Received: 22 August 2019 | Revised: 15 January 2020 | Accepted: 25 January 2020
DOI: 10.1002/eco.2196

RESEARCH ARTICLE

WILEY

Soil moisture variations in response to precipitation in different vegetation types: A multi-year study in the loess hilly region in China

Ran-Ran Cheng[1,3] | Qiu-Wen Chen[2] | Jian-Guo Zhang[4] | Wei-Yu Shi[5] | Guoqing Li[1,2] | Sheng Du[1,2]

[1]State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, Yangling, China

[2]Institute of Soil and Water Conservation, Northwest A&F University, Yangling, China

[3]University of Chinese Academy of Sciences, Beijing, China

[4]Upper and Middle Yellow River Bureau, Yellow River Conservancy Commission of the Ministry of Water Resources, Xi'an, China

[5]School of Geographical Sciences, Southwest University, Chongqing, China

Correspondence
Sheng Du, State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, 26 Xinong Rd, Yangling 712100, China.
Email: shengdu@ms.iswc.ac.cn

Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 41171419, 41471440, 41411140035; National Key R&D Program of China, Grant/Award Number: 2017YFC0504601

Abstract

Vegetation restoration has been widely implemented as an effective approach to the control of soil erosion. However, severe soil desiccation is likely to occur if vegetation types and local precipitation conditions are not accounted for. In this study, an abandoned farmland and three typical vegetation types, including a natural shrubland, a plantation of black locust, and a natural oak secondary forest, were investigated to determine the characteristics of soil moisture in different hydrological years. The responses of soil moisture to precipitation were analysed at different timescales. Higher soil water contents were observed either in wet years or for natural vegetation types. The temporal response of soil moisture to precipitation was largely dependent on the timescale. At monthly scale, shallow soil moisture (0–100 cm) varied consistently with precipitation, whereas on interannual scale, precipitation is positively related to soil moisture along the whole profiles. Black locust and oak lands consumed more soil moisture than the shrubland, and severe soil desiccation developed in deep soil layers in the black locust plantation. The shrubland showed steeper regression slopes than other types for both the changes in soil water storage over time (ΔSWS_t) versus the growing season precipitation and the difference in soil water storage with the abandoned farmland (ΔSWS_v) versus the growing season precipitation, suggesting its higher adaptability to precipitation changes in this region. The results indicate that the shrubland develops optimal water use strategies through coevolution with local conditions and should be given precedence in vegetation restoration initiatives in this region.

KEYWORDS
Loess Plateau, multi-year variation, precipitation, soil moisture, vegetation types

1 | INTRODUCTION

Soil moisture is an essential component of the hydrological and ecological processes that are closely connected to precipitation, runoff, and groundwater (Li et al., 2016; Penna, Borga, Norbiato, & Fontana, 2009; Tsunekawa, Liu, Yamanaka, & Du, 2014). As a critical water resource for vegetation growth and agricultural development (Hu, Shao, Han, & Reichardt, 2011; Li et al., 2016), soil moisture is considered to be the primary limiting factor for the rehabilitation of degraded ecosystems, especially in arid and semiarid regions (Messing, Fagerstrom, Chen, & Fu, 2003). Many studies have characterized the dynamics and magnitude of soil moisture changes to

 © 2020 John Wiley & Sons, Ltd.

understand the influencing factors at different spatiotemporal scales (Deng, Yan, Zhang, & Shangguan, 2016; Mei et al., 2018; Zhao et al., 2017; Zhao et al., 2019). Existing experimental evidence suggests that multiple factors, including vegetation types (Deng et al., 2016; Mei et al., 2018), climate (D'Odorico & Porporato, 2004; Zhao et al., 2017), and topography (Qiu, Fu, Wang, & Chen, 2001; Yu et al., 2018), influence soil moisture and its dynamics. Precipitation and vegetation type have been proposed to be major factors that control soil moisture across the soil profile, as well as across whole landscapes (Chen, Huang, Gong, Fu, & Huang, 2007; Duan, Huang, & Zhang, 2016; Zhao et al., 2017).

The Loess Plateau region in China covers large arid and semiarid areas and is currently undergoing tremendous changes in land use and land cover due to a project known as "Grain for Green," whereby farmland is being converted back to forest or grassland (Deng et al., 2016; Jia, Shao, Zhu, & Luo, 2017). Successful restoration of degraded ecosystems largely depends on the availability of soil water (Jimenez, Pinto, Ripoll, Sanchez-Miranda, & Navarro, 2017; Zheng, Fu, Hu, & Sun, 2014). Crown dieback and early mortality of trees have been observed in this region, owing to soil desiccation (Chen et al., 2007; Yamanaka, Hou, & Du, 2014). It was reported that only 24% of planted trees survived in afforestation projects during 1982–2005 due to the deficit of soil water in arid areas (Wang, Chen, Hasi, & Li, 2008; Wang, Innes, Lei, Dai, & Wu, 2007). As the only source of soil water supplement, precipitation regimes, such as the amount and seasonal or annual changes, have been demonstrated to have a strong influence on the spatiotemporal variations in soil moisture (Salve, Sudderth, St Clair, & Torn, 2011; Schlesinger & Jasechko, 2014). In a study conducted in a shrub-encroached grassland, Li, Liu, Duan, and Wang (2014) found that surface soil moisture and its variations were affected greatly by the amount of precipitation. Precipitation has been considered as the main reference for ecological restoration (Wang, Fu, Gao, Liu, & Zhou, 2013). Besides, approaches applied for the selection of suitable vegetation types, and even specific species of plants, are frequently related to precipitation. Chen, Shao, and Li (2008) suggested that artificial forests and shrubs could be planted widely in the regions with annual precipitation >500 mm, whereas Deng et al. (2016) insisted that vegetation restoration would not exert negative effects on soil moisture only when the precipitation exceeds 600 mm. Considering that precipitation varies greatly over a large scale and from year to year, inconsistent conclusions from many studies restrict extrapolations to other areas. However, to avoid time consumption and labour intensiveness, most studies assessed the effects of restoration on soil moisture under different vegetation types or precipitation regions over a single growing season that did not include different hydrological years (Zhang, Wei, Chen, & Yang, 2019). Little attention has been paid to the responses of soil moisture variations to precipitation through observations of time series in the Loess Plateau.

Vegetation could strongly affect soil moisture and their response to precipitation through a number of complex and mutually interacting hydrologic processes (Chen et al., 2007). However, due to differences in morphological features and eco-hydrological functions, these effects vary with plant species. At a site with annual precipitation of 510 mm in the Loess Plateau, severe depletion of soil moisture content occurred under *Caragana korshinskii* shrubland and *Robinia pseudoacacia* forest, whereas naturally recovered grass species were observed to have balanced soil water conditions (Xiao, Xue, Liu, & Zhang, 2014). As compared with other vegetation types, afforestation with fast-growing trees (e.g., *R. pseudoacacia*) tended to consume large amounts of soil moisture quickly through their extensive root systems and water absorbing capacity (Cao et al., 2011; Jimenez et al., 2017), which frequently resulted in soil water deficit (Cao, Chen, & Yu, 2009). Some studies have shown that soil moisture decreased rapidly after afforestation and that soil moisture in deep soil layers cannot be recharged by natural precipitation (Farley, Jobbagy, & Jackson, 2005). On the other hand, Deng et al. (2016) found no net change in soil moisture across the soil profile of 0–100 cm under a shrubland. Such a dispute might result from different precipitation regions being considered in a study (Mei et al., 2018; Zhao et al., 2019) or because of short timescales (Farley et al., 2005; Wang et al., 2013). Therefore, to gather information that can help maintain the sustainability of reconstructed ecosystems, it is necessary to better characterize the depletion or recovery of soil moisture under different vegetation types by carrying out studies spanning over a number of years in the Loess Plateau.

In this study, three typical vegetation types at a semiarid site were selected with an abandoned farmland as control. The specific objectives of this study were (a) to compare the soil moisture conditions under the vegetation types in different hydrological years (dry, wet, and normal years) and (b) to evaluate the response of soil moisture to precipitation and its variation under different vegetation types. The results may contribute to the understanding of the relationships among vegetation, precipitation, and the soil water budget, which can provide a guideline for the selection of optimum vegetation types for sustainable ecosystem restoration.

2 | MATERIAL AND METHODS

2.1 | Study area

The study was conducted at Mt. Gonglushan (36°25.40′N, 109°31.53′E, 1353 m a.s.l.) in a southern suburb of Yan'an City, Shaanxi Province, in the central part of the Chinese Loess Plateau. The site is located in an ecological transition zone between forest and forest–steppe ecosystems. The climate is classified as temperate semiarid zone, and the topography is loess hills and gullies. According to the Yan'an city meteorological station data, the mean annual precipitation and air temperature during 1956–2015 were 537.9 mm and 10.0°C, respectively. The precipitation in this region is known for its distinct seasonality, with most of the precipitation occurring from June to September. The growing season for most plant species in the region spans from April to October. The soil belongs to *Calcic*

Cambisol group based on the FAO–UNESCO soil classification system, which are derived from silt textured loess parent materials (Wang, Fu, Qiu, & Chen, 2003). The soil has a depth range of 50–200 m, depending on topography. The gravimetric field capacity and wilting percentage of soil water are 20–24% and 3–6%, respectively (Yang & Shao, 2000).

Whereas taking abandoned farmland as a control, three vegetation types that represented natural and planted forests were selected for this study: (a) a natural secondary forest, where the typical forest type was dominated by oak (*Quercus liaotungensis*); (b) a plantation forest with a widespread plantation of the fast-growing introduced specie of black locust, *R. pseudoacacia*; and (c) a natural shrubland, including *Syringa oblata*, *Rosa hugonis*, and *Caragana microphylla*. The four experimental sites share the same climate conditions because they are separated only by approximately a few hundreds of metres. Basic information on the four experimental sites is shown in Tables 1 and 2.

2.2 | Experimental procedures

Since 2007, observation plots had been established in different vegetation types for multipurpose investigations, for example, investigations on forest evapotranspiration (Du et al., 2011; Yan et al., 2016; Zhang et al., 2015; Zhang, Guan, Shi, Yamanaka, & Du, 2015), soil respiration (Shi, Yan, Zhang, Guan, & Du, 2014; Shi, Zhang, Yan, Yamanaka, & Du, 2012), and soil microbial community (Tian et al., 2017). To understand the dynamic changes in soil moisture, three representative points located at the upper, middle, and lower positions were chosen as replicates within each vegetation type, and totally twelve 3-m-long Tecanat® plastic tubes with internal diameter of 42 mm were permanently placed for repetitive time-domain reflectometry measurements. Volumetric soil water content (SWC, cm^3/cm^3) was measured using a time-domain reflectometry moisture measurement system (TRIME, IMKO Micromodultechnik, Ettlingen, Germany). The measurements were commenced after installation for more than 5 months. During the investigated periods from April 25, 2009, to October 25, 2015, the SWC was measured five to seven times per growing season at 20-cm intervals at depths of 0 to 300 cm. To avoid the influence of precipitation, no measurements were conducted within 7 days of precipitation. During the experimental periods, we obtained a total of 152 SWC data sets. The measured data for the SWC were calibrated by an equation established at the study site for gravimetric water contents from drilled soil cores versus soil bulk density across soil profiles.

In addition, rainfall was measured at the site by a tipping-bucket rain gauge (Model 7852, Davis Instruments, USA) connected to a CR1000 data logger (Campbell Scientific, Logan, UT, USA) to evaluate the impacts of precipitation on soil moisture and its variation during the experimental period (2009–2015). More details about the experimental sites have been documented by Du et al. (2007) and Tateno et al. (2007). More than 70% of the total annual precipitation was distributed between May and October with relatively dry periods during the nongrowing seasons. This study focused on the data collected between May and October for all the years from 2009 to 2015.

The relative richness of precipitation has important impacts on soil moisture and reservoir storage. The drought index (DI) was used to quantify this index (Guo et al., 2012; Xin, Zhang, & Wang, 2001). In addition, on the basis of DI values, Xin et al. (2001) proposed a three-category classification to divide the hydrological years into wet year ($DI > 0.35$), normal year ($-0.35 \le DI \le 0.35$), and dry year ($DI < -0.35$). Similarly, in this study, the DIs for May to October were calculated to assess variations and status of precipitation among different years (Equation 1).

$$DI = (P - M)/\sigma, \tag{1}$$

where P (mm) is the actual amount of precipitation recorded during the period of May–October in a specific year, M (mm) is the average amount of precipitation during the period of May–October recorded in 60 years (1956–2015), and σ (mm) is the standard error.

The 60-year average of precipitation in May–October was 469.9 mm with the standard error of 121.3 mm calculated from the data for 1956–2015. As shown in Table 3, the relative richness of precipitation varied from year to year within the study area. The DI values for years, 2009 to 2012, were 1.02, 0.09, 0.33, −0.37, respectively. These four years were defined as wet year, normal year, normal year, and dry year, respectively (Table 3).

2.3 | Calculation of soil moisture changes

Soil water storage (SWS) was used as an indicator of soil water resources, which might control the sustainability of ecosystems in water-limited regions. The SWS was calculated with Equation (2):

TABLE 1 Vegetation characteristics for each experimental site

Vegetation type	Stand Age (year)	Coverage (%)	Height (m)	Stand Density (plants/ha)	DBH (cm)
A	38	<10	NA	NA	NA
S	>60	80	1.0–3.0	2,650	3.8 ± 1.9
L	38	90	8.6 ± 1.8	3,100	9.8 ± 0.3
O	>60	75	5.8 ± 2.2	1,350	10.2 ± 6.1

Abbreviations: A, abandoned farmland; DBH, diameter at breast height. L, black locust land; O, oak land; S, shrubland

TABLE 2 Topographic and soil properties at each experimental site

	Topographic property		Soil property[a]			
Vegetation type	SG	SA	Clay (%)	Silt (%)	Sand (%)	BD (g/cm^3)
A	10	SE	23.8 ± 0.4a	60.1 ± 0.8a	16.0 ± 0.7b	1.2 ± 0.1a
S	10	W	12.3 ± 0.8b	61.2 ± 1.4a	26.5 ± 2.0a	0.9 ± 0.1c
L	26	SE	21.2 ± 3.8a	61.2 ± 1.6a	17.6 ± 2.3b	1.1 ± 0.1b
O	22	SW	10.0 ± 3.8b	60.4 ± 1.2a	29.6 ± 1.9a	0.9 ± 0.1c

Note. The data are presented as mean ± standard errors.
Abbreviations: A, abandoned farmland; BD, bulk density; L, black locust land; O, oak land; S, shrubland; SA, slope aspect; SE, Southeast; SG, slope gradient; SOC, soil organic carbon; SW, Southwest; W, West.
[a]Only the surface, that is, 0–20 cm of the topmost soil layer, was considered.
Different lowercase letters within a column indicate significant difference among the values of different vegetation types for a specific soil property.

TABLE 3 The precipitation observed over the years

Variable	2009	2010	2011	2012	2013	2014	2015
Total annual precipitation (mm)	700.3	564.0	595.6	477.5	891.0	646.0	418.2
Precipitation from May to Oct (mm)	593.9	481.3	510.0	424.9	841.6	521.4	300.8
DI	1.02	0.09	0.33	−0.37	3.06	0.42	−1.39

Abbreviation: DI, drought index.

$$SWS = SWC \times h \times 10, \quad (2)$$

where SWS (mm) is the soil water storage at a specific depth, SWC (cm^3/cm^3) is the mean volumetric soil water content at corresponding depth, h (cm) is the soil depth increment, and 10 (mm/cm) is the unit conversion factor.

The relationship of soil moisture variation with vegetation types and precipitation was evaluated with two methods:

1. For each vegetation type, the difference in SWS (ΔSWS_t, mm) between the initial and the final stages during each growing season was computed (Equation 3), followed by quantitative analysis of the relationship between ΔSWS_t and precipitation in the growing season.
2. At the end of each growing season, the difference in SWS (ΔSWS_v, mm) between each vegetation type and the abandoned farmland was computed (Equation 4). Afterwards, the relationship between ΔSWS_v and the corresponding growing season precipitation was quantitatively analysed.

$$\Delta SWS_t = SWS_f - SWS_i, \quad (3)$$

$$\Delta SWS_v = SWS_n - SWS_a, \quad (4)$$

where ΔSWS_t is the variation in SWS in each growing season. SWS_i and SWS_f denote the SWS measured at the initial and finial growing stages, respectively. SWS_n is the SWS of the land (shrubland, black locust land, and oak land) under consideration for calculation; SWS_a is the SWS of the control, that is, the abandoned farmland. Therefore, ΔSWS_v is the difference of SWS between the vegetation-covered land and the abandoned farmland.

2.4 | Statistical analysis

The SWC over the four vegetation types was calculated via integration of the separate layers across the profile. For each soil layer, the measured SWC was converted into SWS with Equation (2). One-way ANOVA was used to analyse the means of values for the same soil layers across the different vegetation types, as well as the different hydrological years. A general linear model was used to quantify the contribution of precipitation, vegetation type, and their interactions to the total model variations. In addition, the relationship between the SWC and the growing season precipitation and the relationship between ΔSWS_t/ΔSWS_v and growing season precipitation were identified through bivariate correlation analysis. SPSS® (Version 17.0, SPSS Inc., Chicago, IL, USA) was used for all statistical analyses in this study. Significant differences were evaluated at the.05 probability level.

3 | RESULTS

3.1 | Vertical distribution characteristics of the SWC

The vertical distribution of the SWC within the 0 to 300-cm profile was affected more by precipitation than by vegetation types (Figure 1). In the years with high precipitation (such as 2009 and 2011), similar distribution patterns were observed in the four vegetation types. Across the vertical profile in a downward direction, the SWC increased to a maximum value and then declined gradually to a stable status. The value of SWC at maximum and stable states varied at different soil depths in different years. In 2009, the maximum and

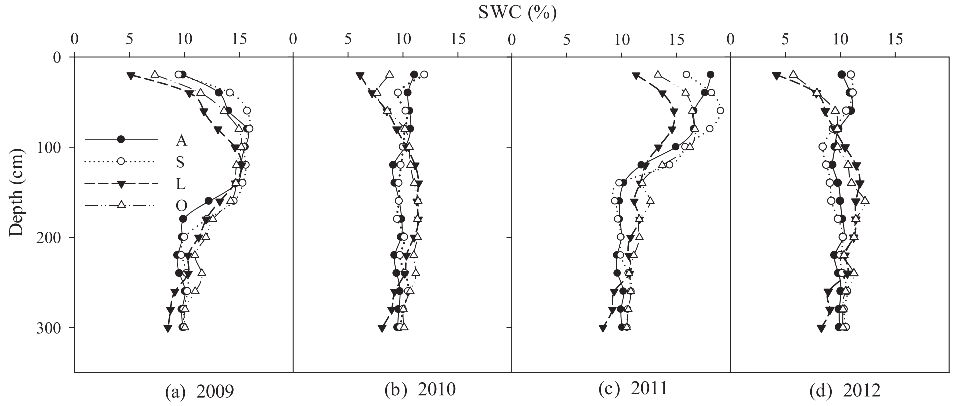

FIGURE 1 Vertical distribution patterns of soil moisture under the four vegetation types in different hydrological years. A, abandoned farmland; L, black locust land; O, oak land; S, shrubland

stable SWC values were observed for soil layers at depths of 80–100 cm and below depths of 180–200 cm, respectively. However, the maximum and stable SWC values were observed at depths of 60–80 cm and below 140–160 cm in 2011, respectively. In the years with low precipitation (such as 2010 and 2012), the SWC decreased till depths of approximately 80–100 cm and then gradually stabilized in the abandoned farmland and the shrubland. However, no downtrend was observed in the oak land till depths of 140–160 cm. No stable status of soil moisture was observed in the land planted with black locust, even in the 200- to 300-cm soil layers.

3.2 | SWC in different hydrological years

The SWC varied with soil depth as demonstrated in Figure 1. Therefore, the SWC in different hydrological years were compared hierarchically in our study (Figure 2 and Table 4). In this study, the SWC measured at the final stage of a growing season (in late October) can be considered as the accumulated result of interactive effects of vegetation types and precipitation. Therefore, we chose the data in October for analysis. In the complete 0 to 300-cm soil profile, higher precipitation was accompanied by higher SWC under all vegetation types. Precipitation significantly affected SWC in shallow (0–100 cm) and middle (100–200 cm) soil layers, where higher SWC values were observed in the years with higher precipitation (2009 and 2011). However, the differences in SWC between the different hydrological years tended to become smaller as the soil depth increased and were not significant in deep soil layers (200–300 cm). Moreover, it was worth noting that significant differences in the SWC were observed among vegetation types, even in deep soil layers. For complete soil profiles, oak land and shrubland showed higher SWC as compared with farmland and the black locust land, although the differences in SWC were not significant among the vegetation types in the dry year.

The general linear model suggested that most of the variation in soil moisture could be explained by the two variables (hydrological year and vegetation type; Table 4). SWC in the shallow (0–100 cm) and middle (100–200 cm) soil layers were significantly affected by precipitation, whereas those in deep soil layers were mainly determined by vegetation types. Of the variables examined, hydrological year explained the largest proportion (82.61%) of the soil moisture variation in shallow soil layer. However, in deep soil layer, more than half of the variation could be explained by vegetation types, whereas only 4.62% of the variation resulted from hydrological year.

3.3 | Responses of the SWC to precipitation at monthly and interannual time scales

Similar temporal responses of the SWC to monthly precipitation were observed for all vegetation types (Figure 3). Larger temporal variations were observed in the shallow soil layers, whereas smaller soil moisture changes were observed in deep soil layers. Soil moisture decreased at the beginning of the growing season (May to June) and then increased sharply during the midgrowing season (July to September) with the arrival of monsoon rains. It finally decreased during the late growing season (September to October).

The depth-averaged SWC under the four vegetation types responded positively to precipitation on interannual time scale (Figure 4). Nevertheless, different responses of soil moisture to precipitation were observed among the four vegetation types, which were reflected by the slopes of the SWC to precipitation. For example, shrubland had the steepest slope among the four vegetation types across the layer with depth of 0–300 cm, whereas black locust land showed a less slope. The responses of soil moisture to precipitation also varied among soil layers. The correlation between the SWC and the precipitation was not significant in the shallow soil layer, whereas it reached a significant level in middle and deep soil layers in oak land and black locust land. In addition, upward tendencies in the regression slope were observed with increasing soil depth under vegetation-covered lands (Figure 4).

3.4 | Variations in the SWS and their response to precipitation

In general, soil moisture was replenished in wet years and was consumed in normal and dry years for all vegetation types. Different ΔSWS_t patterns were observed among vegetation types, and ΔSWS_t showed visibly plus or minus values mainly in soil layers with depths less than 200 cm (Figure 5). For example, the shrubland and the

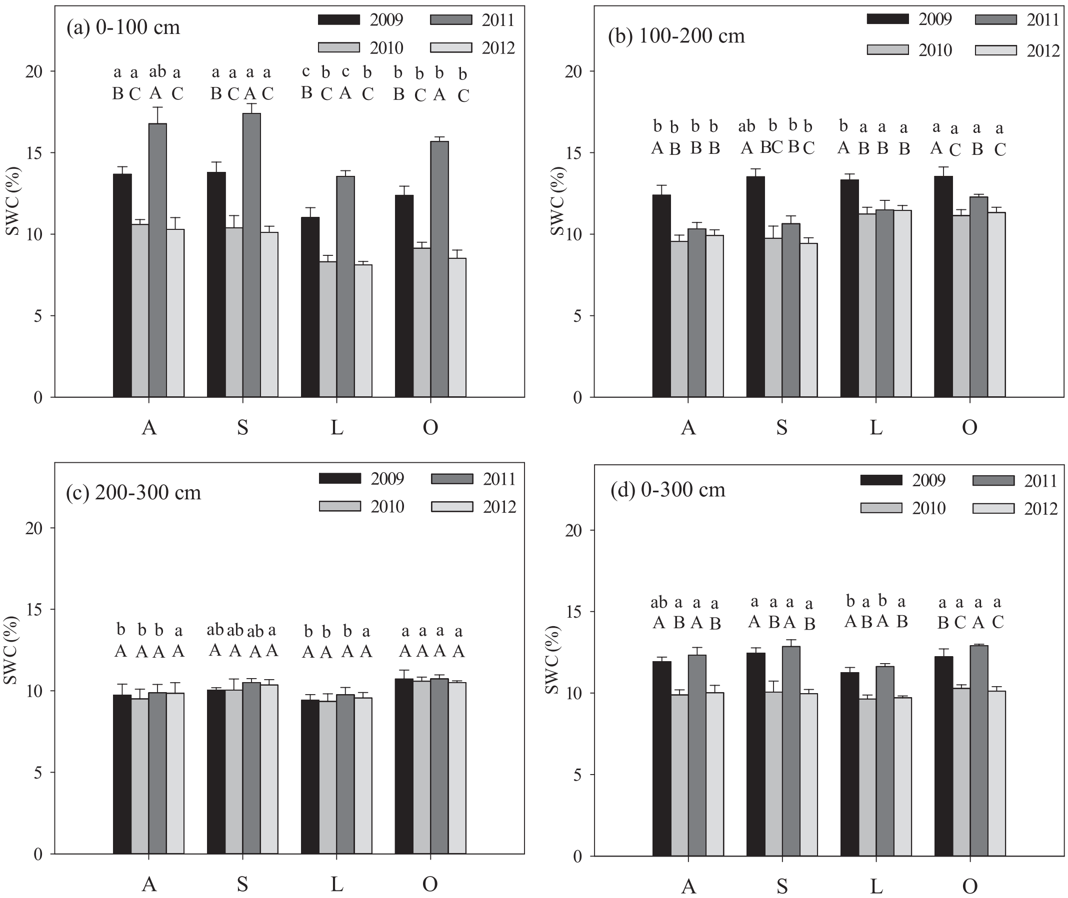

FIGURE 2 A comparative analysis of the depth-averaged SWC in different hydrological years and under different vegetation types. Note that the data are from measurements taken in October (end of growing seasons) and are presented as mean ± standard errors. Different uppercase letters indicate significant differences among values recorded for the hydrological years for a specific vegetation type; different lowercase letters indicate significant differences among the values recorded for vegetation types for a specific hydrological year. A, abandoned farmland; L, black locust land; O, oak land; S, shrubland; SWC, soil water content

TABLE 4 Summary of results from applying ANOVA on the effects of hydrological year, vegetation type, and the interactions using general linear models

		$SWC_{0–100\ cm}$			$SWC_{100–200\ cm}$			$SWC_{200–300\ cm}$		
Source	df	SS	F	SS%	SS	F	SS%	SS	F	SS%
V	3	58.28	64.67**	14.09	20.54	33.29**	22.25	9.03	14.97**	54.40
P	3	341.72	379.19**	82.61	59.61	96.62**	64.59	0.77	1.27	4.62
V * P	9	4.03	1.49	0.97	5.56	3.00*	6.02	0.37	0.20	2.22
R	32	9.61		2.32	6.58		7.13	6.44		38.76

Abbreviations: df, degree of freedom; P, hydrological years; R, residuals; SS, sum of squares; %SS, proportion of variances explained by the variable; V, vegetation types.
$^{*}p < .05$. $^{**}p < .01$.

abandoned farmland got more soil water surplus than the black locust land after growing seasons of 2009 and 2011, whereas the land planted with black locust had the lowest soil water surplus, especially in the shallow soil layer. In the dry year of 2010, more soil moisture was consumed by shrub and oak in the shallow soil layer, indicating that the two vegetation types used soil water effectively even in dry conditions.

Significant positive relationships existed between precipitation and ΔSWS_t for all vegetation types across the 0–300-cm profile ($p < .05$), which indicated that increase in precipitation changed ΔSWS_t from a negative to a positive value (Figure 6). Accordingly, a turning point in ΔSWS_t was observed that was bound by the 510- to 530-mm precipitation level. When precipitation was around 510–530 mm, the replenishment and consumption of soil moisture were in equilibrium,

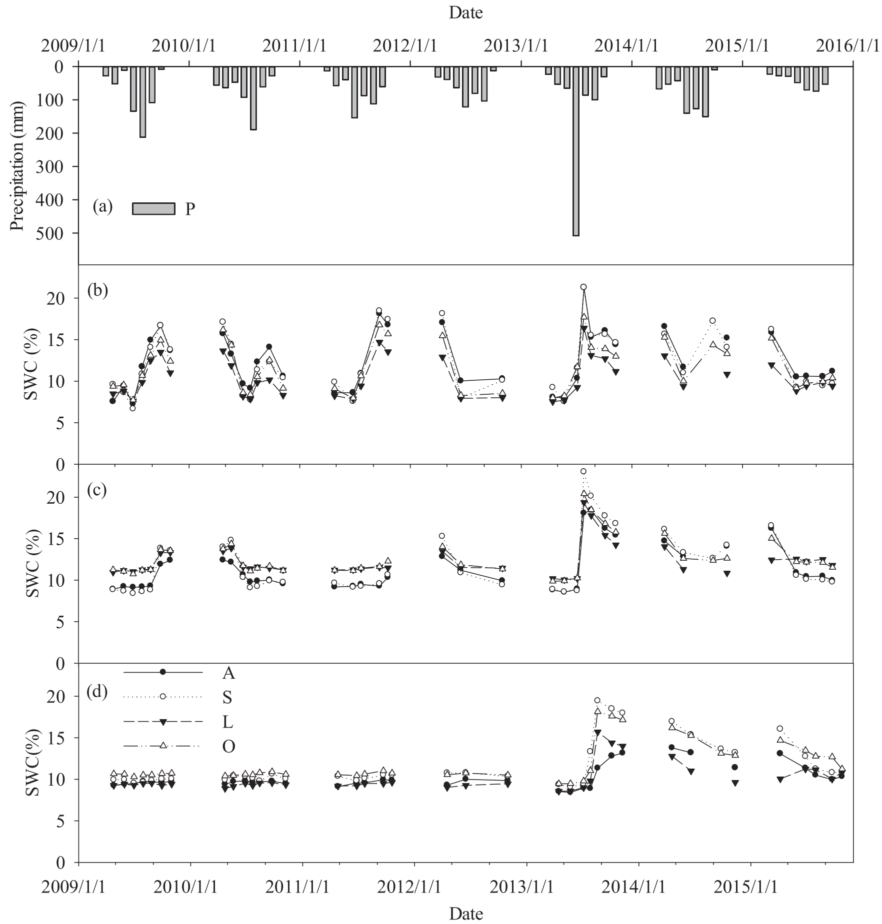

FIGURE 3 Temporal response of the SWC to precipitation at monthly scale. A, abandoned farmland; L, black locust land; O, oak land; S, shrubland; SWC, soil water content

and ΔSWS_t had a value of approximately 0. When precipitation was less than that value, soil moisture was consumed more than it was replenished, and ΔSWS_t appeared to be negative. When precipitation was more than that value, soil moisture was replenished, and ΔSWS_t appeared to be positive. This further verified that soil moisture variation strongly depended on precipitation. In addition, the responses of ΔSWS_t to precipitation differed among vegetation types and were reflected in the regression slopes. For an identical soil layer, shrubland had the steepest slope value, whereas the black locust had the least one. We also observed that the slope changed only slightly from shallow to deep soil layers under vegetation-covered lands, whereas for the abandoned farmland, the slope was much less steep in the deep soil layers.

As compared with the abandoned farmland, soil moisture was greatly consumed under the black locust land, regardless of hydrological years, and severe soil desiccation occurred in the deep soil layer (Figure 7). Across the 0–300-cm profile, ΔSWS_v increased positively with precipitation in the shrubland and the oak land, whereas it decreased under black locust plantations. In the layer with a depth of 200–300 cm, all the three vegetation types contributed to the accumulation of soil moisture (Figure 8). Similar to ΔSWS_t, ΔSWS_v of shrubland was significantly correlated with precipitation and showed the steepest slope regression slope across the entire soil profile (0–300 cm).

4 | DISCUSSION

4.1 | Effects of precipitation and vegetation types on soil moisture

Recently decades, comparisons of soil moisture under different vegetation types or land uses have been well investigated. However, the vegetation type-dependent impacts on soil moisture and its variations could change with different precipitation patterns, which has rarely been explored previously. Longobardi and Villani (2008) reported that climate, precipitation in particular, has a major influence on soil moisture in arid and semiarid regions. In the Loess Plateau, the groundwater level ranges from several tens to hundreds of metres, causing a close dependency of soil moisture on the replenishment by rainfall (Chen et al., 2008; Zhang, Deng, Yan, & Shangguan, 2016). Compared with vegetation types, precipitation was the primary factor that affected soil moisture in the shallow and middle soil layers (Table 4). One potential explanation was that precipitation might exert bottleneck effects for soil moisture in the shallow and middle soil layers in this region. In this case, it was reasonable that the SWC values across the 0 to 300-cm soil profile followed the growing season rainfall sequence (2009 > 2011 > 2010 > 2012) to some extent (Figure 2). This was also consistent with previous studies conducted in different precipitation regions, where higher precipitation was accompanied by

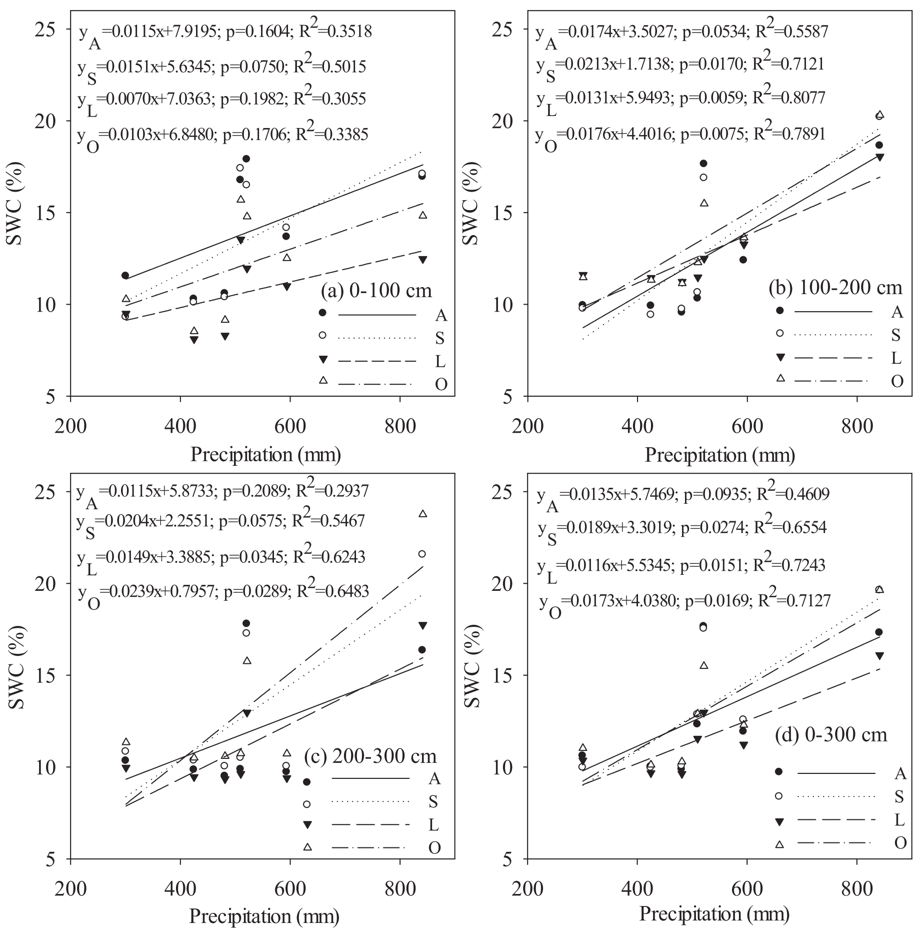

FIGURE 4 Temporal responses of SWC to precipitation on interannual scale. Regressions were applied on SWC at the end of each growing season versus the precipitation in the corresponding period. The data presented here for regressions analysis covered a total of 7 years from 2009 to 2015. A, abandoned farmland; L, black locust land; O, oak land; S, shrubland; SWC, soil water content

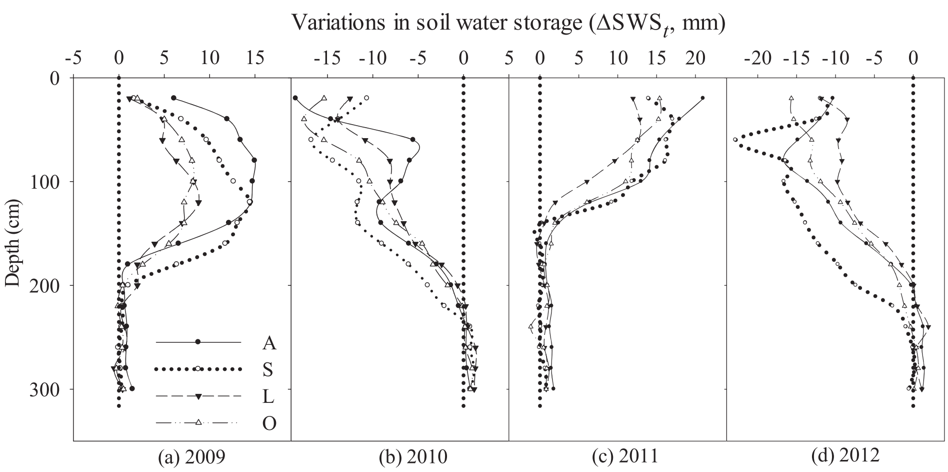

FIGURE 5 Variations in soil water storage (ΔSWS_t, mm) in different hydrological years. ΔSWS_t represents the difference in soil water storage between the initial and the final stage of the growing season. A, abandoned farmland; L, black locust land; O, oak land; S, shrubland

higher SWC (Mei et al., 2018; Zhao et al., 2017). Researchers have pointed out that precipitation affects soil moisture through the infiltration of rainwater (Wang et al., 2008; Wang, Fu, Gao, Yao, & Zhou, 2012), which is directly related to the transformation of limited precipitation into the available soil moisture for plant utilization (Mahmood, 1996). The infiltration process could be largely affected by precipitation features, that is, much amount and strong intensity were conducive for infiltration (Yao, Zhao, Zhang, & Liu, 2013). In this regard, we found that there was an overall increase in the SWC due to high amounts of consecutive monthly rainfall in the extremely wet year, 2013, whereas in general cases, only soil moisture in the shallow depths got replenished (Figure 3). For another thing, precipitation determined the temporal variations in soil moisture. The uneven distribution of precipitation results in significant seasonal variations in soil moisture. The growing season is the main period of precipitation during the year, accounting for more than 70% of the annual precipitation (Table 3). As shown in Figure 3, soil moisture is replenished during the summer rainy season (from June to September), providing the

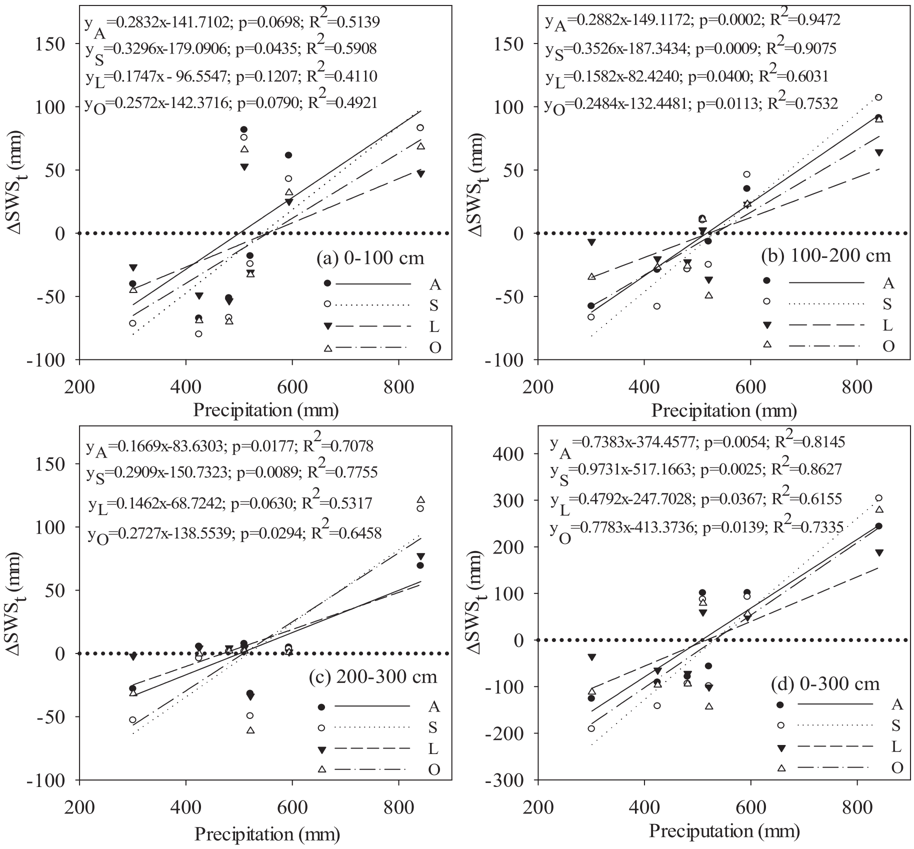

FIGURE 6 Responses of ΔSWS_t versus growing season precipitation in the periods of 2009–2015. ΔSWS_t represents differences of SWS between the initial and final stages of the growing season. The data presented here for regressions analysis covered a total of 7 years from 2009 to 2015. A, abandoned farmland; L, black locust land; O, oak land; S, shrubland

basis for plant growth during the spring of next year. Conversely, winter precipitation accounts for only about 5% of the annual precipitation, where soil moisture is excessively consumed due to steeply increasing evaporative demands during the early spring season (Tsunekawa et al., 2014). In addition, we found that precipitation showed some positive effects on deep soil moisture, and the effects were significant under oak land and black locust land (Figure 4). This result was inconsistent with the reports by Yang, Chen, Wei, Yu, and Zhang (2014) that deep soil moisture (100–200 cm) was relative stable. This discrepancy could be attributed to their relative short experimental periods (only two growing seasons included) and relative lower rainfall during these periods. It further demonstrated the necessity of long-term observations in soil moisture research.

Vegetation type is another important factor influencing soil moisture across the entire soil profile, especially in deep soil layer (Duan et al., 2016). As shown in Table 4, the influence of vegetation types on soil moisture increased with increasing soil depth and was greater than precipitation in deep soil layer. Vegetation types affect hydrologic processes and soil moisture conditions primarily by extracting soil moisture through their roots, affecting the rate of evapotranspiration, and influencing throughfall by their canopies (Famiglietti, Rudnicki, & Rodell, 1998). In the present study, the highest SWC value was observed for the shrubland, whereas severe soil water deficit occurred in the black locust plantation (Figures 2 and 7b). Many researchers have similarly reported severe soil desiccation to occur in both deep and shallow soil layers after ecological restoration (Cao et al., 2011; Liu et al., 2016; Yaseef, Yakir, Rotenberg, Schiller, & Cohen, 2010). They attributed this to a shortage in recharge due to precipitation interception, large amounts of evapotranspiration, and excessive uptake of soil water by plant roots (Jia & Shao, 2014; Jia, Shao, & Jia, 2013). In this study, the land planted with black locust providing 90% canopy coverage intercepted more rainfall than the other vegetation types, which resulted in much lower throughfall and thus less infiltration than other vegetation types. Black locust plantation is a drought-sensitive type of vegetation with a deep root system; however, the annual precipitation in this region cannot meet these demands (Chen et al., 2008; Du et al., 2011). In our study, the soil moisture under the black locust land was deficient in deep soil layer due to this vegetation's strong water consumption capacity. By contrast, both shrubland and oak land were composed of indigenous species, which could manage water supply under both drought and wet conditions (Du et al., 2011). Stand density is another key factor that impacts soil moisture conditions. Vegetation with higher density would more easily lead to soil desiccation due to high transpiration demand (Jiao et al., 2016; Wang et al., 2012). Therefore, the strong consumption capacity combined with high stand density contributed to the intensive consumption of soil water in black locust land, especially in the deep soil layers, where a dry layer had developed (Table 1 and Figure 7). Dry soil layers have become an ominous indicator of soil desiccation phenomenon and ecosystem vulnerability in the Loess Plateau (Fu et al., 2017). Wang, Shao, Zhu, and Liu (2011) summarized three criteria for evaluating dry soil layers and pointed out that a soil layer with a SWC lower

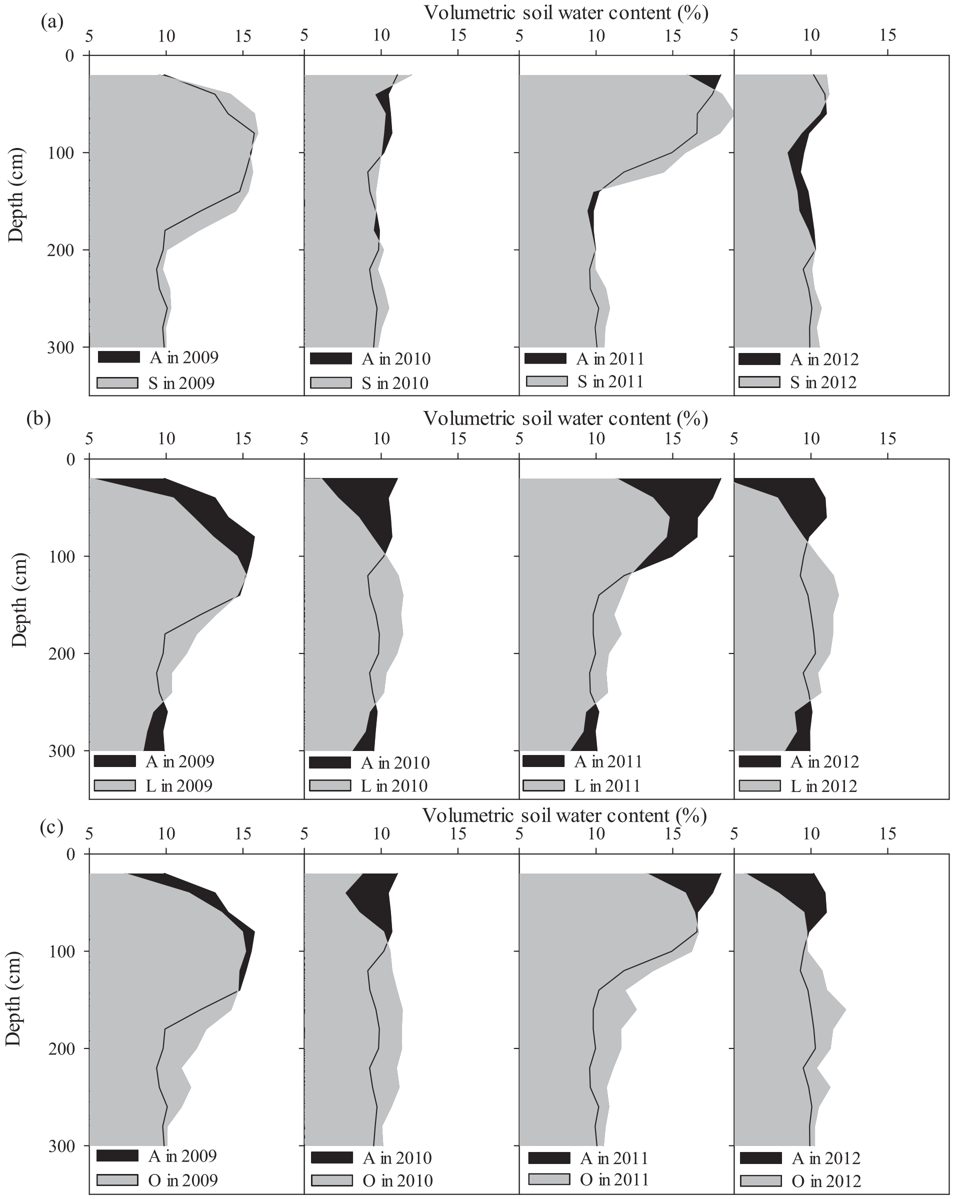

FIGURE 7 Comparison of the soil water content between the abandoned farmland and the other three vegetation types in different hydrological years. A, abandoned farmland; L, black locust land; O, oak land; S, shrubland

than the stable field capacity would be considered as a dry soil layer. In present study, the SWC in black locust land kept decreasing below 200 cm, and no stable status of soil moisture was observed (Figure 1). It was thus possible that a dry soil layer had formed under the deep soil in black locust land.

Variance component analysis demonstrated that vegetation types affected soil moisture across the entire soil profile (0–300 cm) and could explain more than half of the variation in soil moisture in deep soil layer (Table 4). Soil moisture in shallow soil layers showed obvious seasonal and interannual variations, which largely depended on the amount of precipitation (Li et al., 2014). In deep soil layer, soil moisture was mainly determined by vegetation types due to the effects of root water uptake (Wang, Shao, & Shao, 2010; Yang et al., 2014). Our results were generally consistent with the findings of Jin, Fu, Liu, and Wang (2011) and Wang et al. (2013) for the Loess Plateau but were different from the previous studies that reported no significant differences in moisture in deeper soil layers (below 200 cm) among different vegetation types introduced in the region (Yang, Wei, Chen, Jia, & Mo, 2012). This could be due to the similar water use strategies in the vegetation types they investigated.

4.2 | Response of soil moisture to precipitation varied with vegetation type, soil depth, and timescales

Soil moisture variations is a key indicator of catchment water cycling, which represents a coupled result of replenishment and consumption (Qiu et al., 2001). Many factors, such as soil properties, vegetation characteristics, and climate conditions, greatly affect the two processes. And the variation in soil moisture and its response to precipitation were influenced as a result. For example, afforestation could have positive (Joffre & Rambal, 1993), negative (Deng et al., 2016), and negligible (Maestre, Bautista, Cortina, & Bellot, 2001) effects on soil moisture with a decrease in precipitation. In the present study,

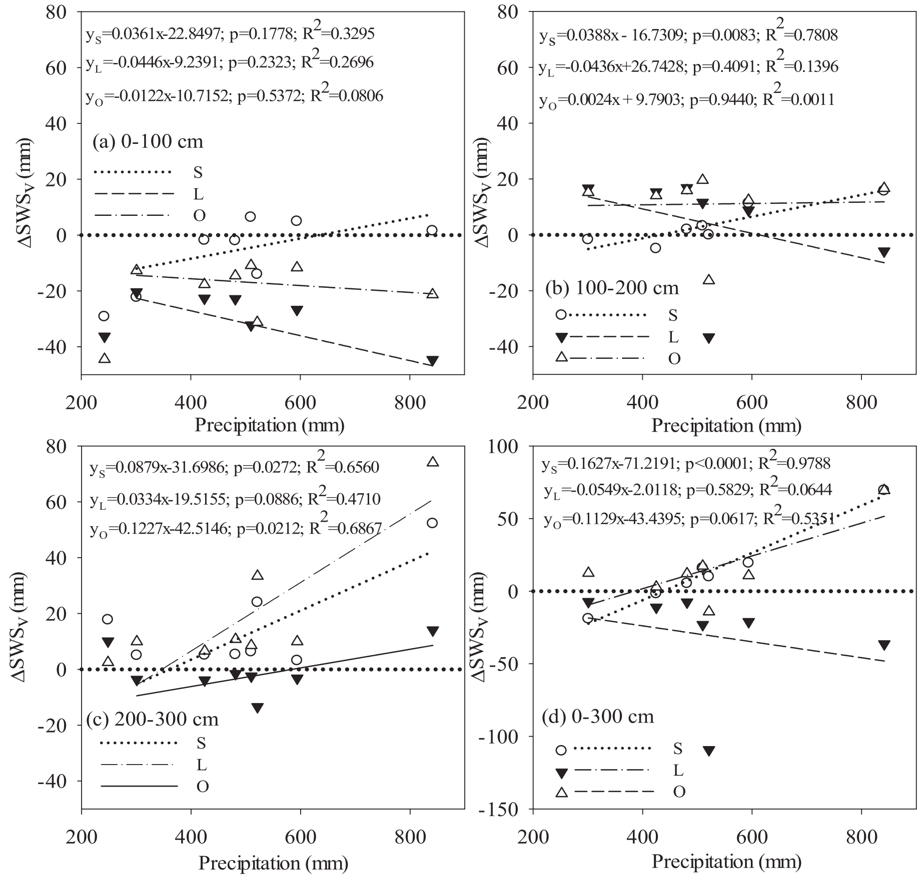

FIGURE 8 Responses of ΔSWS_v versus growing season precipitation in the period: 2009–2015. The data presented here are for regressions analysis performed on data collected over a total of 7 years: 2009–2015. Here, ΔSWS_v represents the differences in soil water storage under each vegetation type as compared with the abandoned farmland. A, abandoned farmland; L, black locust land; O, oak land; S, shrubland

responses of soil moisture to precipitation varied with vegetation types, soil depth, and timescales (Figures 3–8).

Vegetation type affected the responses of soil moisture to precipitation in different ways. The evaluation of impacts of vegetation types on infiltration processes is an important way to determine the responses of soil moisture to precipitation. It is reported that several biophysical factors, including the surface soil features (Klocking & Haberlandt, 2002), soil properties, and vegetation types (Carlyle-Moses & Price, 2006; Descheemaeker et al., 2006), may affect the infiltration processes. Under the long-term effects of vegetation, the topmost soil layer of shrubland showed higher sand content and lower bulk density (Table 2). These features offered shrubland an advantage in the transformation of limited precipitation into soil moisture over black locust land. Favourable soil conditions, accompanied by low bulk density, can effectively improve soil structure, water holding capacity, and infiltration rates (Zhao et al., 2017). As a result, shrub and oak could get more replenishment from precipitation than the other two vegetation types. However, there were no significant differences in the soil properties in deep soil layer (Jiao, Wen, & An, 2011). Therefore, the retaining capacity of soil water in deep layers could be considered as identical among vegetation types. In the present study, shrubland with lower soil bulk density and moderate soil texture compositions had higher SWC (Table 2 and Figure 2), which is consistent with the results of Duan et al. (2016) and Liu et al. (2018). These features also had positive impacts on the response of shrubland soil moisture to precipitation, as reflected by a steeper slope between ΔSWS_t to precipitation (Figure 6). In contrast, black locust land had higher bulk density, which constrained the infiltration of rainwater into soil. It meant that a lot of rainwater lost as runoff in black locust land, and soil moisture cannot be replenished enough. The slope of ΔSWS_t to precipitation was the least in black locust land, showing it less sensitive to annual precipitation. This can be verified by the fact that soil desiccation occurred in deep soil layer in black locust land, even in wet year (Figure 7). This was consistent with the findings of Wang et al. (2012) and Schymanski, Sivapalan, Roderick, Beringer, and Hutley (2008). Different water use strategies among vegetation types can also alter the responses of soil moisture to precipitation (Chen et al., 2007). In the present study, the shrub community consisted of some native species, such as *S. oblata*, *R. hugonis*, and *C. microphylla*. Our results showed that the shrubland could acquire and retain soil moisture more quickly and actively in wet years and utilize soil water efficiently for survival under drought conditions (Figure 6), indicating that optimal water use strategies have developed among these species through coevolution with natural conditions. Black locust plantations have higher evapotranspiration than other vegetation types and need more water to sustain their rapid growth (Deng et al., 2016). Once the precipitation became insufficient, the black locust plantations gradually took up the soil water from the deep soil layer with their deep root system, resulting in excessive water consumption. However, precipitation usually cannot compensate the consumption during growing season. Therefore, it was concluded that black locust markedly disrupted the soil water balance in deep soil layer.

Conversely, shrubs usually have lower evapotranspiration demands, and water uptake is considerably lower from deep soil layers. Consequently, no soil desiccation occurred in shrublands even in the dry years (Figure 7). These results were in agreement with the findings of Xiao et al. (2014). In a comparative study in a region with a mean annual precipitation of 510 mm, severe depletion of soil moisture in deep layer occurred under *R. pseudoacacia* plantations, whereas naturally recovered abandoned cropland showed balanced soil water conditions (Xiao et al., 2014).

Although soil moisture in deep layers was relatively stable, soil moisture in the shallow soil layers was sensitive to monthly precipitation (Figure 3). These can be explained by the interactive effects of infiltration processes and root distribution patterns in different soil layers. Shallow soil layers are the main layers receiving precipitation and providing water for plant growth (Deng et al., 2016). Although the precipitation amounts vary greatly from year to year, the maximum infiltration depth was usually less than 200 cm (Figure 1). This was consistent with the suggestions by Wang et al. (2010) that the infiltrating rainwater usually recharges the 0 to 100-cm soil layer in the Loess Plateau. On the other hand, most of the fine roots distributed mainly in the shallow soil layers, resulting in a greater consumption of soil moisture (Yang et al., 2012). Therefore, soil moisture in the shallow soil layer fluctuated frequently at monthly scale. By contrast, deep soil layer was insensitive to precipitation due to limited supplement from infiltrated rainwater. On interannual scale, positive relationships between precipitation and soil moisture were observed in both shallow and deep soil layers, although the effects were not significant in the shallow soil layer (Figure 4). Shallow soil layers were exposed to many influencing factors and were subject to high evapotranspiration demands, which reduced the effects of precipitation on soil moisture.

4.3 | Implications for restoration

Over the last few decades, large numbers of ecological restoration projects have been implemented and remarkable effects have been achieved in the Loess Plateau. However, these initiatives have also played a significant role in the dynamics of soil moisture, and numerous studies have demonstrated that soil desiccation occurred after ecological restoration (Jin et al., 2011; Wang et al., 2010; Yaseef et al., 2010). Unsuitable vegetation types and improper management were recognized as the main reasons for increasingly serious soil moisture deficit in this region (Chen et al., 2007; Jia et al., 2017; Liu et al., 2018). Therefore, the selection of proper vegetation types and rational management strategies during restoration projects are of great significance to hydrological processes and for the sustainable development of reconstructed ecosystems.

Our study indicated that natural restoration, such as using shrublands and oak land, is better than vegetating a black locust land or an abandoned farmland in maintaining a sustainable soil water balance in this loess hilly region, which is consistent with previous conclusions (Deng et al., 2016). Under natural conditions, there is a dynamic balance between vegetation growth/succession and precipitation (Chen et al., 2008). In the present study, the shrubland showed higher soil water content, whereas dry soil layers might have developed in the land planted with black locust in its deep soil layers. Vegetation reconstruction or restoration should be adapted to local conditions, which means that proper vegetation types are supposed to be selected according to precipitation and soil water conditions (Liu et al., 2018; Wang et al., 2013). For example, it was reported that black locust and understory species exerted favourable ecological effects in the regions with annual precipitation of more than 500 mm (Jin et al., 2011). However, in regions with insufficient precipitation, large area degradation and plant mortality occurred under black locust plantations due to severe desiccation (Liang et al., 2018). Besides, attention should be given to the management of reconstructed vegetation. For example, the black locust in our experimental sites was initially planted with a density of about 3,300 plants per hectare. However, due to the intense competition for limited water resource among the individual trees, the overly high stand density led to high mortality of the plants (Jin et al., 2011). Previous studies have shown that 4,950–6,600 plants per hectare and less than 1,000 plants per hectare might be an optimal density for shrub and black locust in the Loess Plateau, respectively (Jin et al., 2011; Yang & Shao, 2000).

Furthermore, in the background of global warming, the trends of precipitation amount and its characteristics in the Loess Plateau become more complicated. Sun et al. (2016) suggested that consecutive dry days have significantly increased since 1980, and extreme precipitation events will become more violent and frequent in the Loess Plateau in the future. Therefore, vegetation types with better adaptability to varying precipitation will have competitive advantages under the climate conditions of the future. Accordingly, the protection and improvement of natural shrubland should be performed prior to artificial rehabilitation during future ecological restoration initiatives in this region, which will be more conducive to the growth of vegetation type and structure.

5 | CONCLUSIONS

Higher soil water content was observed either in the wet years or under natural shrublands all across the 0 to 300-cm soil profile. Both precipitation and vegetation type exhibited a strong influence on soil moisture. Precipitation showed a strong influence on soil moisture in shallow soil layers only, whereas vegetation types significantly affected soil moisture in deep soil layers. The temporal response of soil moisture to precipitation depended on timescales. Soil moisture in deep soil layer generally kept stable at monthly scale but showed positive responses on interannual scale. Shrubland showed steeper slope of ΔSWS_t to precipitation, implying its better adaptability to varying precipitation in this region. In addition, this vegetation type could significantly contribute to soil moisture accumulation, as reflected by the higher regression slope between ΔSWS_v and precipitation. Therefore, to maintain the sustainability of vegetation and prevent negative effects on soil moisture, natural shrubs should be the best choice for soil moisture conservation and ecological restoration efforts in the future.

ACKNOWLEDGEMENTS

This research was supported by the National Key R&D Program of China (grant 2017YFC0504601) and the National Natural Science Foundation of China (grants 41171419, 41471440, and 41411140035).

CONFLICT OF INTEREST

The authors declare that they have no conflict interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Ran-Ran Cheng https://orcid.org/0000-0002-2368-2484
Sheng Du https://orcid.org/0000-0002-5580-399X

REFERENCES

Cao, S., Chen, L., Shankman, D., Wang, C., Wang, X., & Zhang, H. (2011). Excessive reliance on afforestation in China's arid and semi-arid regions: Lessons in ecological restoration. *Earth-Science Reviews*, *104*(4), 240–245. https://doi.org/10.1016/j.earscirev.2010.11.002

Cao, S., Chen, L., & Yu, X. X. (2009). Impact of China's Grain for Green Project on the landscape of vulnerable arid and semi-arid agricultural regions: A case study in northern Shaanxi Province. *Journal of Applied Ecology*, *46*(3), 536–543. https://doi.org/10.1111/j.1365-2664.2008.01605.x

Carlyle-Moses, D. E., & Price, A. G. (2006). Growing-season stemflow production within a deciduous forest of southern Ontario. *Hydrological Processes*, *20*(17), 3651–3663. https://doi.org/10.1002/hyp.6380

Chen, H., Shao, M., & Li, Y. (2008). Soil desiccation in the Loess Plateau of China. *Geoderma*, *143*(1-2), 91–100. https://doi.org/10.1016/j.geoderma.2007.10.013

Chen, L. D., Huang, Z. L., Gong, J., Fu, B. J., & Huang, Y. L. (2007). The effect of land cover/vegetation on soil water dynamic in the hilly area of the loess plateau, China. *Catena*, *70*(2), 200–208. https://doi.org/10.1016/j.catena.2006.08.007

Deng, L., Yan, W. M., Zhang, Y. W., & Shangguan, Z. P. (2016). Severe depletion of soil moisture following land-use changes for ecological restoration: Evidence from northern China. *Forest Ecology and Management*, *366*, 1–10. https://doi.org/10.1016/j.foreco.2016.01.026

Descheemaeker, K., Nyssen, J., Poesen, J., Raes, D., Haile, M., Muys, B., & Deckers, S. (2006). Runoff on slopes with restoring vegetation: A case study from the Tigray highlands, Ethiopia. *Journal of Hydrology*, *331*(1-2), 219–241. https://doi.org/10.1016/j.jhydrol.2006.05.015

D'Odorico, P., & Porporato, A. (2004). Preferential states in soil moisture and climate dynamics. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(24), 8848–8851. https://doi.org/10.1073/pnas.0401428101

Du, S., Wang, Y. L., Kume, T., Zhang, J. G., Otsuki, K., Yamanaka, N., & Liu, G. B. (2011). Sapflow characteristics and climatic responses in three forest species in the semiarid Loess Plateau region of China. *Agricultural and Forest Meteorology*, *151*(1), 1–10. https://doi.org/10.1016/j.agrformet.2010.08.011

Du, S., Yamanaka, N., Yamamoto, F., Otsuki, K., Wang, S. Q., & Hou, Q. C. (2007). The effect of climate on radial growth of *Quercus liaotungensis* forest trees in Loess Plateau, China. *Dendrochronologia*, *25*(1), 29–36. https://doi.org/10.1016/j.dendro.2007.01.005

Duan, L. X., Huang, M. B., & Zhang, L. D. (2016). Differences in hydrological responses for different vegetation types on a steep slope on the Loess Plateau, China. *Journal of Hydrology*, *537*, 356–366. https://doi.org/10.1016/j.jhydrol.2016.03.057

Famiglietti, J. S., Rudnicki, J. W., & Rodell, M. (1998). Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas. *Journal of Hydrology*, *210*(1-4), 259–281. https://doi.org/10.1016/s0022-1694(98)00187-5

Farley, K. A., Jobbagy, E. G., & Jackson, R. B. (2005). Effects of afforestation on water yield: A global synthesis with implications for policy. *Global Change Biology*, *11*(10), 1565–1576. https://doi.org/10.1111/j.1365-2486.2005.01011.x

Fu, B., Wang, S., Liu, Y., Liu, J., Liang, W., & Miao, C. (2017). Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the Loess Plateau of China. *Annual Review of Earth and Planetary Sciences 45*, 223-243. https://doi:10.1146/annurev-earth-063016-020552

Guo, S., Zhu, H., Dang, T., Wu, J., Liu, W., Hao, M., … Syers, J. K. (2012). Winter wheat grain yield associated with precipitation distribution under long-term nitrogen fertilization in the semiarid Loess Plateau in China. *Geoderma*, *189*, 442–450. https://doi.org/10.1016/j.geoderma.2012.06.012

Hu, W., Shao, M. A., Han, F. P., & Reichardt, K. (2011). Spatio-temporal variability behavior of land surface soil water content in shrub- and grass-land. *Geoderma*, *162*(3-4), 260–272. https://doi.org/10.1016/j.geoderma.2011.02.008

Jia, X. X., Shao, M. A., Zhu, Y. J., & Luo, Y. (2017). Soil moisture decline due to afforestation across the Loess Plateau, China. *Journal of Hydrology*, *546*, 113–122. https://doi.org/10.1016/j.jhydrol.2017.01.011

Jia, Y. H., & Shao, M. A. (2014). Dynamics of deep soil moisture in response to vegetational restoration on the Loess Plateau of China. *Journal of Hydrology*, *519*, 523–531. https://doi.org/10.1016/j.jhydrol.2014.07.043

Jia, Y. H., Shao, M. A., & Jia, X. X. (2013). Spatial pattern of soil moisture and its temporal stability within profiles on a loessial slope in northwestern China. *Journal of Hydrology*, *495*, 150–161. https://doi.org/10.1016/j.jhydrol.2013.05.001

Jiao, F., Wen, Z., & An, S. (2011). Changes in soil properties across a chronosequence of vegetation restoration on the Loess Plateau of China. *Catena*, *86*(2), 110–116. https://doi.org/10.1016/j.catena.2011.03.001

Jiao, L., Lu, N., Fu, B. J., Gao, G. Y., Wang, S., Jin, T. T., … Zhang, D. (2016). Comparison of transpiration between different aged black locust (*Robinia pseudoacacia*) trees on the semi-arid Loess Plateau, China. *Journal of Arid Land*, *8*(4), 604–617. https://doi.org/10.1007/s40333-016-0047-2

Jimenez, M. N., Pinto, J. R., Ripoll, M. A., Sanchez-Miranda, A., & Navarro, F. B. (2017). Impact of straw and rock-fragment mulches on soil moisture and early growth of holm oaks in a semiarid area. *Catena*, *152*, 198–206. https://doi.org/10.1016/j.catena.2017.01.021

Jin, T. T., Fu, B. J., Liu, G. H., & Wang, Z. (2011). Hydrologic feasibility of artificial forestation in the semi-arid Loess Plateau of China. *Hydrology and Earth System Sciences*, *15*(8), 2519–2530. https://doi.org/10.5194/hess-15-2519-2011

Joffre, R., & Rambal, S. (1993). How tree cover influences the water-balance of mediterranean rangelands. *Ecology*, *74*(2), 570–582. https://doi.org/10.2307/1939317

Klocking, B., & Haberlandt, U. (2002). Impact of land use changes on water dynamics—A case study in temperate meso and macroscale river basins. *Physics and Chemistry of the Earth*, *27*(9-10), 619–629. https://doi.org/10.1016/s1474-7065(02)00046-3

Li, S., Liang, W., Fu, B., Lu, Y., Fu, S., Wang, S., & Su, H. (2016). Vegetation changes in recent large-scale ecological restoration projects and subsequent impact on water resources in China's Loess Plateau. *Science of the Total Environment*, *569*, 1032–1039. https://doi.org/10.1016/j.scitotenv.2016.06.141

Li, X. Y., Liu, L. C., Duan, Z. H., & Wang, N. (2014). Spatio-temporal variability in remotely sensed surface soil moisture and its relationship with precipitation and evapotranspiration during the growing season in the Loess Plateau, China. *Environmental Earth Sciences*, *71*(4), 1809–1820. https://doi.org/10.1007/s12665-013-2585-7

Liang, H. B., Xue, Y. Y., Li, Z. S., Wang, S., Wu, X., Gao, G. Y., … Fu, B. J. (2018). Soil moisture decline following the plantation of Robinia pseudoacacia forests: Evidence from the Loess Plateau. *Forest Ecology and Management*, *412*, 62–69. https://doi.org/10.1016/j.foreco.2018.01.041

Liu, Y., Miao, H. T., Huang, Z., Cui, Z., He, H. H., Zheng, J. Y., … Wu, G. L. (2018). Soil water depletion patterns of artificial forest species and ages on the Loess Plateau (China). *Forest Ecology and Management*, *417*, 137–143. https://doi.org/10.1016/j.foreco.2018.03.005

Liu, Y. X., Zhao, W. W., Wang, L. X., Zhang, X., Daryanto, S., & Fang, X. N. (2016). Spatial variations of soil moisture under *Caragana korshinskii Kom.* from different precipitation zones: field based analysis in the Loess Plateau, China. *Forests*, *7*(2), 31. https://doi.org/10.3390/f7020031

Longobardi, A., & Villani, P. (2008). Baseflow index regionalization analysis in a mediterranean area and data scarcity context: Role of the catchment permeability index. *Journal of Hydrology*, *355*(1-4), 63–75. https://doi.org/10.1016/j.jhydrol.2008.03.011

Maestre, F. T., Bautista, S., Cortina, J., & Bellot, J. (2001). Potential for using facilitation by grasses to establish shrubs on a semiarid degraded steppe. *Ecological Applications*, *11*(6), 1641–1655. https://doi.org/10.1890/1051-0761(2001)011[1641:pfufbg]2.0.co;2

Mahmood, R. (1996). Scale issues in soil moisture modelling: Problems and prospects. *Progress in Physical Geography*, *20*(3), 273–291. https://doi.org/10.1177/030913339602000302

Mei, X. M., Zhu, Q. K., Ma, L., Zhang, D., Liu, H. F., & Xue, M. J. (2018). The spatial variability of soil water storage and its controlling factors during dry and wet periods on loess hillslopes. *Catena*, *162*, 333–344. https://doi.org/10.1016/j.catena.2017.10.029

Messing, I., Fagerstrom, M. H. H., Chen, L. D., & Fu, B. J. (2003). Criteria for land suitability evaluation in a small catchment on the Loess Plateau in China. *Catena*, *54*(1-2), 215–234. https://doi.org/10.1016/s0341-8162(03)00066-3

Penna, D., Borga, M., Norbiato, D., & Fontana, G. D. (2009). Hillslope scale soil moisture variability in a steep alpine terrain. *Journal of Hydrology*, *364*(3-4), 311–327. https://doi.org/10.1016/j.jhydrol.2008.11.009

Qiu, Y., Fu, B. J., Wang, J., & Chen, L. D. (2001). Spatial variability of soil moisture content and its relation to environmental indices in a semi-arid gully catchment of the Loess Plateau, China. *Journal of Arid Environments*, *49*(4), 723–750. https://doi.org/10.1006/jare.2001.0828

Salve, R., Sudderth, E. A., St Clair, S. B., & Torn, M. S. (2011). Effect of grassland vegetation type on the responses of hydrological processes to seasonal precipitation patterns. *Journal of Hydrology*, *410*(1-2), 51–61. https://doi.org/10.1016/j.jhydrol.2011.09.003

Schlesinger, W. H., & Jasechko, S. (2014). Transpiration in the global water cycle. *Agricultural and Forest Meteorology*, *189*, 115–117. https://doi.org/10.1016/j.agrformet.2014.01.011

Schymanski, S. J., Sivapalan, M., Roderick, M. L., Beringer, J., & Hutley, L. B. (2008). An optimality-based model of the coupled soil moisture and root dynamics. *Hydrology and Earth System Sciences*, *12*(3), 913–932. https://doi.org/10.5194/hess-12-913-2008

Shi, W. Y., Yan, M. J., Zhang, J. G., Guan, J. H., & Du, S. (2014). Soil CO_2 emissions from five different types of land use on the semiarid Loess Plateau of China, with emphasis on the contribution of winter soil respiration. *Atmospheric Environment*, *88*, 74–82. https://doi.org/10.1016/j.atmosenv.2014.01.066

Shi, W. Y., Zhang, J. G., Yan, M. J., Yamanaka, N., & Du, S. (2012). Seasonal and diurnal dynamics of soil respiration fluxes in two typical forests on the semiarid Loess Plateau of China: Temperature sensitivities of autotrophs and heterotrophs and analyses of integrated driving factors. *Soil Biology & Biochemistry*, *52*, 99–107. https://doi.org/10.1016/j.soilbio.2012.04.020

Sun, W. Y., Mu, X. M., Song, X. Y., Wu, D., Cheng, A. F., & Qiu, B. (2016). Changes in extreme temperature and precipitation events in the Loess Plateau (China) during 1960-2013 under global warming. *Atmospheric Research*, *168*, 33–48. https://doi.org/10.1016/j.atmosres.2015.09.001

Tateno, R., Tokuchi, N., Yamanaka, N., Du, S., Otsuki, K., Shimamura, T., … Hou, Q. C. (2007). Comparison of litterfall production and leaf litter decomposition between an exotic black locust plantation and an indigenous oak forest near Yan'an on the Loess Plateau, China. *Forest Ecology and Management*, *241*(1-3), 84–90. https://doi.org/10.1016/j.foreco.2006.12.026

Tian, Q., Taniguchi, T., Shi, W. Y., Li, G. Q., Yamanaka, N., & Du, S. (2017). Land-use types and soil chemical properties influence soil microbial communities in the semiarid Loess Plateau region in China. *Scientific Reports*, *7*, 45289. https://doi.org/10.1038/srep45289

Tsunekawa, A., Liu, G. B., Yamanaka, N., & Du, S. (2014). *Restoration and Development of the Degraded Loess Plateau, China*. Tokyo: Springer.

Wang, G. Y., Innes, J. L., Lei, J. F., Dai, S. Y., & Wu, S. W. (2007). Ecology. China's forestry reforms. *Science*, *318*(5856), 1556–1557. https://doi.org/10.1126/science.1147247

Wang, J., Fu, B. J., Qiu, Y., & Chen, L. D. (2003). Analysis on soil nutrient characteristics for sustainable land use in Danangou catchment of the Loess Plateau, China. *Catena*, *54*(1-2), 17–29. https://doi.org/10.1016/s0341-8162(03)00054-7

Wang, S., Fu, B. J., Gao, G. Y., Liu, Y., & Zhou, J. (2013). Responses of soil moisture in different land cover types to rainfall events in a re-vegetation catchment area of the Loess Plateau, China. *Catena*, *101*, 122–128. https://doi.org/10.1016/j.catena2012.10.006

Wang, S., Fu, B. J., Gao, G. Y., Yao, X. L., & Zhou, J. (2012). Soil moisture and evapotranspiration of different land cover types in the Loess Plateau, China. *Hydrology and Earth System Sciences*, *16*(8), 2883–2892. https://doi.org/10.5194/hess-16-2883-2012

Wang, X. M., Chen, F., Hasi, E., & Li, J. C. (2008). Desertification in China: an assessment. *Earth-Science Reviews*, *88*(3-4), 188–206. https://doi.org/10.1016/j.earscirev.2008.02.001

Wang, Y., Shao, M., Zhu, Y., & Liu, Z. (2011). Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China. *Agricultural and Forest Meteorology*, *151*(4), 437–448. https://doi.org/10.1016/j.agrformet.2010.11.016

Wang, Y. Q., Shao, M. A., & Shao, H. B. (2010). A preliminary investigation of the dynamic characteristics of dried soil layers on the Loess Plateau of China. *Journal of Hydrology*, *381*(1-2), 9–17. https://doi.org/10.1016/j.jhydrol.2009.09.042

Xiao, L., Xue, S., Liu, G. B., & Zhang, C. (2014). Soil moisture variability under different land uses in the Zhifanggou catchment of the Loess Plateau, China. *Arid Land Research and Management*, *28*(3), 274–290. https://doi.org/10.1080/15324982.2013.860500

Xin, N., Zhang, Y. Q., & Wang, L. X. (2001). *The Study on Dryland Agriculture in North China*. Beijing: Chinese Agriculture Press.

Yamanaka, N., Hou, Q. C., & Du, S. (2014). Vegetation of the Loess Plateau. In *Restoration and Development of the Degraded Loess Plateau, China* (pp. 49–60). Tokyo: Springer.

Yan, M. J., Zhang, J. G., He, Q. Y., Shi, W. Y., Otsuki, K., Yamanaka, N., & Du, S. (2016). Sapflow-based stand transpiration in a semiarid natural oak forest on China's Loess Plateau. *Forests*, *7*(10), 227. https://doi.org/10.3390/f7100227

Yang, L., Chen, L. D., Wei, W., Yu, Y., & Zhang, H. D. (2014). Comparison of deep soil moisture in two re-vegetation watersheds in semi-arid regions. *Journal of Hydrology*, *513*, 314–321. https://doi.org/10.1016/j.jhydrol.2014.03.049

Yang, L., Wei, W., Chen, L. D., Jia, F., & Mo, B. R. (2012). Spatial variations of shallow and deep soil moisture in the semi-arid Loess Plateau, China. *Hydrology and Earth System Sciences*, *16*(9), 3199–3217. https://doi.org/10.5194/hess-16-3199-2012

Yang, W. Z., & Shao, M. A. (2000). *Studies on Soil Moisture on the Loess Plateau*. Beijing: Science Press.

Yao, S. X., Zhao, C. C., Zhang, T. H., & Liu, X. P. (2013). Response of the soil water content of mobile dunes to precipitation patterns in Inner Mongolia, northern China. *Journal of Arid Environments*, *97*, 92–98. https://doi.org/10.1016/j.jaridenv.2013.06.003

Yaseef, N. R., Yakir, D., Rotenberg, E., Schiller, G., & Cohen, S. (2010). Ecohydrology of a semi-arid forest: Partitioning among water balance components and its implications for predicted precipitation changes. *Ecohydrology*, *3*(2), 143–154. https://doi.org/10.1002/eco.65

Yu, B. W., Liu, G. H., Liu, Q. S., Wang, X. P., Feng, J. L., & Huang, C. (2018). Soil moisture variations at different topographic domains and land use types in the semi-arid Loess Plateau, China. *Catena*, *165*, 125–132. https://doi.org/10.1016/j.catena.2018.01.020

Zhang, J. G., Guan, J. H., Shi, W. Y., Yamanaka, N., & Du, S. (2015). Interannual variation in stand transpiration estimated by sap flow measurement in a semi-arid black locust plantation, Loess Plateau, China. *Ecohydrology*, *8*(1), 137–147. https://doi.org/10.1002/eco.1495

Zhang, J. G., He, Q. Y., Shi, W. Y., Otsuki, K., Yamanaka, N., & Du, S. (2015). Radial variations in xylem sap flow and their effect on whole-tree water use estimates. *Hydrological Processes*, *29*(24), 4993–5002. https://doi.org/10.1002/hyp.10465

Zhang, Q. D., Wei, W., Chen, L. D., & Yang, L. (2019). The joint effects of precipitation gradient and afforestation on soil moisture across the Loess Plateau of China. *Forests*, *10*(3), 285. https://doi.org/10.3390/f10030285

Zhang, Y. W., Deng, L., Yan, W. M., & Shangguan, Z. P. (2016). Interaction of soil water storage dynamics and long-term natural vegetation succession on the Loess Plateau, China. *Catena*, *137*, 52–60. https://doi.org/10.1016/j.catena.2015.08.016

Zhao, Y. L., Wang, Y. Q., Wang, L., Fu, Z. H., Zhang, X. Y., & Cui, B. L. (2017). Soil-water storage to a depth of 5 m along a 500-km transect on the Chinese Loess Plateau. *Catena*, *150*, 71–78. https://doi.org/10.1016/j.catena.2016.11.008

Zhao, Y. L., Wang, Y. Q., Wang, L., Zhang, X. Y., Yu, Y. L., Jin, Z., … An, Z. S. (2019). Exploring the role of land restoration in the spatial patterns of deep soil water at watershed scales. *Catena*, *172*, 387–396. https://doi.org/10.1016/j.catena.2018.09.004

Zheng, Z. M., Fu, B. J., Hu, H. T., & Sun, G. (2014). A method to identify the variable ecosystem services relationship across time: A case study on Yanhe Basin, China. *Landscape Ecology*, *29*(10), 1689–1696. https://doi.org/10.1007/s10980-014-0088-x

How to cite this article: Cheng R-R, Chen Q-W, Zhang J-G, Shi W-Y, Li G, Du S. Soil moisture variations in response to precipitation in different vegetation types: A multi-year study in the loess hilly region in China. *Ecohydrology*. 2020;e2196. https://doi.org/10.1002/eco.2196