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Decline in soil moisture due to vegetation restoration on the Loess Plateau of China

Bingqian Su[1,2,3] | Zhouping Shangguan[1,3]

[1] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling 712100, PR China
[2] University of Chinese Academy of Sciences, Beijing 100049, PR China
[3] Chinese Academy of Sciences and Ministry of Water Resources, Institute of Soil and Water Conservation, Yangling 712100, PR China

Correspondence
Prof. Zhouping Shangguan, Xinong Rd. 26, Institute of Soil and Water Conservation, Yangling, Shaanxi 712100, PR China.
Email: shangguan@ms.iswc.ac.cn

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Abstract

Afforestation brings lots of water-related benefits, including reducing soil erosion and improving water conservation, simultaneously; it is considered to be a land use activity, which threatens water resources security. Characterizing the response of soil moisture to revegetation is important for the sustainability of water and plants on the Loess Plateau of China. In this study, we conducted a meta-analysis of 1,262 observations from 66 published studies to evaluate the effect of land use on the soil moisture of forest, shrubland, and grassland regions at a depth of 5 m in different ecological zones of the Loess Plateau. The results indicated that (a) Soil moisture content (SMC) decreased after land use conversion in all three ecological zones and was inconsistent among different soil layers. (b) Except for other grassland species, changes in the response size for soil moisture were not significant among any tree species, including *Pinus tabuliformis*, *Robinia pseudoacacia*, other forest species, *Caragana korshinskii*, other shrubland species, and *Medicago sativa*. (c) Soil moisture changes varied with different restoration types and ages. (d) The change in response to precipitation was not significant, whereas the change in response to temperature was significant. In addition, the responses of the initial soil moisture levels exhibited a negative correlation with revegetation. These results indicate that it is vital for scientific afforestation in the Loess Plateau to complement local climate conditions and soil properties.

KEYWORDS

ecohydrology, land use types, Loess Plateau, soil moisture, vegetation restoration

1 | INTRODUCTION

Soil moisture is a critical variable controlling many terrestrial ecosystem processes, including atmospheric, hydrologic, geomorphic, and biologic processes (Legates et al., 2011). Soil moisture acts as an essential component of plant growth and an important water resource for maintaining the sustainable development of the eco-environment, particularly in the arid and semiarid regions. Improving the knowledge about soil moisture dynamics is of key importance to accurately understand the soil moisture status (Wang, Shao, & Liu, 2013). However, soil moisture is highly variable in space scales and time scales resulted from soils, vegetation, topography, land uses, and climate that play together to determine soil moisture dynamics (Vereecken et al., 2014). Therefore, it is necessary to understand the changes in soil moisture and the soil water distribution patterns in the arid and semiarid regions.

Land degradation has been considered a vital economic, social, and ecological problem owing to its impact on food security and ecological environment (Lu, Batistella, Mausel, & Moran, 2010), which has stroked the attention of the world, especially on the Loess Plateau of China. The Loess Plateau, characterized by the deepest loess deposits in the world, not only has a unique landscape but is also known for its fragile ecosystem, which is especially vulnerable to soil erosion (Fu et al., 2016). Although some measures, such as the construction of check dams (Zhao, Mu, Wen, Wang, & Gao, 2013) and terraces (Wei et al., 2016), have resulted in prominent reductions in soil erosion, vegetation restoration has also had an important influence on soil and water conservation (Lu et al., 2012). In addition, vegetation plays a critical role in the global carbon cycle and provides important mechanisms in terrestrial ecosystems that enhance their carbon sequestration capacity and decrease greenhouse gas emissions (Bonan, 2008; Jackson et al., 2008; Pan et al., 2011; Piao et al., 2009).

The Grain for Green program, implemented by the Chinese government in 1999, was one of six major forestry projects (Wu et al., 2008) in China aiming to control serious soil erosion (Cerda, 1998; Deng, Shangguan, & Li, 2012; Nearing et al., 2005) and restore the ecological environment. Due to this program, vegetation coverage increased from 31.6% in 1999 to 59.6% in 2013 due to the conversion of sloping farmland to forest, shrubland, and grassland, and the annual sediment discharge of the Yellow River declined to historically low levels of approximately 0.2 Gt (Chen et al., 2015). However, in water-limited arid and semiarid areas, large-scale artificial afforestation is considered a land use activity that severely impacts soil water conditions through transpiration, infiltration, and interception (Aijm & Keenan, 2007), which may cause negative effects, such as a 'dried soil layer' (Wang, Shao, Zhu, & Liu, 2011). Conversely, soil moisture substantially affects the growth and development of vegetation, which may impact the growth form, resulting in 'little-old-man tree' forms in dry areas (Shao, Jia, Wang, & Zhu, 2016). Furthermore, food deficits (Chen et al., 2015), ecosystem service reductions (Liu, Li, Ouyang, Tam, & Chen, 2008), and other negative impacts have occurred in this region. Accordingly, vegetation may directly and indirectly affect the regulation of the hydrologic cycle (Gerten, Schaphoff, Haberlandt, Lucht, & Sitch, 2004), thus influencing the distribution pattern of soil moisture (An et al., 2017).

Previous studies have mainly focused on changes in soil moisture caused by different vegetation types in some scattered locations of the Loess Plateau. However, whether to continue the expansion of revegetation remains a controversial topic in different studies, and the large-scale estimation of SMC dynamics may be limited by the use of a small number of sampling sites. Accordingly, we conducted a meta-analysis to quantify the effects of large-scale afforestation and reforestation on SMC across the Chinese Loess Plateau in this study. The objectives of this study were (a) to quantify the effect of afforestation and reforestation on the SMC of five soil layers by different land use types in three ecological zones; (b) to compare the changes in the SMC among common vegetation types; and (c) to demonstrate the relationships between the SMC under current land use conditions and initial conditions. Overall, the results evaluate the factors affecting SMC in the 0- to 500-cm soil profile, which will provide information for the sustainable management of land use changes, the selection of vegetation species, and the utilization of water sources in the Loess Plateau and other similar regions.

2 | MATERIALS AND METHODS

2.1 | Data sources

Literature searches were performed using Web of Science (United States) and CNKI (China Knowledge Resource Integrated Database, China; 2000–2017) with the search terms 'soil water' or 'soil moisture' and 'Loess Plateau.' To avoid publication bias, the following criteria were set to select related studies: (a) at least one of the relevant vegetation types (i.e., forest, shrubland, and grassland) and a control (farmland or grassland) representing the soil moisture conditions before the land use conversion was reported; (b) the gravimetric farmland within the 0- to 500-cm layer (0–100, 100–200, 200–300, 300–400, and 400–500 cm) was measured or calculated in both the control and treatments; (c) location, temperature, and precipitation were clearly recorded; (d) studies were excluded if the experiments were conducted in the laboratory. Data presented in graphical forms were extracted using WebPlotDigitizer (Burda, O'Connor, Webber, Redmond, & Perdue, 2017). In general, all available data from the publications were extracted, including sites, latitude (N), longitude (E), mean annual temperature (MAT), mean annual precipitation (MAP), ecological zones (EZ), slope, restoration type, land use type, species, restoration age, replications, initial soil moisture, and soil moisture after the vegetation restoration. The Loess Plateau was divided into three different ecological zones in accordance with the fragility of eco-environment, which was calculated by using annual precipitation as the dominant factor and combining with other meteorological, erosion, vegetation, social, and economic factors, including the arid and semiarid area in the north (EZ 1), semiarid area in the middle (EZ 2), and semihumid area in the south (EZ 3; Wu & Yang, 1998). The 1,262 total observations from five provinces across the Loess Plateau of China (Figure 1) are shown in Table 1.

2.2 | Meta-analysis

In this study, the response ratio (r) of each variable in the individual studies was calculated as the ratio of the mean soil moisture content of the current land use type (X_e) compared with that of the control plots (X_c) to show the size of the effect, Equation (1):

$$r = X_e / X_c. \tag{1}$$

Most of the published papers reported only mean values without standard deviations or standard errors; therefore, we used unweighted meta-analysis, as described in earlier studies (Deng, Yan, Zhang, & Shangguan, 2016; Powers, Corre, Twine, & Veldkamp, 2011). The mean response size (R) was defined as

$$R = r - 1. \tag{2}$$

The 95% confidence interval (CI) of the means was calculated by Equations 3 and 4 using a previously described method (Luo, Hui, & Zhang, 2006):

$$SE_R = \sqrt{\frac{V_R}{N}}, \tag{3}$$

$$95\%\text{CI} = 1.96 \times SE_R, \tag{4}$$

where SE_R is the standard error of the response size for soil moisture, V_R is the variance in the response size, and N is the number of observations. The 95% CI was calculated for the overall data and for each category: If the 95% CI overlapped with zero, no significant response was detected. The grouping factors were considered significantly different from each other if their 95% CIs did not include zero.

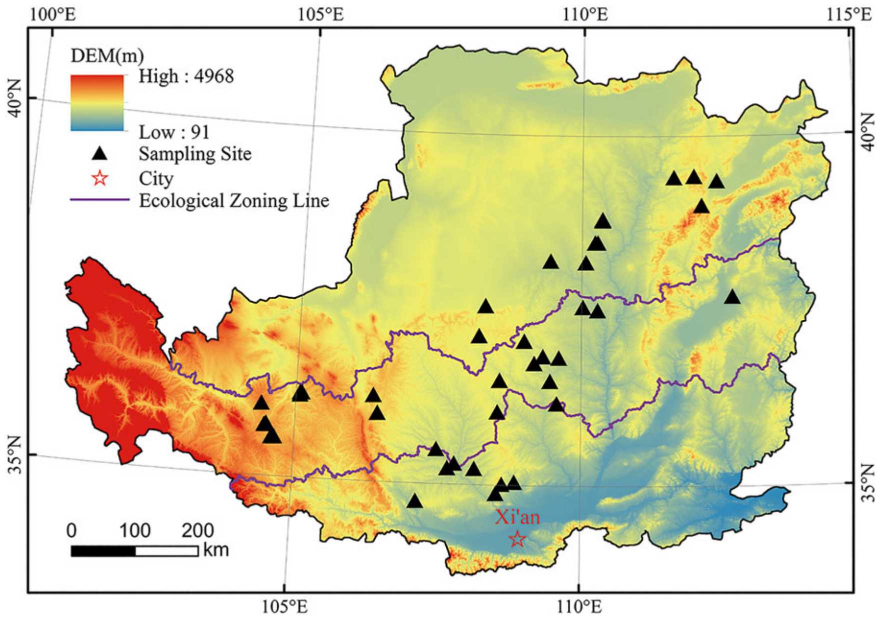

FIGURE 1 The distribution of sampling sites on the Loess Plateau [Colour figure can be viewed at wileyonlinelibrary.com]

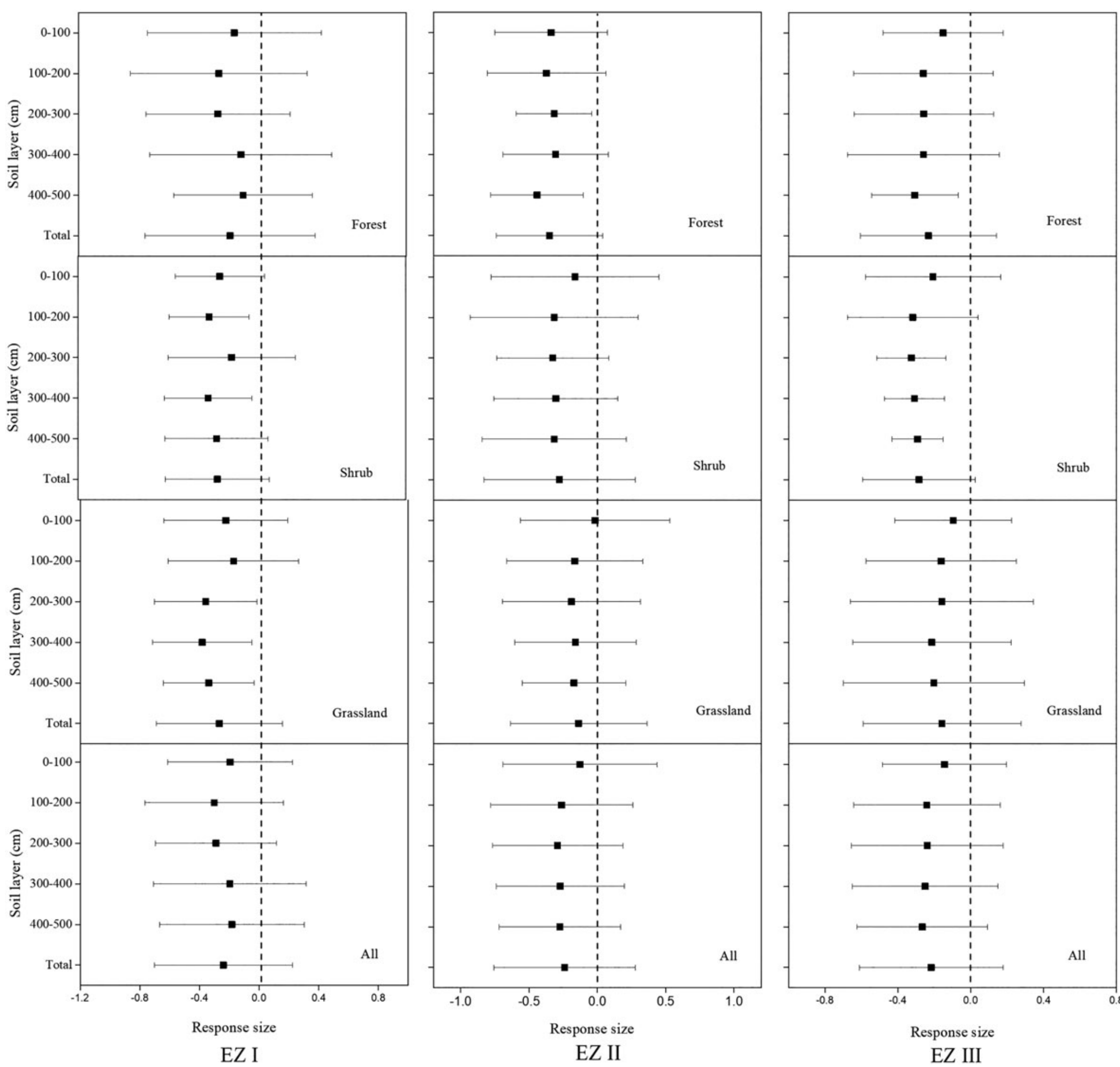

FIGURE 2 Response size of forest, shrubland, and grassland in five soil layers in three ecological zones (1, 2, and 3). The block with the error bar indicates the mean response size with a 95% CI

2.3 | Data analysis

The mean values (Mean) and standard deviations (SD) of the response size of each group were calculated. The SD is not appropriate for comparing data with vastly different means, so we also calculated the coefficient of variation (CV; Owe, Jones, & Schmugge, 1982) in this study, which is defined as the SD divided by the Mean, to better compare the SMC response sizes. The concerned variables of SMC changes were evaluated by analysis of variance (ANOVA). Least significant difference (LSD) was applied to distinguish among different plots. Levene's test was applied to test homogeneity of variance. The correlations between the relative changes in soil moisture after revegetation and the initial soil moisture were examined by linear regression analysis. All statistical analyses were conducted by the SPSS statistical package version 22.0 (SPSS Inc., Chicago, Illinois).

3 | RESULTS

3.1 | Decrease in soil moisture due to changes in land use types

Across all the soil profiles, all response sizes of the SMC in 0–500 cm are negative values for each land use type in three ecological zones (Figure 2). In Ecological Zone 1, the decrease in SMC in the surface layer (−0.19 in 0–100 cm) and in the deeper layers (−0.20 in 300–400 cm and −0.18 in 400–500 cm) was not significant (p = 0.978 and 0.824), whereas that in the 100- to 200-cm layer (−0.30) and in the 200–300 cm (−0.29) was significant (p = 0.009 and 0.028). In Ecological Zone 2, the land use conversion had a significant (p = 0.000 for 0–100 cm and other four layers) reduction on soil moisture in the shallower layers (−0.13 in 0–100 cm) and in the deeper layers (−0.26 in 100–200 cm, −0.29 in 200–300 cm, −0.27 in 300–400 cm, and − 0.28 in 400–500 cm), but there was no significant (p = 0.492) reduction between the four deeper layers. In Ecological Zone 3, there was a significant (p = 0.026) decrease in SMC in the five soil layers (0–100 [−0.14], 100–200 [−0.24], 200–300 [−0.24], 300–400 [−0.25], and 400–500 cm [−0.27]). Moreover, the SMC in the 0- to100-cm layer displayed a higher variability (i.e., CV) compared with other soil layers no matter which ecological zone or which vegetation type (Table S2).

Overall, the forest, shrubland, and grassland in the three ecological zones exhibited similarly negative effects (−0.24 in 0–500 cm) on the soil moisture content (Supplementary Table, Figure 2). In the case of forest, there was no significant (p = 0.146) reduction between the five soil profiles in Ecological Zone 1; there was obvious difference in the SMC of the 0- to 100-cm layer compared with that of the other soil layers (p = 0.013 for 100–200 cm, p = 0.000 for 200–300 cm, p = 0.001 for 300–400 cm, and p = 0.002 for 400–500 cm) in Ecological Zone 2. In Ecological Zone 3, the reduction of SMC in the 0- to 100-cm layer was decreased nonsignificantly (p = 0.054 and 0.106) than that in the 200- to 30-cm layer and the 300- to 400-cm layer; nevertheless, that in the 100- to 200-cm layer and 400- to 500-cm layer was reduced significantly (p = 0.029 and 0.026). In the case of shrubland, there was no significant (p = 0.109, 0.082, and 0.304) decrease in the SMC of the five soil layers in the three ecological zones. In the case of grassland, the reduction in the surface layer (0–100 cm) soil moisture of Ecological Zone 2 was significantly different than that in the other four layers (p = 0.007, 0.002, 0.011, and 0.009 for 100–200, 200–300, 300–400, and 400–500 cm, respectively). In addition, the soil moisture in Ecological Zones 1 and 3 exhibited nonsignificant variations (p = 0.259 and 0.292) among the five soil layers.

3.2 | Decrease in soil moisture of different vegetation types

All measured soil moisture contents displayed decreasing trends in response to the natural or artificial regeneration of vegetation (Table 1). The response size was not significant (p = 0.066) for all species types, except for the other grassland species (OG), which was associated with an average decrease of 14%. No significant (p = 0.201, 0.084, 0.098, and 0.258) difference was found in the response of the soil moisture content among five soil layers of *Pinus tabuliformis* (PT), other forest species (OF), *Caragana korshinskii* (CK), and OG. However, response size of *Robinia pseudoacacia* (RP) in the 0- to 100-cm layer had a significant (p = 0.006 and 0.012) difference with that in the 200- to 300-cm layer and 400- to 500-cm layer but had no significant (p = 0.031 and 0.19 for 100–200 and 300–400 cm, respectively) difference with those of the other soil layers. For other shrub species (OS), response size in the 0–100 cm was only significantly different with that in the 100- to 200-cm layer and 200- to 300-cm layer (p = 0.009 and 0.037). In contrast, for *Medicago sativa* (MS), the differences in the response size of the 0- to 100-cm layer and those of the other layers were significant (p = 0.000 for other four layers).

3.3 | Changes in soil moisture due to restoration type and restoration age

Natural restoration and artificial afforestation did not cause significant (p = 0.985) declines in SMC (Figure 3). For natural restoration, significant (p = 0.008 and p = 0.004) differences in the SMC changes between the forest and the shrubland or grassland were found. However, there were no significant (p = 0.565) differences between the change in the SMC of the shrubland and grassland. The SMC in the forest and shrubland was significantly more decreased than that in the grassland (p = 0.000 and p = 0.004), whereas the SMC in the forest was not significantly more decreased than that in the shrubland (p = 0.461).

A marginally significant (p = 0.008) decrease in SMC occurred under restoration periods of 1–10 and >20 years, but the change between 10 and 20 and >20 years was not significant (p = 0.539). For forest, nonsignificant (p = 0.130) decreases were identified among different restoration periods (i.e., 1–20, 20–40, and >40 years), which was the same case for shrubland among three restoration periods (i.e., 1–10, 10–20, and >20 years, p = 0.175). For grassland, response size of 1–10 years had a significant (p = 0.001 and P = 0.009) difference with that of 10–20 and >20 years. Nevertheless, there was no

TABLE 1 The impact of forest, shrubland, and grassland on soil moisture in different soil layers. The values representing response size are mean ± 95% CI, and the numbers of observations are displayed in the parenthesis. The same lowercase letters indicate nonsignificant differences among the five soil layers, and the same uppercase letters indicate nonsignificant differences between different vegetation types, and different lowercase letters and uppercase letters indicate significant differences

Land use types	Species	Soil layer (cm) 0–100	100–200	200–300	300–400	400–500	Total
Forest	PT	−0.16 ± 0.17a (*n* = 15)	−0.24 ± 0.20a (*n* = 15)	−0.28 ± 0.19a (*n* = 14)	−0.24 ± 0.29a (*n* = 10)	−0.28 ± 0.12a (*n* = 10)	−0.24 ± 0.21B (*n* = 64)
	RP	−0.15 ± 0.21a (*n* = 23)	−0.29 ± 0.22a (*n* = 21)	−0.35 ± 0.23a (*n* = 17)	−0.33 ± 0.22a (*n* = 13)	−0.36 ± 0.18a (*n* = 10)	−0.28 ± 0.23B (*n* = 84)
	OF	−0.21 ± 0.25a (*n* = 45)	−0.32 ± 0.23a (*n* = 43)	−0.33 ± 0.22a (*n* = 34)	−0.29 ± 0.26a (*n* = 29)	−0.25 ± 0.26a (*n* = 25)	−0.28 ± 0.25B (*n* = 176)
Shrubland	CK	−0.14 ± 0.29a (*n* = 24)	−0.29 ± 0.32a (*n* = 22)	−0.31 ± 0.18a (*n* = 21)	−0.24 ± 0.28a (*n* = 20)	−0.29 ± 0.29a (*n* = 14)	−0.25 ± 0.28B (*n* = 101)
	OS	−0.22 ± 0.23a (*n* = 32)	−0.34 ± 0.19a (*n* = 29)	−0.32 ± 0.16a (*n* = 23)	−0.31 ± 0.14a (*n* = 21)	−0.30 ± 0.15a (*n* = 17)	−0.29 ± 0.19B (*n* = 122)
Grassland	MS	−0.05 ± 0.28a (*n* = 33)	−0.26 ± 0.22b (*n* = 33)	−0.32 ± 0.16b (*n* = 29)	−0.28 ± 0.16b (*n* = 26)	−0.28 ± 0.21b (*n* = 21)	−0.23 ± 0.24B (*n* = 142)
	OG	−0.13 ± 0.22a (*n* = 54)	−0.19 ± 0.26a (*n* = 54)	−0.14 ± 0.28a (*n* = 41)	−0.12 ± 0.24a (*n* = 36)	−0.12 ± 0.21a (*n* = 26)	−0.14 ± 0.25A (*n* = 211)

Note. CK: *Caragana korshinskii*; MS: *Medicago sativa*; OF: other forest species; OG: other grassland species; OS: other shrub species; PT: *Pinus tabuliformis*; RP: *Robinia pseudoacacia*.

significant (p = 0.825) difference between the change in the SMC of 10–20 and >20 years.

3.4 | Changes in soil moisture under various precipitation and temperature conditions

The climatic conditions of the study sites, MAP, and MAT, also affected the soil moisture content. A decrease in soil moisture was observed in the forest, shrubland, and grassland regardless of the change in precipitation between the different sites. However, the response size under various precipitation was not significant (p = 0.523). In contrast, the change in the response size under different temperatures only between <6°C and 8–10°C was significant (p = 0.001). Compared with the response under temperatures of <6°C and >10°C, there was a more pronounced decrease when the temperature was 6–8°C and 8–10°C (Figure 4).

3.5 | Relationship between the soil moisture after vegetation restoration and the initial soil moisture

The response size of revegetation displayed significantly negative correlations with the initial soil moisture in all three ecological zones (Figure 5). In terms of land use types, a significantly negative interaction between the soil moisture after vegetation restoration and the initial soil moisture was found for the responses of forest, shrubland, and grassland in Ecological Zones 1 and 2, whereas the interaction between the soil moisture after vegetation restoration and the initial soil moisture in Ecological Zone 3 exhibited a negative but nonsignificant correlation in the forest and shrubland areas (Figure 5i,j).

3.6 | Changes in soil moisture affected by other factors

In our study, we provided the definition of 'sunny' and 'shady.' It is sunny when the azimuth changes between 135° and 315° (due north is 0°), otherwise is shady (i.e., azimuth changes between 0°–135° and 315°–360°). SMC changes in forest and shrubland were significantly (p = 0.000 and 0.373) affected by the slope aspect, namely, sunny or shady. However, aspect affected nonsignificantly (p = 0.583) the SMC of the grassland (Figure 6).

In regard to different forest types, there was no significant (p = 0.569) difference in SMC changes between the broad-leaved forest and coniferous forest (Figure 7). It could be because the broad-leaved forest and coniferous forest in our study have the similar growth conditions during the period of revegetation.

4 | DISCUSSION

4.1 | Vertical distribution of soil moisture in the Loess Plateau

Our results indicated a decrease in the soil moisture content of the entire soil profile (0–500 cm) in the Loess Plateau, which is consistent

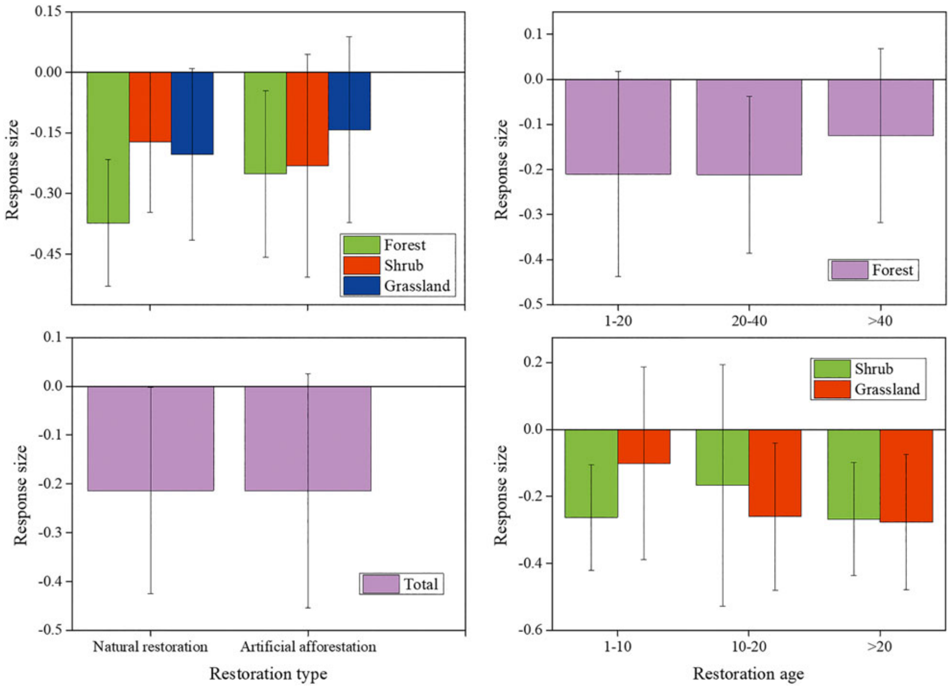

FIGURE 3 Response size of two restoration types (natural restoration and artificial afforestation) and three restoration ages (1–10, 10–20, and >20 years) for three land use types (forest, shrubland, and grassland) [Colour figure can be viewed at wileyonlinelibrary.com]

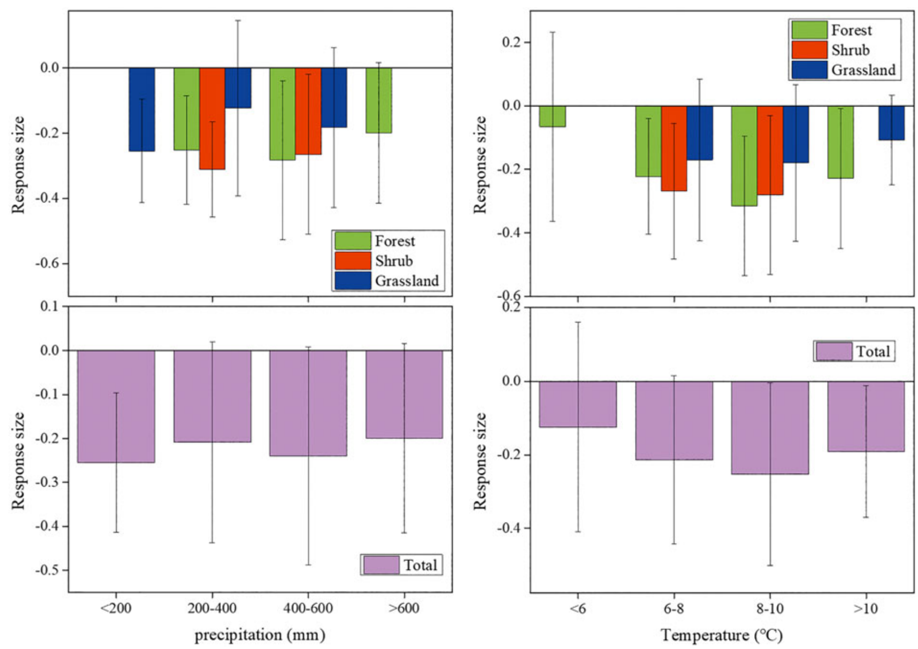

FIGURE 4 Response size of precipitation and temperature in three land use types (forest, shrubland, and grassland) [Colour figure can be viewed at wileyonlinelibrary.com]

with early findings (Yang, Wei, Chen, & Mo, 2012). However, as we showed earlier, changes in SMC were not uniform in different soil layers. Some studies have reported a decrease in SMC in the 0- to 250-cm layer and an increase in SMC in the 250- to 500-cm layer (Wang et al., 2013). Moreover, changes in SMC differed among the three ecological zones due to the differences in climate conditions, soil properties, human activities, and other factors.

The Grain for Green Program has largely decreased soil moisture in the Loess Plateau due to the intensification of the soil water consumption under plant roots, which may cause considerable impacts on human lives and water shortages. The changes in land use may significantly affect the hydrological processes in the soil–vegetation–atmosphere system and thus impact water resources based on the root densities of the various soil layers (Wang et al., 2013). For example,

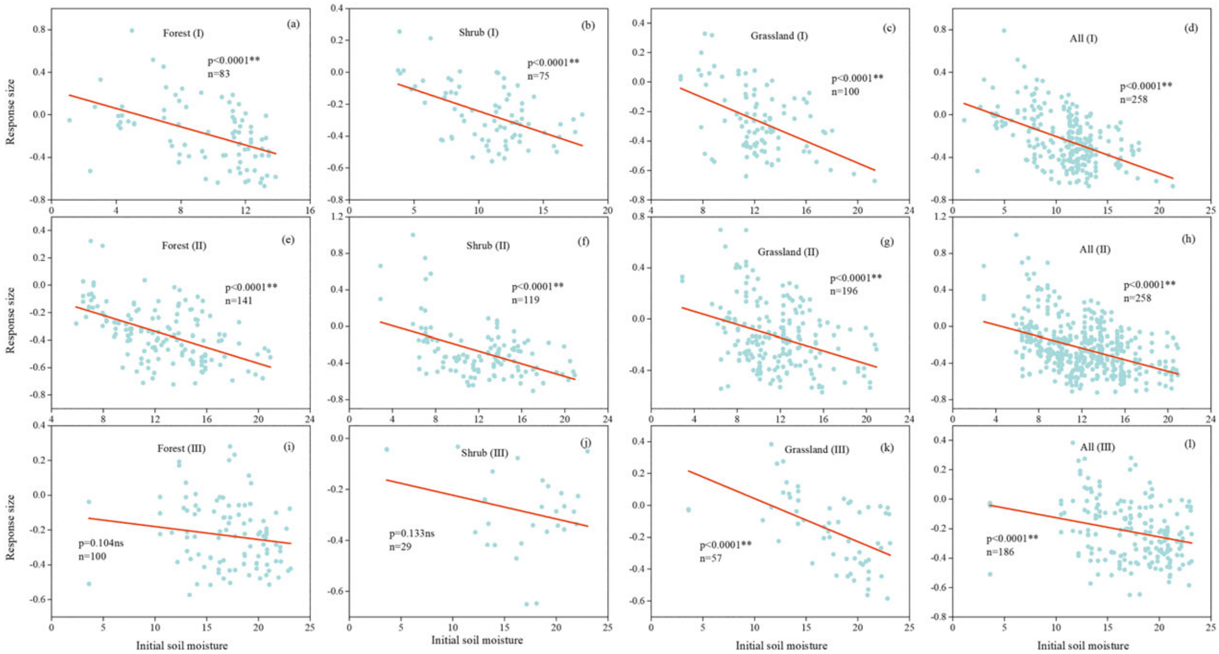

FIGURE 5 Response size of current land use soil moisture changes compared with the initial soil moisture level of forest, shrubland, and grassland in three ecological zones (1, 2, and 3) [Colour figure can be viewed at wileyonlinelibrary.com]

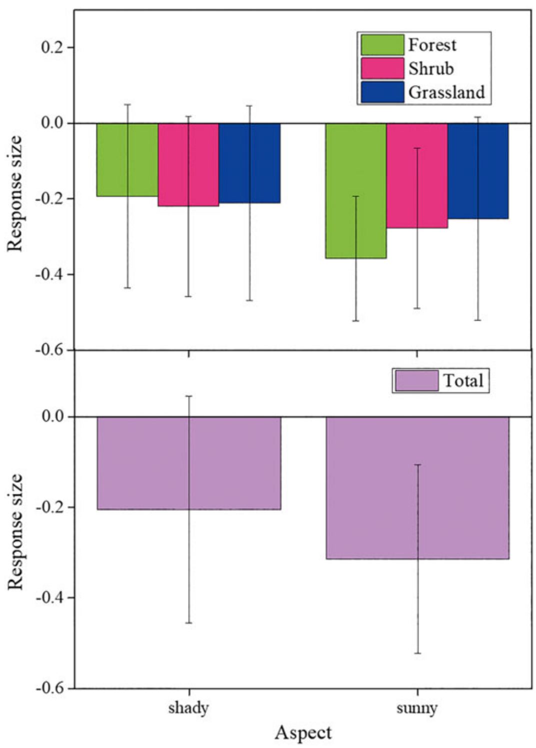

FIGURE 6 Response size of slope aspect (shady or sunny) in three land use types (forest, shrubland, and grassland) [Colour figure can be viewed at wileyonlinelibrary.com]

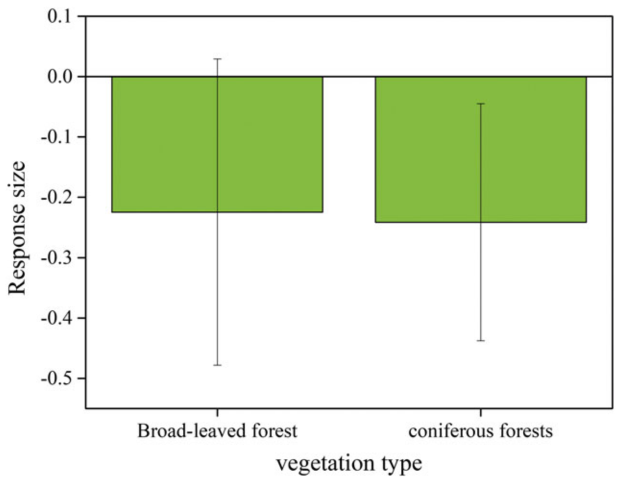

FIGURE 7 Response size of soil moisture content for two vegetation types (broad-leaved forest and coniferous forest) [Colour figure can be viewed at wileyonlinelibrary.com]

compared with shrubland and grassland species, the forest species in this study, including *P. tabuliformis*, *R. pseudoacacia*, and others, caused greater decreases in soil moisture, probably due to their deeper roots. Forests consume more water, and their root systems can lead to soil moisture deficits (Markewitz, Devine, Davidson, Brando, & Nepstad, 2010) and ultimately give rise to dry soil layers, which may occur not only in forest sites but also in shrubland and grassland sites (Yan, Deng, Zhong, & Shangguan, 2015). Plant roots deposit deeper soil water into shallower layers when plants are allowed to consume soil water (Lee, Oliveira, Dawson, & Fung, 2005). In this way, the water transport efficiency of deep roots increases, meeting the demands of the plants during the dry season. This implies that the distribution pattern of SMC under different land use types is closely related to the root profile distribution. For example, for the shallow soil layer (i.e., 0–75 cm), where roots of all land use types exist, variabilities in the soil moisture profiles were mainly influenced by land use types and topography. For the deep soil layer, climate, soil texture, and other factors also influenced the SMC distributions (Wang et al., 2013).

4.2 | Factors affecting soil moisture after changes in land use

In our study, 1,262 observations clearly indicated that vegetation restoration could induce the decline in soil moisture. Other research also pointed out that restoration of forest and grassland may decrease soil moisture, which impacts the growth and development of vegetation (Jia, Shao, Zhu, & Luo, 2017). In addition to the above factors, the differences in soil moisture may be ascribed to the sampling seasons. Furthermore, precipitation during the sampling period induced discrepancies in soil moisture, and these discrepancies were considerably different in each sampling site, especially in the 0- to 100-cm soil layer, because soil moisture in the topsoil could be temporarily increased by precipitation.

The dynamic changes in the influence of diverse factors affecting soil moisture on the response size differed under various climate, soil and topographical conditions, and different vegetation types. Understanding the dominant factors affecting the SMC distribution is essential to the sustainable management of water resources, land use, and vegetation plantation. For example, changes in slope position, aspect, elevation, and degree have widely been demonstrated to affect soil moisture in the three studied land use types. In addition to the effect of slope aspect on SMC we analyzed in the paper, some researchers concluded that slope gradients (Yang, Dou, Liu, & An, 2017) and slope positions (Cao, Jiang, Ying, Zhang, & Han, 2011) influenced soil moisture spatial heterogeneity. Due to the existence of loess in the Loess Plateau, it is essential to take soil texture into account when evaluating soil moisture conditions. Some studies have shown that SMC had positive correlations with the clay and silt contents and a negative correlation with the sand content (Wang et al., 2013), implying that soil texture is a factor affecting the distribution of SMC.

Currently, land overuse, especially overgrazing, is deteriorating the fragile ecological environment. The variations in grazing seasons, grazing periods, and grazing intensities may be another reason for the differences in the SMC decrease.

In our meta-analysis, nonsignificant declines in SMC were found between natural restoration and artificial afforestation. Ren et al. (2018) also compared the effect of afforestation and natural revegetation on soil moisture and suggested that afforestation is the better option for the Loess Plateau only in areas with adequate annual rainfalls. Liang et al. (2018) analyzed spatial–temporal variations in soil moisture following the plantation of *R. pseudoacacia* forests on the Loess Plateau and suggested that afforestation should be avoided in areas where the local total precipitation is insufficient for replenishing the soil moisture. Many vegetation recovery activities, such as planting nonnative trees that consume a large amount of water in dry areas and indiscriminately increasing planting density (Wang & Shao, 2004) in the process of vegetation construction, have been inappropriate and resulted in a sharp decline in SMC. Coupled with the low precipitation, high evaporation, and unsupplied groundwater in the Loess Plateau (Yang et al., 2012), the soil moisture in this region is insufficient to meet the requirements of vegetation growth. Accordingly, it is vital to select vegetation types based on theoretically matching plant characteristics to the climate conditions and soil properties of certain places (Chen, Shang, Qian, Jing, & Liu, 2017), and local tree species with a lower demand for water resources should be considered an optimal choice for further afforestation of the Loess Plateau (Liang et al., 2018).

4.3 | Implications for soil and vegetation management

In our study, the restored and control sites are comparable because they are at the same site conditions, with similar slope, aspect, and elevation. The SMC in farmlands or native grasslands could be considered the initial soil moisture condition serving as the baseline soil moisture level in order to develop a better plan for vegetation recovery (Chen et al., 2017). So, our results indicate that the soil moisture in restored sites is of importance in determining the land use conversion. It would be unfavorable for vegetation growth and development if the initial soil moisture is too high or too low. Response sizes are negative and the absolute value is large under the circumstance of high initial soil moisture (Figure 5), which means high soil moisture consumption for vegetation, and it may be attributed to climate changes and human activities; whereas low initial soil moisture may result in insufficient water uptake in plants. Consequently, more attention should be paid to the range of initial soil moisture, which is suitable for planting trees and grasses in future researches. Understanding the importance of initial soil moisture would enable more possibilities for successful and effective ecological restoration programs in the future.

It is necessary to predict changes in SMC over a large area for hydrological process, land management, and soil survey applications (Qiu, Fu, Wang, & Chen, 2001). Furthermore, the relationships between soil moisture and influencing factors found in this paper may offer useful information for the formation and development of models associated with SMC.

An increase in soil water effectively relieves the water stress in both plants and soil organisms, promoting plant nutrient absorption and thus stimulating plant growth and vice versa under drought conditions (Zhou et al., 2016). To rapidly acquire a large amount of data and cover a large area, we should further recognize the relationships between vegetation and soil moisture combined with net primary production (NPP) based on remote sensing technology (Chen et al., 2017). Simultaneously, because water and carbon cycles are intimately coupled, further studies should consider both of these cycles when predicting how land use and climate change will impact the soil water balance.

Our knowledge about how to satisfy both the water source demands and water use of ecological vegetation is still limited; we need to increase our understanding of vegetation management in the Loess Plateau in order to improve the ecosystem stability and sustainability of the Loess Plateau.

5 | CONCLUSIONS

The changes in the SMC throughout the 0- to 500-cm soil layers and related factors were analyzed and evaluated by a meta-analysis of data from 35 representative sites across the Loess Plateau of China. Across all the soil profiles, all response sizes of the SMC in 0–500 cm exhibited negative effects for the forest, shrubland, and grassland in three ecological zones. With the exception of other grassland species, changes in the SMC in comparison with control plots were not significant under any tree species, including *P. tabuliformis*, *R. pseudoacacia*, other forest species, *C. korshinskii*, other shrubland species, and *M. sativa*. Furthermore, restoration type, restoration age, MAP, MAT, initial soil moisture, and other factors had different effects on soil moisture. Understanding the relationships between SMC and the factors that affect it is important for the sustainable management of land use and the balance of water resources, and it is beneficial to restore the ecological environment of the Loess Plateau.

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ORCID

Bingqian Su https://orcid.org/0000-0003-0446-8164

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