Effects of two typical revegetation methods on soil moisture in the semi-arid Loess Plateau, China

Qian Zhao, Lei Yang, Xin Wang, Runcheng Bi and Qindi Zhang

ABSTRACT

Understanding the effects of vegetation on soil moisture is vital to the ecosystem restoration in water-restricted areas. For this study, the effects of introduced revegetation and natural revegetation on soil water (0–1.8 m) were investigated in the Chinese Loess Plateau, which was based on an *in situ* vegetation removal experiment and two years of soil moisture monitoring. The results indicated that under introduced revegetation, pasture grassland had lower soil moisture but higher temporal variations over the growing season. Compared with abandoned farmlands and native grasslands under natural revegetation, pasture grasslands revealed greater negative effects on deep soil moisture (1–1.8 m), which was difficult to recover following soil desiccation. In contrast, for abandoned farmlands and native grasslands, the surface soil moisture (0–0.4 m) was mainly impacted, which was easily replenished through rainfall events. These outcomes implied that natural revegetation, rather than introduced revegetation, should be the first choice in water-limited regions toward the rehabilitation of degraded ecosystems.

Key words | *in situ* vegetation removal experiment, introduced revegetation, log response ratio, natural revegetation, soil moisture content

Qian Zhao
Xin Wang
Runcheng Bi
Qindi Zhang (corresponding author)
College of Life Sciences, Shanxi Normal University,
Linfen 041000,
China
E-mail: *nyzqd@126.com*

Lei Yang
State Key Laboratory of Urban and Regional Ecology,
Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences,
Beijing 100085,
China

INTRODUCTION

The revegetation of degraded ecosystems supports various ecological benefits, such as carbon storage and the control of soil erosion, which has further benefits for humanity (Peters *et al.* 2019; Zhang *et al.* 2019). However, the rapid expansion of revegetation potentially exacerbates conflicts between vegetation growth and high water demands due to anthropogenic water use; therefore, the practice has been criticized in terms of water resource security (Feng *et al.* 2016; Yu *et al.* 2019). There remains widespread controversy over whether to continue the expansion of vegetation restoration (Su & Shangguan 2019). Indeed, vegetation plays a key role in water balance, while its effects are strongly contingent on the species involved (Casalini *et al.* 2019). This is because the interception of precipitation, root uptake and transpiration vary widely for different vegetative structures, and revegetation significantly modifies the composition of plant communities (Hu *et al.* 2008). Hence, the characterization of the effects of various revegetation strategies (such as introduced and natural revegetation) on soil moisture is critical for water conservation in the soil of water-limited regions (Fu *et al.* 2003).

Previous studies in the literature have quantified the effects of revegetation on soil-dwelling water in various areas, although their results have not always been consistent (Woziwoda & Kopeć 2014). For instance, in the Loess Plateau, China, Yang *et al.* (2012) noted that the concentrations of water in farmland soils were significantly higher than that of abandoned cropland and natural grassland, whereas Chen *et al.* (2007) found that natural grassland had improved soil water conditions over farmland. The potential causes of these inconsistent results are manifold. First, most studies assessed the effects of vegetation on soil

doi: 10.2166/nh.2019.011

moisture by setting nearby farmlands or grasslands as controls (Wang *et al.* 2012; Jia & Shao 2014). Aside from plant community structures, topographic properties and climatic conditions are variable between target vegetation types and controls, which may lead to problems in distinguishing vegetation effects from those of topography and climate. In contrast, the *in situ* vegetation removal experiments can overcome this problem (Gross *et al.* 2008). Nevertheless, such similar research is currently lacking due to the requirements of additional time and effort. Second, soil moisture obviously has temporal variability, particularly with precipitation (Su & Shangguan 2019). Practical studies concerning the impacts of vegetation on soil water also exposed a similar process (Zucco *et al.* 2014). Insufficient measurements may limit the accurate assessment of the effects of vegetation. Therefore, in order to clearly elucidate the temporal dynamics of the effects of vegetation on soil water throughout the growing season, the frequent long-term monitoring of soil moisture is required and critical. Given the above, a clear understanding of the effects of vegetation on soil moisture is key for the provision of reliable data in terms of ecosystem restoration and reconstruction in water-restricted regions.

In the Loess Plateau of China, large-scale revegetation projects such as ‘Grain to green’ were launched to alleviate the serious situation of the degradation of vegetation (Fu *et al.* 2003). For these projects, both introduced and natural revegetation coexist. Introduced revegetation following farmland abandonment involves anthropogenically initiated succession, via the introduction of plants such as alfalfa (*Medicago sativa*), while natural revegetation is the spontaneous succession of vegetation following abandonment (Woziwoda & Kopeć 2014). However, with the implementation of these projects, excessive revegetation consumed significant quantities of soil moisture, which led to soil desiccation in some areas (Wang *et al.* 2011). The reasonable selection of revegetation techniques in water-limited areas is critical for sustainable restoration while ensuring water resource security (Yang *et al.* 2014; Zhang *et al.* 2019). Therefore, to promote the sustainable management of abandoned farmlands, while preventing ecological degradation, it is extremely urgent to quantify the effects of these revegetation methods on soil moisture.

Toward the achievement of this goal, introduced and naturally revegetated grasslands were selected in the Loess Plateau of China. Both *in situ* vegetation removal experiments and two years of monitoring (2016–2017) were implemented to assess the impacts of two typical revegetation methods on soil moisture content. We considered which strategy was optimal for the management of vegetation toward the conservation of soil moisture. Hence, the aims of this research were to (1) detect the effects of vegetation on soil water content under two typical revegetation strategies, (2) identify the determinate factors that were responsible for these effects on soil moisture and (3) conduct feasibility analyses of the two typical revegetation methods for ecological protection in such semi-arid regions.

STUDY AREA AND DATA

Study area

The study area was the Longtan watershed (35°43′–35°46′ N, 104°27′–104°21′ E), which is located in the Western Loess Plateau of China. The specific administrative division is the Dingxi City of Gansu Province (Figure 1), where the climate in the watershed is typically semi-arid. The annual average precipitation is 386 mm, which primarily occurs from July to September, and the annual average temperature is 6.8 °C. The potential evapotranspiration of 1649 mm is ~4.3 times the precipitation level, and the soil porosity is generally ~60%, with low soil moisture/nutrient content. The most serious ecological issues in the area are soil erosion and land degradation. The zonal vegetation is typical steppe, which is dominated by bunge needlegrass (*Stipa bungeana*), common leymus (*Leymus secalinus*), Altai heterpappus (*Heteropappus altaicus*), capillary wormwood (*Artemisia capillaris*), alfalfa, among others.

Data collection

In the study area, 15 grassland sites were selected to represent two typical revegetation methods: introduced revegetation and natural revegetation. The grassland with introduced vegetation (pasture grassland hereafter) was converted from farmland through the introduction of alfalfa in 2003, which was mown annually for hay. The auxiliary species in the pasture grassland were common leymus and

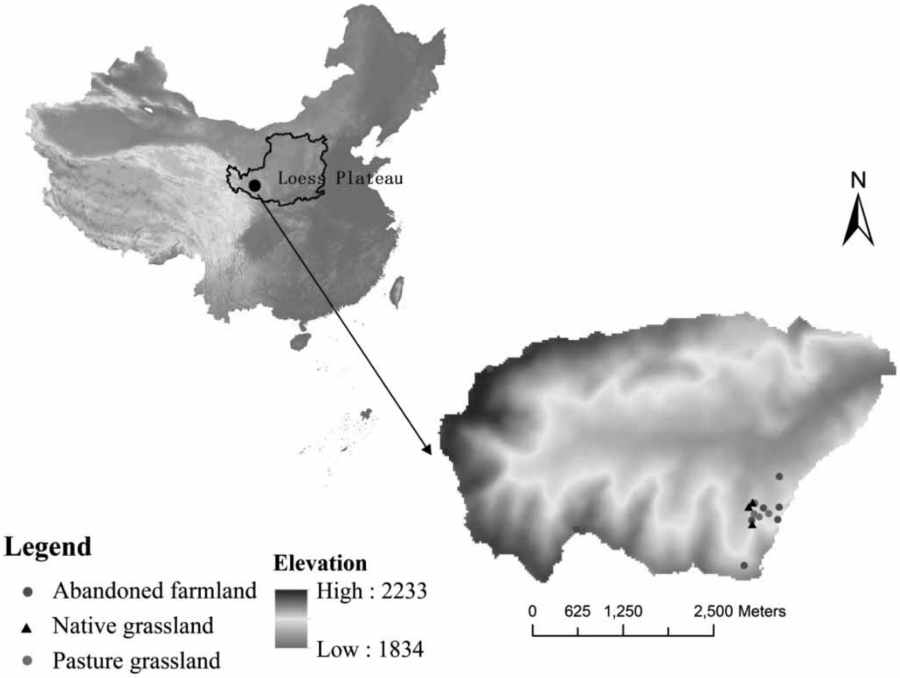

Figure 1 | Characteristics of the experimental sites.

Altai heterpappus. For natural revegetation, two vegetation types were selected: abandoned farmland and native grassland. The abandoned farmland represented the early stage of natural succession following the farmland abandonment in 2002. The dominant species was the common leymus, whereas the subdominant species was ciliate roegneria (*Roegneria pendulina*). The native grassland was, for the most part, free from anthropogenic interference for over 50 years and is considered as the peak plant community in this region, which represents the late stage of natural succession (Yang *et al.* 2014). The native grassland was rich in plant species and dominated by bunge needlegrass. Table 1 shows

Table 1 | Experimental site data

Vegetation types	Sample name	Year	Species richness	Elevation (m)	Aspect (°)	Slope (°)	SOM (g/kg)	BD (g/cm^3)
AF	AF-1	15	8	2,174.1	265	2	7.85	1.19
	AF-2		8	1,986.2	325	2	9.33	1.22
	AF-3		6	2,049.0	283	13	11.01	1.09
	AF-4		7	2,058.2	294	21	9.20	1.21
	AF-5		6	2,075.7	275	15	7.58	1.11
	AF-6		6	2,067.5	295	20	12.09	1.14
	AF-7		8	2,212.2	155	12	8.57	1.15
	AF-8		7	2,212.2	155	12	13.65	1.26
NG	NG-1	>50	10	2,031.5	65	12	12.03	1.10
	NG-2		11	2,067.4	292	14	10.41	1.18
	NG-3		10	2,017.3	278	32	12.11	1.11
PG	PG-1	15	5	2,011.1	294	19	9.24	1.17
	PG-2		5	2,033.1	285	17	5.99	1.25
	PG-3		5	2,006.8	88	23	7.89	1.23
	PG-4		6	2,025.2	45	20	16.16	1.12

Note: AF represents abandoned farmland; NG represents native grassland; PG represents pasture grassland; SOM represents soil organic matter; BD represents bulk density.

the detailed data and species richness of each experimental site for the three selected vegetation types.

An *in situ* removal experiment was conducted at each site. Two adjacent plots (Ø 4.0 m) were delimited side by side for the monitoring of soil moisture, with one of them being randomly selected for the removal of all vegetation. Specifically, the above-ground plants were initially removed with a sickle in the early spring of 2015, which was then regularly sprayed with a herbicide to keep the surface free from any plants during the growing seasons (from May to October in 2015–2017). To minimize the impacts of plant residues such as root systems on soil water in the bare plots, soil moisture data were obtained from the second year (2016). At the center of each plot, a time-domain reflectometry (TDR) tube with a length of 1.8 m was installed. By using a TDR instrument (Trime–FM, IMKO, Ettlingen, Germany), the volumetric soil moisture content (unit: ml/ml) was measured at a depth of 1.8 m at two-week intervals (15th and 30th of each month). The measurement duration was the annual growing season (May to October) for 2016 and 2017. Five automatic rain gauges were evenly distributed in the watershed to record the rainfall events.

To avoid interference of soil moisture monitoring, the following measurements were conducted externally to the monitoring plots. For each site, the species composition and mean vegetation height within three 1 m × 1 m plots were separately recorded. Biomass samples were collected from three 0.5 m × 0.5 m plots and transferred to the laboratory, where they were first oven-dried at 105 °C for 0.5 h, and then oven-dried at 80 °C for over 24 hours. Hereinto, the belowground biomass (root system) was collected at a depth of 0–0.6 m. A LAI-2200C plant canopy analyzer (Li-Cor, Lincoln, USA) was employed to determine the leaf area index (LAI). The slope aspect (clockwise from North) and the gradient of each site was measured using a compass. The longitude, latitude and altitude were determined with a Garmin GPS 60. Undisturbed soil cores were obtained using a metal cylinder (100 cm^3). The ratio of dry weight to volume was used to describe the soil bulk density (BD), whereas the soil organic matter (SOM) content was measured via the dichromate oxidation method.

METHODS

The log response ratio (LNRR) was used to quantify the impacts of vegetation on soil water at the sites (Gross *et al.* 2008)

$$\mathrm{LNRR} = \ln\left(\frac{\mathrm{SMV}}{\mathrm{SMB}}\right) \tag{1}$$

where SMV/SMB represents the soil moisture content with/without vegetation. When the LNRR value was greater than 0, it indicated that vegetation could lead to a reduction in soil water, while when the LNRR value was less than 0, it referred to an increase in soil water.

The basic statistical analysis was performed using SPSS Statistics 17.0. Significant differences in SMV and SMB were evaluated by a paired sample *t*-test, whereas significant differences in biomass between the three selected vegetation types were determined via the least significant difference. Plotting was generated through Origin 8.0. To reveal the correlation between soil water and its impact factors (topographical properties and community characteristics), canonical correspondence analysis (CCA) was performed with CANOCO version 5.0.

RESULTS

Vertical distribution of soil moisture

The total rainfall amounts from May to October in 2016 (drought year) and 2017 (normal year) were 155.65 and 202.64 mm, respectively. Figure 2 reveals the distribution profiles of SMV vs. SMB in 2016 and 2017 for each vegetation type. Overall, the SMV was lower at the measured soil depths compared with SMB, where the differences between SMV and SMB were more obvious in the normal year than the drought year. In the abandoned farmland, a significant difference between the SMV and SMB was found at depths from 0 to 1.0 m (Figure 2(a)). The significant differences in the natural grassland in 2016 and 2017 were concentrated from 0 to 0.6 m and 0 to 1.8 m, respectively (Figure 2(b)). In contrast, the pasture grassland had a

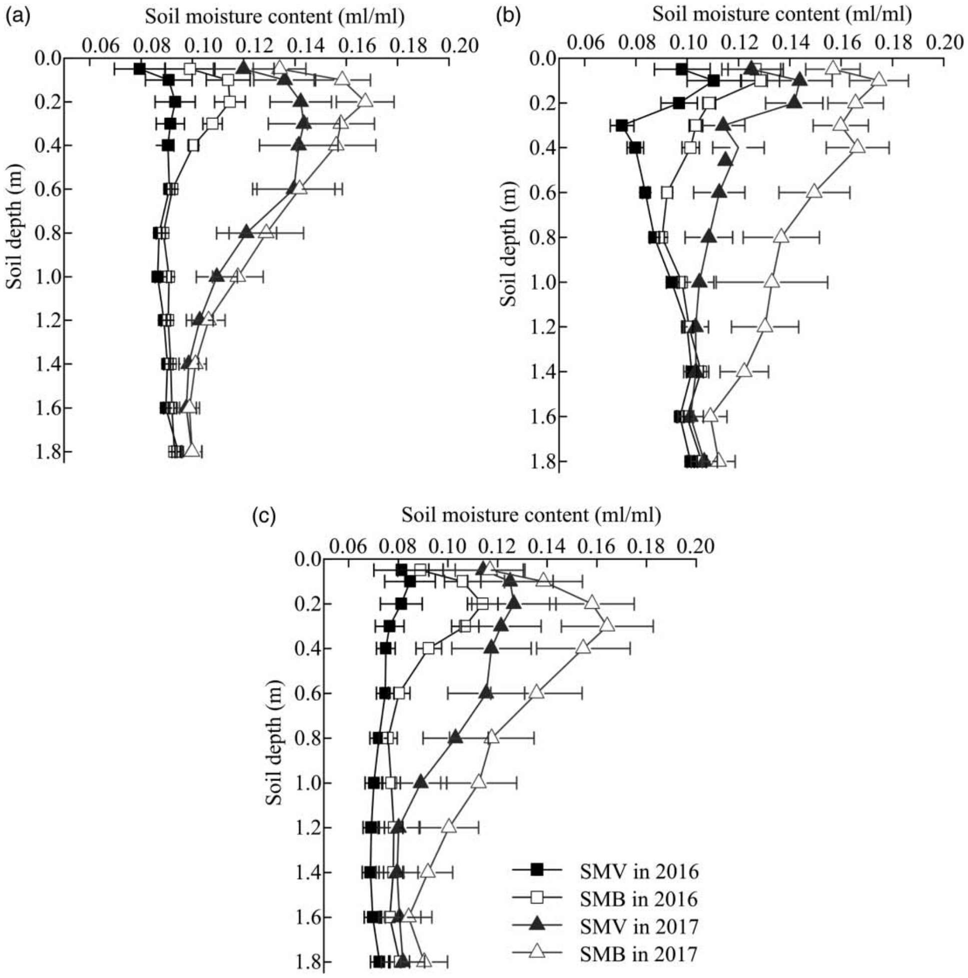

Figure 2 | Vertical variations of soil moisture content with and without vegetation for the three selected vegetation types: (a) abandoned farmland, (b) native grassland and (c) pasture grassland. SMV/SMB represent the soil moisture content in the plots with/without vegetation.

lower soil moisture value than the bare control plots at the measured soil depths (Figure 2(c)), which indicated that the alfalfa consumed more water from the soil than the other vegetation types.

Temporal variations of soil water

Figure 3 shows the temporal variability of the SMV vs. SMB in 2016 and 2017 for the three vegetation types. Owing to the difference in rainfall between 2016 and 2017, the soil moisture decreased during the growing season of 2016, whereas it increased in 2017. Furthermore, the soil moisture content within 0.4 m exhibited high temporal variability with rainfall events and reached two low values in late May and early August. In contrast, the soil moisture at depths from 1.0 to 1.8 m remained relatively stable over the entire growing season, which indicated that temporal variations of soil moisture below 1.0 m were less affected by rainfall events. Table 2 presents the differences between the SMV and SMB each month for the three vegetation types. Significant differences between the SMV and SMB at depths from 0 to 0.4 m were found over the entire growing season regardless of vegetation types. In the abandoned farmland and native grassland, these differences at depths from 0.4 to 1 m appeared only in August and September. In the pasture grassland, significant differences between the SMV and SMB were primarily distributed at depths from 0 to 1 m; however, sometimes they extended to 1.8 m.

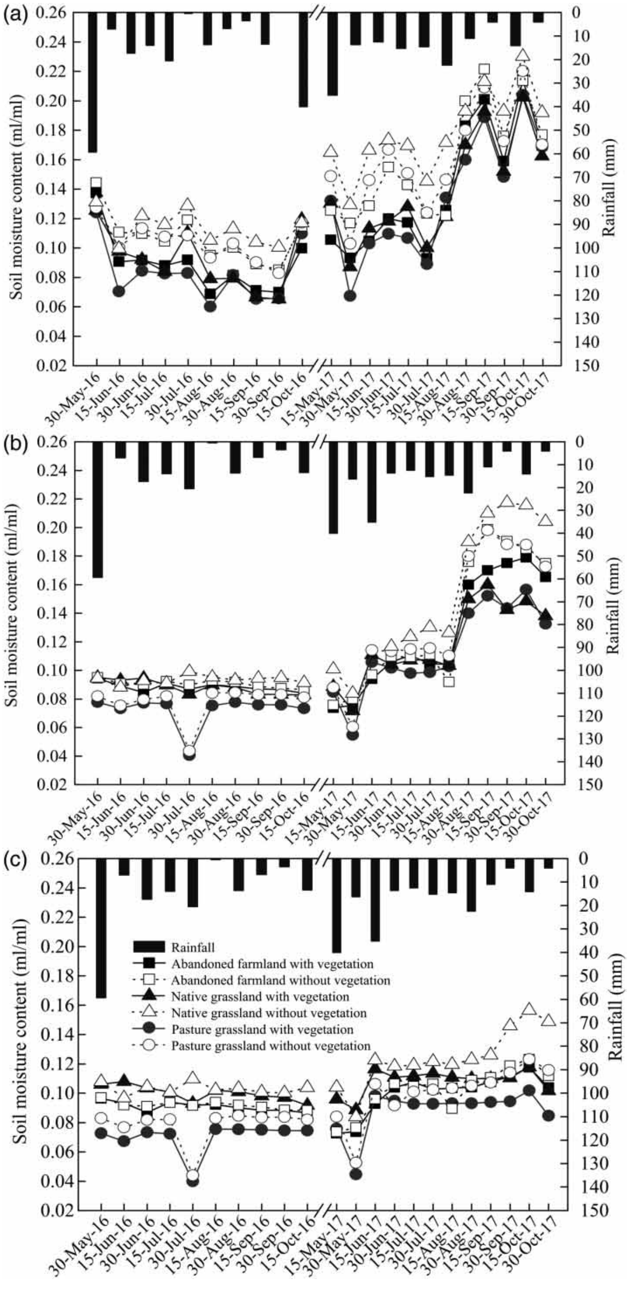

Figure 3 | Temporal variations of soil water at depths of (a) 0–0.4 m, (b) 0.4–1 m and (c) 1–1.8 m.

Comparison of LNRR between the three vegetation types and determinant factors

The effects of vegetation on soil moisture content (LNRR) were examined between the three vegetation types (Figure 4). The LNNR revealed an increasing trend with the soil profiles; however, the LNRR values were less than zero at all measured soil depths. This confirmed that the three selected vegetation types caused a reduction in soil moisture in contrast to the bare control plots. The results also revealed that the LNRR at depths from 0 to 0.4 m was not significantly different between the three vegetation types. The abandoned farmland had a higher LNRR at depths from 0.4 to 1 m, while the pasture grassland had a lower LNRR below 1 m.

The SMV and 7 explained variables at the 15 sites were analyzed by CCA (Figure 5). The results revealed that both underground and aboveground biomasses were the more critical drivers of the SMV differences between sites. The biomass was positively correlated with the SMV at depths from 0 to 0.4 m, and negatively related to the SMV at depths from 0.4 to 1.8 m. Furthermore, significant differences in underground and aboveground biomass were found between the various vegetation types (Table 3). Due to high biomass and strong root systems, the negative impact of the pasture grassland on deep soil moisture was significantly higher than the other vegetation types, which is consistent with Figure 4.

DISCUSSION

Temporal changes in soil moisture under two typical revegetation methods

Our study revealed that soil moisture was gradually stabilized with increasing soil depth (Figure 3), which aligned with the conclusion of Korres *et al.* (2015). Soil moisture at depths from 0 to 0.4 m exhibited greater temporal variations over the growing season in comparison with other layers. The surface soil moisture was more sensitive to rainfall patterns, which also revealed significant temporal variability (Koster *et al.* 2003). The surface soil water increased quickly via soil infiltration during rainfall events. As such, the temporal dynamics of the surface soil water were primarily driven by rainfall patterns. It is noted in this study that changes in soil moisture were not completely synchronous with rainfall (Figure 3(a)). This might be explained by the observation that increased soil moisture tended to exhibit a time-lag response to rainfall events (Recha *et al.* 2016).

Table 2 | Monthly variation of SMV vs. SMB

		May		June		July		August		September		October	
Soil depth	**Vegetation types**	**SMV**	**SMB**	**SMV**	**SMB**	**SMV**	**SMB**	**SMV**	**SMB**	**SMV**	**SMB**	**SMV**	**SMB**
0–0.4 m	Abandoned farmland	0.116 a	0.135 b	0.105 a	0.132 b	0.096 a	0.124 b	0.112 a	0.135 b	0.127 a	0.146 b	0.157 a	0.168 a
	Native grassland	0.114 a	0.142 b	0.105 a	0.140 b	0.105 a	0.142 b	0.104 a	0.139 b	0.110 a	0.142 b	0.161 a	0.180 a
	Pasture grassland	0.108 a	0.126 b	0.092 a	0.132 b	0.088 a	0.123 b	0.109 a	0.131 b	0.117 a	0.139 b	0.161 a	0.169 a
0.4–1 m	Abandoned farmland	0.084 a	0.087 a	0.097 a	0.100 a	0.098 a	0.101 a	0.110 a	0.117 b	0.131 a	0.142 b	0.143 a	0.150 a
	Native grassland	0.085 a	0.093 a	0.101 a	0.153 a	0.100 a	0.113 a	0.102 a	0.117 b	0.109 a	0.149 b	0.123 a	0.170 b
	Pasture grassland	0.072 a	0.077 a	0.089 a	0.096 b	0.084 a	0.095 b	0.099 a	0.115 b	0.112 a	0.138 b	0.121 a	0.147 b
1–1.8 m	Abandoned farmland	0.084 a	0.085 a	0.097 a	0.098 a	0.099 a	0.098 a	0.097 a	0.099 a	0.099 a	0.101 a	0.102 a	0.106 a
	Native grassland	0.097 a	0.099 a	0.110 a	0.111 a	0.107 a	0.113 a	0.105 a	0.110 b	0.105 a	0.117 a	0.104 a	0.136 b
	Pasture grassland	0.064 a	0.073 b	0.083 a	0.089 a	0.079 a	0.088 a	0.084 a	0.094 b	0.084 a	0.097 b	0.087 a	0.107 b

Note: SMV/SMB represent the average monthly soil moisture with/without vegetation; different letters for SMV and SMB within the same line mean that there is a significant difference between them at $p < 0.05$.

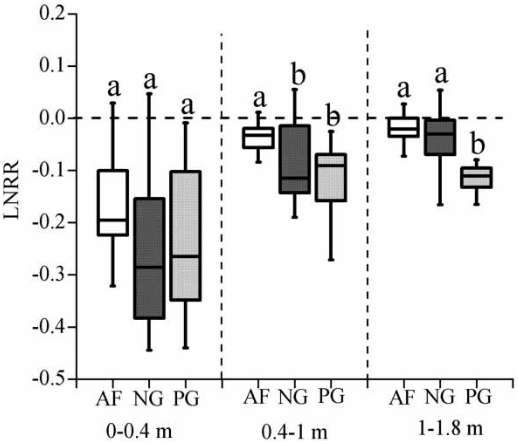

Figure 4 | Comparison of LNRR in the three different vegetation types. *Note:* AF represents abandoned farmland; NG represents native grassland; PG represents pasture grassland.

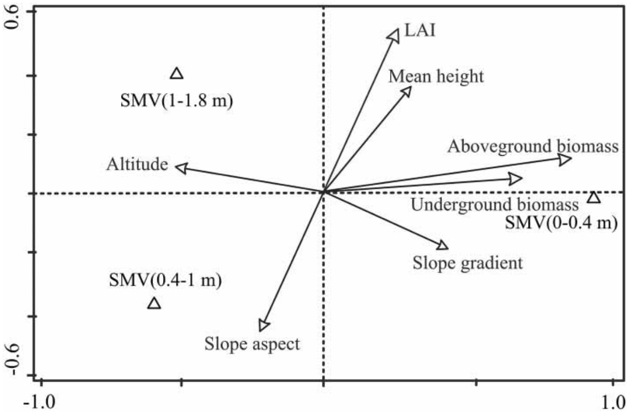

Figure 5 | Canonical correspondence analysis described the correlation between SMV and its explained variables. SMV represents soil moisture content with vegetation.

Table 3 | Comparison of biomass between different vegetation types

	Underground biomass (g/m^2)			
Vegetation type	**0–0.2 m**	**0.2–0.4 m**	**0.4–0.6 m**	**Aboveground biomass (g/m^2)**
Abandoned farmland	136.59 a	48.49 a	11.93 a	619.07 a
Native grassland	177.71 ab	40.66 a	17.84 a	685.22 a
Pasture grassland	290.18 b	176.47 b	91.79 b	1,012.88 b

Note: different letters within the same column mean significantly different between different vegetation types at $p < 0.05$.

Furthermore, soil moisture decreased from the wet to drought periods due to water uptake by roots and evaporation (Suleiman & Ritchie 2003).

Compared with abandoned farmland and native grassland, the pasture grassland possessed higher temporal variations at depths from 1 to 1.8 m, although temporal variations presented a consistent declining trend with the soil profile. Due to the limited impacts of precipitation infiltration and soil evaporation, the deep (1–1.8 m) soil water was relatively stable (Wang *et al.* 2016). However, we noted that deep soil moisture in the pasture grassland was markedly reduced during drought periods (July 2016 and May 2017) (Figure 3(c)). The temporal dynamics of deep soil water were more susceptible to vegetation roots and community structures. Compared with native grasses, alfalfa had higher aboveground biomass and developed deep root systems (Table 3), which could extend taproots to 3.0 m (Wang *et al.* 2010). With insufficient precipitation infiltration, the alfalfa depleted deep soil moisture as well, which led to severe declines in moisture. On the contrary, shallow-rooted grasses such as bunge needlegrass and common leymus dominated the abandoned farmland and native grassland. Therefore, grasslands under natural revegetation contained higher soil moisture and lower temporal variations at depths from 1 to 1.8 m.

The impacts of two typical vegetation restoration methods on soil water

This study revealed that three grasslands under two typical revegetation methods had negative effects on soil moisture (LNRR < 0) at the measured soil depths, which was based on *in situ* removal experiments. This was consistent with previous comparative studies of different land uses (Flanagan & Johnson 2005; Yang *et al.* 2014). Compared with bare plots, vegetation altered several hydraulic processes such as precipitation infiltration, plant uptake and soil evaporation (Rodriguez-Iturbe 2000). On one hand, biomass accumulation was at the cost of soil moisture, via root water uptake. Therefore, the SMB was obviously higher than the SMV. On the other hand, high root allocation also enhanced the soil infiltration capacity via root channels during rainfall events (Wu *et al.* 2017; Yang *et al.* 2018). This was also confirmed by insignificant differences between the SMV and SMB at depths from 0 to 0.4 m during the wet period (October 2017) (Figure 3(a)) (Table 2). Similar results were also reported in previous studies. For example, Gross *et al.* (2008) believed that there was significantly lower soil moisture in a French subalpine grassland than that in an *in situ* unvegetated land following a rainfall event. Further, canopy cover can act to decrease soil temperature and evaporation (Suleiman & Ritchie 2003). Based on the above discussion, these vegetation processes had opposite effects on soil moisture. However, the three grasslands showed negative effects on soil moisture during the two growing seasons, which implied that soil moisture consumption via plant uptake was greater than soil moisture conservation, by improving water infiltration and reducing soil evaporation.

Multiple comparisons of the LNRR between the three grasslands revealed that the negative effects on soil moisture differed between the two typical revegetation methods at depths from 1 to 1.8 m (Figure 4). Specifically, no significant differences were found in the LNRR at depths from 0 to 1 m between the two typical revegetation methods, whereas the grassland under introduced revegetation (pasture grassland) had greater negative effects on deep soil moisture (1–1.8 m) than those under natural revegetation (e.g. abandoned farmland and native grassland). Due to the relatively high biomass and deep root distribution (Table 3), the pasture grassland consumed more deep soil water, thus resulting in lower LNRR. This was consistent with the CCA results that both underground and aboveground biomass appeared as the primary factors related to the effects of vegetation on soil moisture (Figure 4). Further, we also noted that the LNRR decreased with the soil profile, indicating that the three grasslands mainly consumed shallow soil moisture. One potential explanation was that root distribution influenced the vertical patterns of soil moisture (Monti & Zatta 2009). For this study, the grassland root systems were primarily concentrated within 0.4 m (Table 3), which imparted greater negative effects on soil moisture within this layer.

Feasibility analysis of two revegetation methods in semi-arid areas

In water-restricted areas, soil moisture is undoubtedly a key constraint to vegetation rejuvenation in water-limited areas (Bonet 2004; Fu *et al.* 2016). As vegetation is considered the main factor that influences soil moisture, the prudent selection of revegetation strategies is crucial for the realization of sustainable vegetation restoration (Zhang *et al.* 2019). Taking the Longtan watershed as an example, the zonal vegetation is a typical steppe with a mean annual precipitation of 386 mm. Therefore, grassland should initially be considered for revegetation practices. In contrast to natural revegetation, grassland under introduced revegetation had lower soil moisture but higher temporal variations during the growing season. Furthermore, due to relatively larger underground and aboveground biomass, the negative impacts of introduced revegetation on soil water at 1–1.8 m was greater relative to natural revegetation. This also confirmed that higher vegetation production is not conducive to the conservation of deep soil water (Chen *et al.* 2007). Since the deep soil moisture balance is not easily remediated in semi-arid regions, previous research showed that large-scale introduced revegetation was not suitable, where the mean annual precipitation was less than 400 mm (Yang 1996). Accordingly, introduced vegetation such as alfalfa grassland should be strongly discouraged for revegetation practices in these areas due to precipitation conditions.

In contrast, grasslands with natural revegetation exhibited primarily negative effects on the near-surface soil moisture, which could be easily replenished by rainfall events. Furthermore, the natural revegetation process was beneficial for other functions such as the control of soil erosion (Jia & Shao 2014), species diversity reserves (Zhang 2005) and carbon sequestration (Lee *et al.* 2002). In our study, species richness and SOM were also found to be higher under natural revegetation, particularly in the native grassland (Table 1). Finally, the effects of vegetation on soil moisture revealed no significant difference between the early stage of natural succession (abandoned farmland) and late stage (native grassland). This indicated that soil moisture deficits could be alleviated following the abandonment of introduced vegetation. In summary, we highly recommend that natural revegetation, rather than introduced revegetation, is the first choice to prevent soil moisture desiccation and to rehabilitate degraded ecosystems in such semi-arid regions.

CONCLUSIONS

Based on a two-year soil moisture monitoring and *in situ* removal experiment, the effects of introduced revegetation and natural revegetation on soil moisture content within a 1.8 m soil depth were quantified in a typical watershed in the Loess Plateau of China. First, pasture grassland under introduced revegetation had lower soil moisture, but higher temporal variations over the growing season. In addition, the pasture grassland revealed greater negative effects on deep soil moisture (1–1.8 m) due to high biomass and deep root distribution. In contrast, abandoned farmland and native grassland under natural revegetation primarily affected surface soil moisture. Thus, introduced revegetation is not recommended in semi-arid areas, whereas natural revegetation is a more suitable option. Our findings provide scientific guidance for the restoration of degraded ecosystems in such semi-arid areas.

ACKNOWLEDGEMENTS

This study was supported by National Natural Science Foundation of China (Nos. 41601027, 41871164), National Key Research and Development Program of China (No. 2016YFC0501701) and the Science and Technology Service Network Initiative of Chinese Academy of Sciences (No. KFJ-STS-ZDTP-036). We thank the four anonymous reviewers for their constructive comments.

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First received 27 January 2019; accepted in revised form 24 June 2019. Available online 17 July 2019