drilling method. Soil samples were collected in the 0- to 300-cm profile at 10-cm intervals. For each grassland and scrubland, three parallel plots (10 × 10 m) were set, and three sampling points were randomly taken from each plot, yielding a total of nine sampling point for each grassland per month (1,080 soil samples per month). All soil samples were immediately weighed after sampling and then reweighed after oven drying at 105°C for 48 hr.

Below-ground biomass was measured by using a 9-cm diameter root auger to collect samples in the 0- to 100-cm soil profile at 10-cm intervals. Three parallel sampling points were set at each plot, and the final sample was a mixture of the three samples from the same soil layer. In the laboratory, roots were separated from the soil with a 2-mm sieve, and the separated roots were washed with water to remove soil particles and oven dried at 75°C for 72 hr.

The soil water steady-state infiltration rates of different grasslands were measured using an automatic soil infiltrability measurement system (Huang, Tian, Wu, Liu, & Dang, 2017; Mao et al., 2016; Wu et al., 2016b). Three parallel measurements were done for each grassland type. Soil bulk density for the 0- to 100-cm depth was determined using a stainless steel cutting ring of 5-cm diameter and 5-cm height (98.2 cm^3). Soil bulk density below the depth of 100 cm was considered to be the same as that at the depth of 90–100 cm. The volumetric SWC ($\mathrm{cm}^3\ \mathrm{cm}^{-3}$) was calculated as follows (Gao, Fan, Peng, Wang, & Mi, 2014):

$$\mathrm{SWC} = h \times \theta \times BD \times 10^{-1}. \quad (1)$$

where *h* is the soil depth (cm), θ is the gravimetric SWC (% of weight), and *BD* is the soil bulk density ($\mathrm{g\ cm}^{-3}$).

The most common method for analysing temporal stability of SWC is based on the relative difference (RD). The analysis of RD can be used to estimate the positive or negative bias of SWC during each field survey. The RD was calculated as follows (Liu & Shao, 2014; Vachaud et al., 1985; Wang et al., 2015):

$$\mathrm{RD}_{ij} = \frac{\mathrm{SWC}_{ij} - \overline{\mathrm{SWC}_j}}{\overline{\mathrm{SWC}_j}}, \quad (2)$$

where RD_{ij} is the deviation of SWC at depth *i* from the mean SWC at the sampling time *j*, SWC_{ij} is the SWC at depth *i* and the sampling time *j*, and $\overline{SWC_j}$ is the mean SWC of 0- to 300-cm soil profile at each grassland during the sampling time *j*. The mean SWC was computed as follows:

$$\overline{\mathrm{SWC}_j} = \frac{1}{n}\sum_{i=1}^{n}\mathrm{SWC}_{ij}, \quad (3)$$

where *n* is the total number of sampling layers at the sampling time *j*, and in this study, *n* was equal to 30.

The mean relative difference (MRD) and its standard deviation of relative difference (SDRD) at depth *i* and sampling time *j* were calculated as:

$$\mathrm{MRD}_i = \frac{1}{m}\sum_{j=1}^{m}\mathrm{RD}_{ij}, \quad (4)$$

$$\mathrm{SDRD}_i = \sqrt{\frac{1}{m-1}\sum_{j=1}^{m}\left(\mathrm{RD}_{ij} - \mathrm{MRD}_i\right)^2}, \quad (5)$$

where *m* is the total number of sampling times. The lower the difference (positive or negative) between SWC_{ij} and $\overline{SWC_j}$, the closer MRD is to zero value, the lower SDRD is. Low values of SDRD correspond to high temporal stability, whereas high values of SDRD are associated with low temporal variability (Ben-Salem et al., 2018; López-Vicente & Álvarez, 2018). The statistical descriptive analyses and one-way ANOVA, Least Significant Difference (LSD) tests were conducted using the SPSS 18.0 software. All figures were created using Revolution R Enterprise 8.0 (Microsoft Corporation R version 3.2.2 2015) and OriginPro 2015.

3 | RESULTS

3.1 | Rainfall characteristics

During the observation period, rainfall events mainly occurred from July to September in 2015 and 2016 (Figure 2). The annual precipitation in 2015 (241.5 mm) was 34% lower than that in 2016 (367.6 mm). Most of the rainfall and daily maximum rainfall (>30 mm day^{-1}) occurred in September 2015 and July 2016.

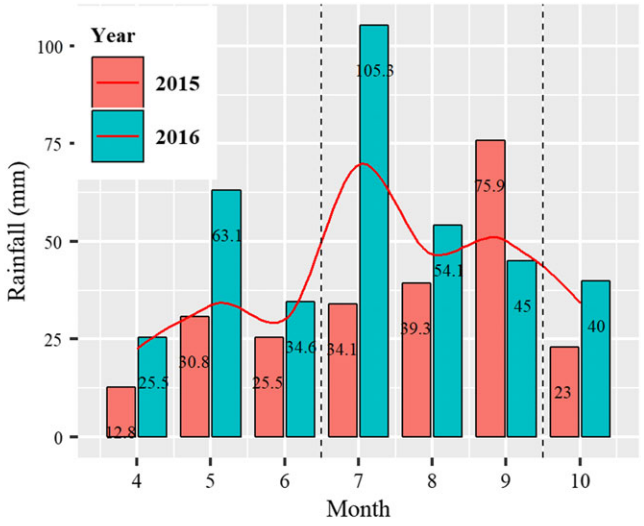


FIGURE 2 Rainfall distribution from April to October in 2015 and 2016. The red curve represented the mean value of monthly rainfall of 2015 and 2016

3.2 | Temporal and spatial changes of SWC in the soil profile

Lower SWC was observed in the plots with *C. korshinskii* scrubs at the depth of 0–100 cm and 200–300 cm compared with the values measured at 100–200 cm. The SWC of *C. korshinskii* scrubland showed an increasing and then decreasing trend with the increasing soil depth. However, SWC was lower below the 100-cm soil depth in the *M. sativa* grassland (Figure 3). Additionally, SWC was higher in *A. cristatum* and *S. capillata* grasslands, with relative lower values observed at the depth of 150–300 cm and 150–220 cm, respectively (Figure 3). Compared with *C. korshinskii* scrubland and *M. sativa* grassland, SWC of *A. cristatum* and *S. capillata* grasslands in the top soil layer (0–100 cm) was higher. Moreover, in the *C. korshinskii* scrubland and the *M. sativa* and *A. cristatum* grasslands, SWC below the 100-cm soil layer reached a relatively stable level (Figure 3). We also found that the mean SWC (±standard deviation) in the 0- to 300-cm soil layers of *S. capillata* grassland (6.37 ± 1.09 cm^3 cm^{-3}) was significantly higher than that in the *A. cristatum* grassland (6.18 ± 0.82 cm^3 cm^{-3}), which was followed by the *C. korshinskii* scrubland (5.06 ± 0.63 cm^3 cm^{-3}) and the *M. sativa* grassland (4.95 ± 0.72 cm^3 cm^{-3}; Figure 4, $P < 0.05$).

3.3 | The temporal stability of SWC

The variation range of MRD was −22–10% in the *C. korshinskii* scrubland, −8–5% in the *M. sativa* grassland, −10–21% in the *A. cristatum* grassland, and −11–9% in the *S. capillata* grassland. The mean MRD were 1.64%, 0.39%, 0.44%, and 0.39% in the *C. korshinskii* scrubland

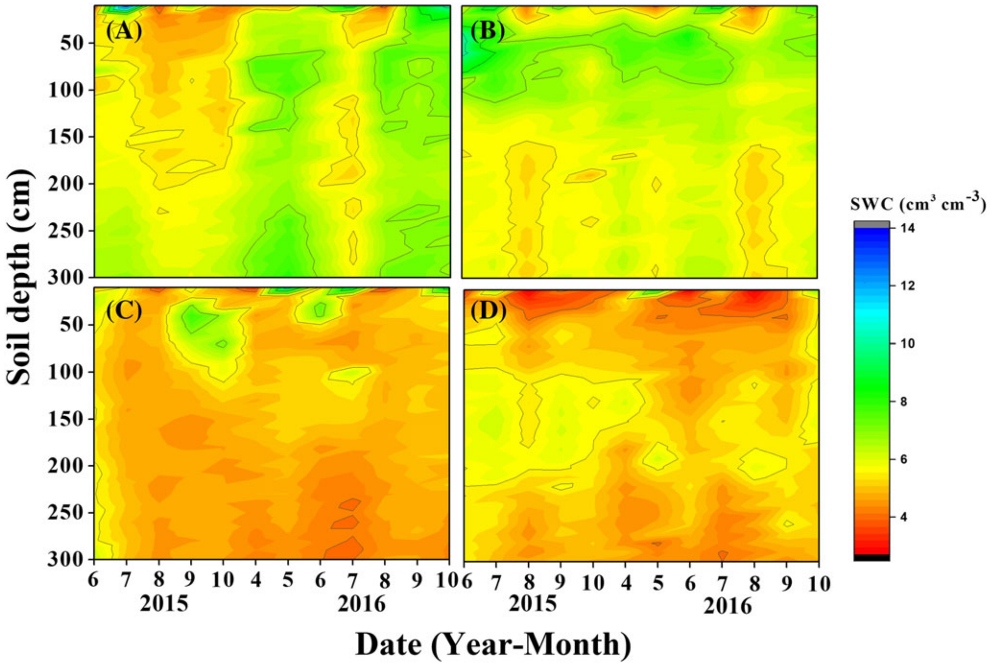


FIGURE 3 Time series of soil water content at different soil depth in (a) *Stipa capillata*, (b) *Agropyron cristatum*, and (c) *Medicago sativa* grasslands and (d) *Caragana korshinskii* scrubland under natural rainfall conditions during the study period (from June to October 2015 and April to October 2016)

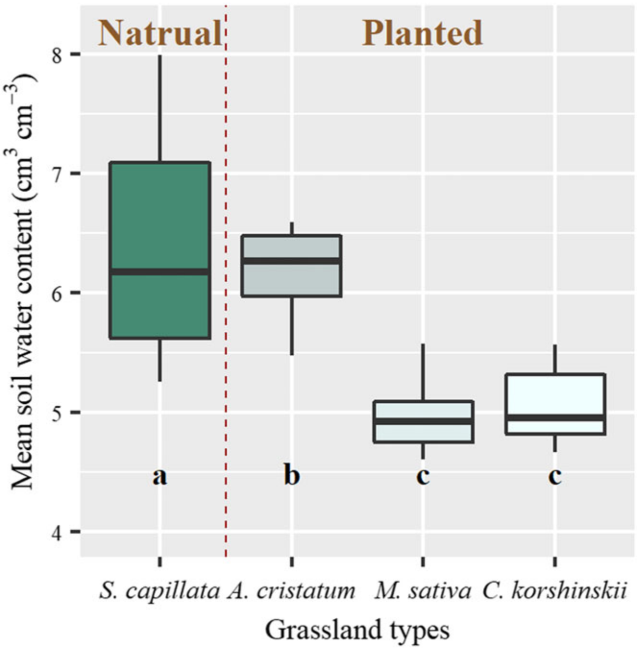


FIGURE 4 Mean soil water content within the whole study period (from June to October 2015 and April to October 2016) at different soil depth in *Stipa capillata*, *Agropyron cristatum*, and *Medicago sativa* grasslands and *Caragana korshinskii* scrubland. *S. capillata* grassland was natural grassland, whereas *A. cristatum* and *M. sativa* grasslands and *C. korshinskii* scrubland were artificially planted. Different lower case letters below the bars indicate significant differences between grassland types at the 0.05 level

and *M. sativa*, *A. cristatum*, and *S. capillata* grasslands, respectively. Among them, SWC of *M. sativa* and *S. capillata* grasslands showed better temporal stability than the others. Additionally, the MRD was higher at the 0- to 40-cm and 110- to 200-cm depth in the *C. orshinskii* scrubland, whereas it decreased with increasing soil depth in *A. cristatum* and *S. capillata* grasslands. Compared with the *C. korshinskii* scrubland and *M. sativa* grassland, the temporal stability of SWC was lower in the 0- to 50-cm soil layers in *A. cristatum* and *S. capillata* grasslands (Figure 5).

3.4 | Below-ground biomass distribution and infiltration rates

Below-ground biomass distributions of all grasslands and scrubland decreased markedly with increasing soil depth, and there were significant differences among different grassland types (Figure 6, $p < 0.05$). Below-ground biomass of *M. sativa* grassland and *C. korshinskii* scrubland was mainly distributed in the 0- to 60-cm soil layers, whereas in the *A. cristatum* and *S. capillata* grasslands, it was mainly distributed in the 0- to 30-cm soil layers. Moreover, approximately 80% of the total below-ground biomass appeared in the 0- to 100-cm soil layers in different grasslands. There was significantly more below-ground biomass in the *M. sativa* and *A. cristatum* grasslands and the *C. korshinskii* scrubland than in the *S. capillata* grassland at the depth of 50–80 cm (Figure 6; $p < 0.05$).

The steady-state infiltration rate in the *M. sativa* grassland (28.67 ± 6.90 mm h^{-1}) was significantly higher than that in the *S. capillata* grassland (16.60 ± 1.11 mm h^{-1}; Figure 7; $p < 0.05$). The infiltration rates in the *A. cristatum* grassland (20.27 ± 4.24 mm h^{-1}) and the *C. korshinskii* scrubland (21.00 ± 2.42 mm h^{-1}) were approximately 20% lower than that in the *M. sativa* grassland, but there was no significant difference in the infiltration rate between the *A. cristatum* grassland and the *C. korshinskii* scrubland.

4 | DISCUSSION

Although precipitation was the only source of water for soil water supplementation, most of the precipitation was insignificant for significant SWC changes in the long term, because most of the rainfall was consumed by the plants and lost by evaporation and transpiration. Effective rainfall events (>10 mm) led to different water distributions in the soil profiles with different plants and were associated with the utilization of water at different depths (Schwinning & Sala, 2004). In this study, SWC was lower in the three PGs than in the NG along the soil profile, especially below the 200-cm soil depth. Such trend suggested that PGs can transpire deeper soil water that was accessed by the roots in comparison with the NG, and such result is more obvious for the planted legume grasslands. Our results showed that the mean SWC was lower in the legume grasslands than in the gramineous grasslands and agreed with those of Jia and Shao (2013), who suggested that legume species (*C. korshinskii* and *M. sativa* grasslands) can consume more soil water from deeper soil layers owing to their deep roots distribution. A previous study has demonstrated that the rainfall infiltration was higher in the interspaces than beneath the canopies in the smallest events (Bhark & Small, 2003); but the infiltrated water was only stored in the top soil layers, which would be rapidly consumed by evaporation in arid and semiarid regions (Chen et al., 2008). Thus, soil water variation is mainly influenced by transpiration and evaporation (Wilcox, 2002), and it depends upon the distribution of plant roots (Lauenroth & Bradford, 2006). The differences in SWC and the water portion in the soil profile between different vegetation types were mainly influenced by root distribution and rooting depth (Cheng et al., 2009; Fu, Wang, Chen, & Qiu, 2003; Schenk & Jackson, 2002; Yang, Wei, Chen, Chen, & Wang, 2014a). A previous study indicated that root water uptake is related to root biomass, and thus soil water consumption would increase with increasing root biomass during the summer drought (Li, Zhao, Song, Sheng, & Zhu, 2010). However, legume grasslands had higher below-ground biomass than gramineous grasslands (Wu, Liu, Tian, & Shi, 2016a). Our study also showed that the below-ground biomass was mainly concentrated at the depth of 0–60 cm for the legume grasslands and 0–30 cm for the gramineous grasslands. Because the majority of roots were found at such depths, there was more soil water consumption and lower SWC at these depths (Cheng et al., 2009; Fu, Huang, Gallichand, & Shao, 2012).

Infiltration rates also played an important role in SWC (Cheng et al., 2009). Grasslands with higher below-ground biomass would improve the infiltration rate (Wu, Yang, et al., 2016b). The steady-state infiltration rate of the NG was lower than those of the PGs (Huang et al., 2017). However, less precipitation weakened the advantage of artificial grasslands resulting from their higher water consumption, which led to lower SWC than that in the gramineous grasslands along the soil profile.

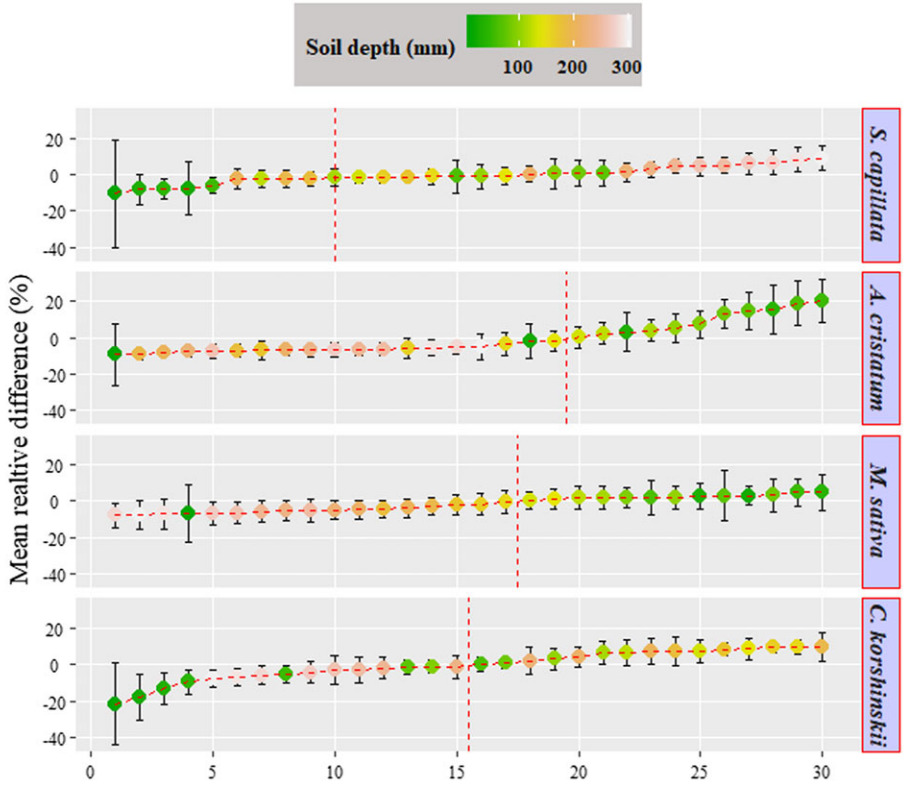


FIGURE 5 Ranked mean relative differences (MRD) of soil water content in the 0- to 300-cm soil layers in *Stipa capillata*, *Agropyron cristatum*, and *Medicago sativa* grasslands and *Caragana korshinskii* scrubland. Error bars were the standard deviation of relative difference (SDRD). The closer to zero values of MRD and lower SDRD indicate the stronger temporal stability of soil water content

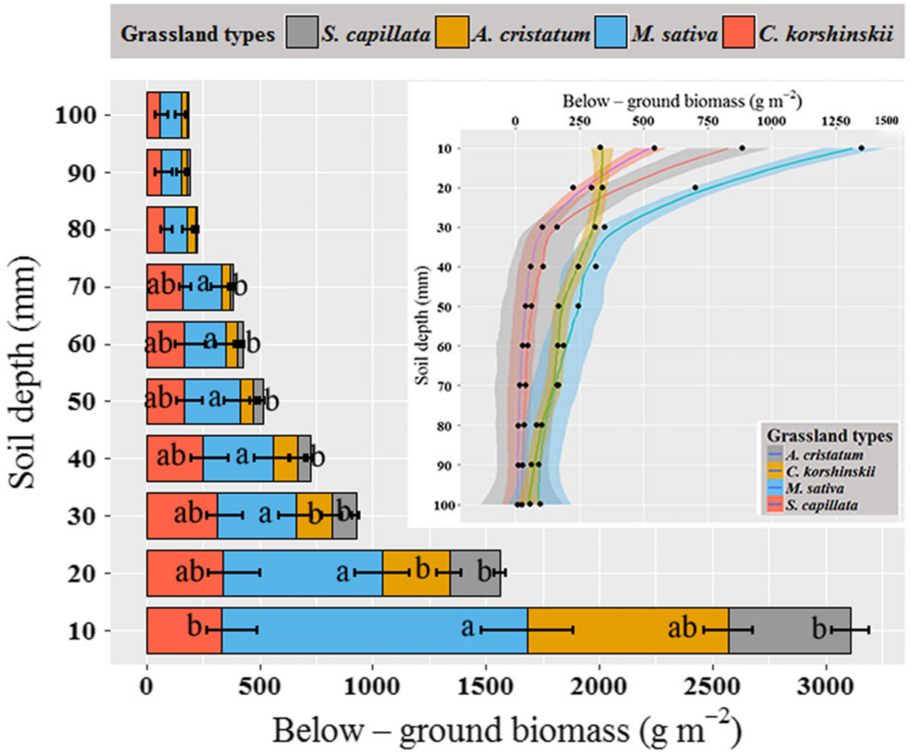


FIGURE 6 The distribution of below-ground biomass (BGB) within the 0- to 100-cm soil layer of *Stipa capillata*, *Agropyron cristatum*, and *Medicago* sativa grasslands and *Caragana korshinskii* scrubland. Data are presented as (a) mean ± SD. Values followed by different lower case letters at the same soil depth in different grasslands are significantly different at the 0.05 level (LSD). The figure in the right corner showed the variation of BGB in different grassland types, and the shadow was the confidence interval

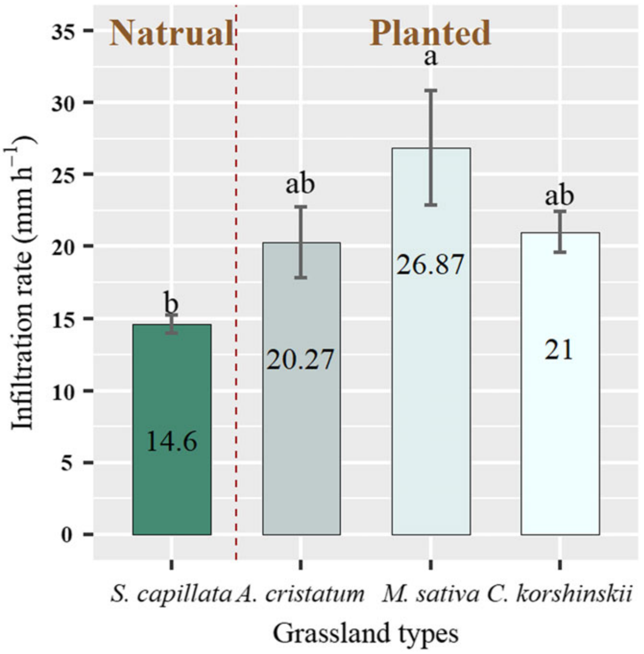


FIGURE 7 Soil steady-state infiltration rate of *Stipa capillata*, *Stipa capillata*, and *Medicago sativa* grasslands and *Caragana korshinskii* scrubland. Different lower case letters above the bars indicate significant differences between grassland types at the 0.05 level (LSD)

This result was consistent with the observations of Yang, Chen, Wei, Yu, and Zhang (2014b), who reported that introduced grasslands (*M. sativa* grassland and *C. korshinskii* scrubland) consumed more deep soil water compared with native grassland (*Stipa bungeana* dominated grassland) in semiarid regions. Liu and Shao (2014) also found that legume grasslands consumed more deep soil water than gramineous grasslands. Deep-rooted plants are high water consumers that can utilize soil water from deeper soil layers, whereas plants with fibrous roots are relatively low water consumers (Jia & Shao, 2013; Pelaez, Distel, Boo, Elia, & Mayor, 1994; Zhao et al., 2017). Legume grassland plants with deep taproots need more water during the growing season and tend to dry the soil and reduce the water availability in arid regions (Xu, Gichuki, Shan, & Li, 2006). In contrast, gramineous grassland plants have fibrous roots and less below-ground biomass distribution in deeper soil layers, thus consuming less soil water (Jia & Shao, 2013; Ruiz-Sinoga, Galeote, Murillo, & Marín, 2011).

Our study showed that all values of MRD were lower than 30% over the test period, suggesting a strong temporal stability of SWC in the arid area. The studies of Jia and Shao (2013) and Wang et al. (2015) also suggested that the temporal stability of SWC became stronger under dry conditions. The values of MRD were higher in the top soil layers (0–50 cm), because the vertical distribution of roots are concentrated in these layers. Soil water was more sensitive to precipitation under the concentrated distribution layer of roots. Roots were the major factor affecting the standard deviation of the RDs (Xu et al., 2017). Wang et al. (2015) also indicated that the SDRD of SWC was larger within the root zone (0–30 cm). The temporal stability of SWC became stronger with increasing soil depth, and these results were consistent with previous research studies, which indicated that SWC in deeper layers were relatively stable despite the seasonal changes (Fu et al., 2003; Liu & Shao, 2014). Compared with the PG, the values of MRD were lower in the NG, suggesting that NG had a stronger SWC stability. PG had deep roots and higher infiltration rates, which result in more variable SWC over the test period than in the NG. These results suggested that soil water accumulation under PG was weaker than that under NG, in accordance with the observations of Zhao et al. (2017). Legume grasslands have relatively deeper roots and can utilize more soil water than gramineous grasslands, thus further aggravating soil water deficit, which is not conducive to the sustainability of vegetation restoration. Among the grasslands and the scrubland in this study, the NG had a higher SWC and stronger temporal stability of SWC; therefore, NG is considered a better choice for vegetation restoration in arid and semiarid regions.

5 | CONCLUSIONS

The vertical distribution and temporal stability of SWC were statistically different among the selected grasslands and the scrubland. SWCs of PGs were significantly lower than that of the NG, especially below the 200-cm soil depth. Planted legume grasslands consumed more soil water through the uptake of deeper soil water by deep roots. The dry conditions of the arid study area accounted for the strong temporal stability of the SWC observed during the 2-year study period. The temporal stability of SWC was weak at the 0- to 50-cm soil depth, and more stable conditions appeared with increasing soil depth. The temporal stability of SWC was stronger in the NG than in the artificial grasslands. Therefore, NG is a more feasible choice for vegetation restoration in arid and semiarid regions.

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ORCID

Gao-Lin Wu http://orcid.org/0000-0002-5449-7134

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