Forest Ecology and Management 458 (2020) 117767

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Mixed-species plantations can alleviate water stress on the Loess Plateau

Chen Gong[a,b], Qingyue Tan[d], Mingxiang Xu[a,b,c,*], Guobin Liu[a,b,c,*]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China

[b] University of Chinese Academy of Sciences, Beijing 100049, China

[c] Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China

[d] College of Forestry, Northwest A&F University, Yangling 712100, China

ARTICLE INFO

Keywords:
Mixed-species plantations
Soil moisture
Water stress
The Loess Plateau

ABSTRACT

In recent years, the ability of mixed-species plantations to cope with environmental changes has been a focus of research. Despite compelling evidence indicating that mixed-species plantations can provide many economic, environmental and social benefits, whether they can also enhance regional stress responses to drought remains unclear. Therefore, a meta-analysis was conducted based on 457 field observations to assess the effects of different planting patterns on the soil moisture of 500 cm on the Loess Plateau. The results showed that both monoculture and mixed-species plantations consumed significant soil moisture content. However, compared with monoculture plantations, mixed-species plantations were better able to maintain the soil moisture at 0–400 cm. Soil moisture content varied by topography, climate, vegetation species and planting age. We observed that afforestation was a good choice for areas with the high precipitation (> 500 mm), the middle elevation (1200–1600 m) and slope (20–30°). Furthermore, the arbors mixed with shrubs did not significantly consume the soil moisture content and was more sensitive to the change in planting ages. In addition, the response sizes of soil moisture among different vegetation species were negatively correlated with the initial soil moisture content. We therefor concluded that mixed-species plantations, especially arbors mixed with shrubs were conducive to enhancing drought resistance in arid and semiarid regions. In considering future afforestation activities, planners need to be aware that different environments support different vegetation species and patterns. This study provides a reference and guidance for the scientific planning and sustainable development of forest ecosystem in arid and semiarid regions.

1. Introduction

Soil moisture is a critical variable that affects regional hydrological processes and plant morphology and function, especially in arid and semiarid regions (D'Odorico et al., 2010; Legates et al., 2011). Water stress caused by soil water deficit is a common risk factor and can directly affect the growth and development of vegetation (Stocker et al., 2019). Moreover, plants can directly affect the dynamics of soil moisture in the region by participating in the water cycle, but their effects are dependent on the type, structure and composition of the vegetation (Legates et al., 2011; Wang et al., 2019). Therefore, studying and understanding the impact of different vegetation patterns on regional eco-hydrological processes is essential (Gao et al., 2018). Previous studies have demonstrated that mixed species can improve the stability and flexibility of ecosystems through ecological niche partitioning or resource complementarity (Loreau et al., 2001; Jactel and Brockerhoff, 2007). However, intense intraspecific and interspecific competition can also lead to an uneven distribution of resources, such as light, water and nutrients (Manson et al., 2013; Forrester, 2015). Currently, whether mixed-species plantations have a positive impact on water stress is unclear (Vereecken et al., 2014). Therefore, improving our understanding of how mixed-species plantation affects regional soil moisture content and drought resistance is crucial to the planning, design and sustainable development of regional vegetation.

Ecological theories suggest that multigroup composite structures often show large differences in ecological strategies for coping with environmental stress (Richards et al., 2010; Forrester and Bauhus, 2016). Some previous studies have reported contradictory findings about the relationship between water stress and plant diversity.

* Corresponding authors at: Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, 26 Xinong Road, Yangling, Shaanxi 712100, China.

E-mail addresses: xumx@nwsuaf.edu.cn (M. Xu), gbliu@ms.iswc.ac.cn (G. Liu).

https://doi.org/10.1016/j.foreco.2019.117767
Received 23 June 2019; Received in revised form 12 November 2019; Accepted 15 November 2019
Available online 14 December 2019
0378-1127/

Lebourgeois et al. (2013) and Pretzsch et al. (2013) showed that the mixed-species plantation was divided by hydrological niches, which reduced the competition for limited water resources and strengthened regional drought resistance. For example, the differences in the distribution and structure of plant roots of different species lead to less overall competition for water (Schwendenmann et al., 2015). In addition, plants also respond to water stress by changing their physiological activities, which is known as ecological adaptation; examples of such behavior include regulating leaf water status, reducing the photosynthetic rate and gas exchange, and adjusting fluorescence parameters (Jiao et al., 2016; Yan et al., 2017). However, if the interacting species have similar functional characteristics (i.e., functional redundancy), ecological niche overlap may lead to increased water competition, which in turn increases the degree of drought. For example, mixed-species plantations will largely absorb the water from shallow soil layers and shift to deeper soil layers when precipitation decreases (Tang et al., 2018). Additionally, due to the interception of the canopy and the water consumption of roots, herbs are effective competitors for water (van der Waal et al., 2009; Prevosto et al., 2016). Overall, due to the multiple interrelated processes and complex feedback mechanisms between plant diversity and water stress, it is still unknown whether mixed-species plantations can attenuate regional water stress.

Due to steep topography, frequent heavy rainfall in summer months and improper land use, the Loess Plateau of China has become one of the regions with the most severe soil erosion in the world (Zhao et al., 2013; Gao et al., 2016). To repair the fragility of the natural environment in the area, a series of large-scale ecological restoration projects focusing on soil and water conservation have been implemented since the 1980s, including returning farmland to forests (Cao et al., 2009). Over the past two decades, the vegetation coverage of the Loess Plateau increased from 31.6% in 1999 to 59.6% in 2013, and the amount of sediment entering the sea from the Loess Plateau in 2015 was only 8.9% of that in the 1950s (Chen et al., 2015; Li et al., 2019). However, in arid and semiarid regions where water resources are limited, the expansion of the planted area directly affects the balance between regional water supply and demand, causes severe soil drying and limits the normal growth and morphology of plants (An et al., 2017). According to the related researches, vegetation restoration on the Loess Plateau is nearing the threshold of regional water limits, and regional runoff has been significantly reduced by more than 50% (Sun et al., 2006; Feng et al., 2016). Mixed-species plantations are also widely used in the initial planting stage due to their high soil retention and carbon sequestration capabilities compared to monoculture plantations (Montagnini et al., 2003; Carnol et al., 2014). However, the impact of mixed-species plantations on the soil moisture of the Loess Plateau is still controversial. Recent studies have shown that mixed-species plantations can improve regional drought tolerance and vegetation survival. For example, Chen et al. (2018) suggested that *Robinia pseudoacacia* would stimulate *Platycladus orientalis* growth by increasing the availability of soil moisture and suppressing the development of arbuscular mycorrhizal symbiosis. Zhang et al. (2019) confirmed that mixed-species plantation soil had a greater capacity to intercept and store rainwater than monoculture plantation soil. However, other studies have shown that mixed-species plantations have significantly lower soil moisture content than monoculture plantations. For example, Gao et al. (2018) showed that mixed-species plantation of *Robinia pseudoacacia* and *Hippophae rhamnoides* had high carbon sequestration but exhibited significant deep soil moisture consumption. Tang et al. (2018) showed that mixed plantations of *Pinus tabuliformis* and *Hippophae rhamnoides* would largely consume shallow soil moisture and shift to deep soil moisture when precipitation decreased. To date, previous studies have focused on a few scattered locations or specific vegetation types, leading to a lack of comparability among the results. In addition, few studies have comprehensively explored how soil moisture content in mixed-species plantations are affected by factors such as climate, stand characteristics and topography.

To address this information gap, we extracted 457 samples from the Loess Plateau for a meta-analysis to quantify the effects of mixed-species plantations and monoculture plantations on soil moisture content on the Loess Plateau. The objectives of this study are to (a) quantify the effects of mixed-species plantations and monoculture plantations on soil moisture content in five soil layers of 0–500 cm; (b) compare soil moisture changes in different types of mixed-species plantations and monoculture plantations; (c) analyze the main factors affecting soil moisture content; and (d) study the relationship between soil moisture and initial soil moisture content under different types of vegetation. This study will provide a reference for the sustainable use of water resources and guidance for the selection and rational allocation of vegetation species on the Loess Plateau.

2. Materials and methods

2.1. Data sources

Literature searches were performed using the Web of Science (United States) and CNKI (China Knowledge Resource Integrated Database, China; 2000–2018) with the search terms “soil water” or “soil moisture” and “Loess Plateau” and “mixed plantation” or “mixed species” or “mixed forest” or “plant diversity”. To avoid publication bias, the following criteria were chosen to select relevant research:

(a) include at least one type of associated mixed-species plantation (i.e., arbors mixed with shrubs and mixed arbors) and a control (farmland or grassland);
(b) measure the experimental and control soil moisture content within the 0–500 cm layer (0–100 cm, 100–200 cm, 200–300 cm, 300–400 cm and 400–500 cm); and
(c) include only the data from field monitoring and analysis to exclude the data from laboratory control experiments.

In addition, all available data were extracted from the publication, including location, latitude (N), longitude (E), mean annual temperature (MAT), mean annual precipitation (MAP), slope angle, slope aspect, slope position, elevation, tree age, sample size and initial soil moisture content.

According to the topics and the screening criteria of this study, 169 related papers were reviewed, and 457 samples from 30 studies were selected for the meta-analysis (Fig. 1 and Appendix Dataset A). All the raw data were extracted from the text, tables, charts and appendices in the publication. When the data were presented graphically, the numerical data were obtained using the Get Data Graph Digitizer ver. 2.24 (Russian Federation). ArcGIS ver. 10.4.1 (ESRI, California, USA) was used to illustrate the location of the research area. To clearly depict the vertical distribution of soil moisture content, the collected data were divided into five depths: surface layer (0–100 cm), sub-surface layer (100–200 cm), middle layer (200–300 cm), sub-deep layer (300–400 cm) and deep layer (400–500 cm).

2.2. Meta-analysis

The response ratio is defined as the ratio of the amount measured for the experimental group and the control group, and it is usually used as a measure of the experimental effect, which can quantify the proportional change produced by the experimental operation (Hedges et al., 1999). In our study, the response ratio (r) was defined as the ratio of the soil moisture content under the current land use (X_e) to the soil moisture content in the associated control plots (X_c), as follows:

$$r = \frac{X_e}{X_c} \quad (1)$$

Most of the studies only reported mean values without standard deviations or standard errors. To analyze the trends and characteristics

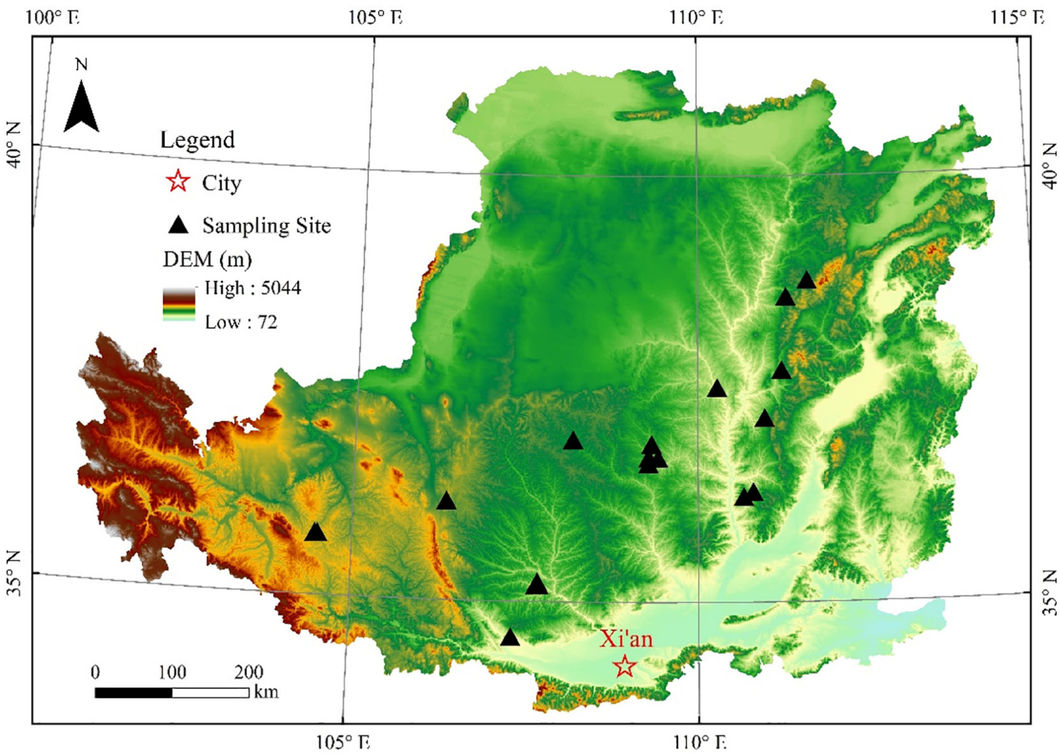

Fig. 1. Distribution of the sampling sites on the Loess Plateau.

of the data more effectively, we used an unweighted meta-analysis as described in earlier studies (Powers et al., 2011; Deng et al., 2016; Su and Shangguan, 2019). A negative (or positive) change in the mean response size (R) indicated a decrease (or increase) in the value under the current land use (X_e) relative to control plots (X_c), as follows:

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

The 95% confidence intervals (CIs) of the means for soil moisture content were calculated based on previous studies (Luo et al., 2006), as shown in Eqs. (3) and (4):

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

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

where SE_R is the standard error of the response size of soil moisture, V_R is the variance in the response size, and N is the observed number. If the 95% CI overlaps with zero, no significant response was detected.

2.3. Data analysis

The mean value (Mean) and standard deviation (SD) of the response size were calculated. To compare the magnitude of the response size of soil moisture more effectively, we also calculated the coefficient of variation (CV), which is defined as the SD divided by Mean. The variables related to soil moisture changes were assessed by an analysis of variance (ANOVA), and multiple comparisons were performed using the least significant difference (LSD) method. The relationship between the response size of soil moisture and initial soil moisture content was examined by a general linear model (GLM). All the statistical analyses were performed using the SPSS statistical package version 24.0 (SPSS Inc., Chicago, Illinois, USA), and the related figures were drawn using Origin 9.0 (Originlab Corporation, Hampton, USA).

3. Results

For both monoculture plantations and mixed-species plantations, the response sizes of soil moisture in the 0–500 cm layer were negative (Fig. 2 and Appendix Dataset A). Afforestation severely consumed soil moisture content, and the overall response size of soil moisture was −0.18 (Fig. 2a and Table 1), with mixed-species plantations and monoculture plantations was −0.17 and −0.20, respectively (Fig. 2b, c and Table 1). In addition, as the depth of the soil increased, the response size of soil moisture gradually decreased, with the response size of soil moisture in the deep soil layer (400–500 cm, −0.28) showing significantly lower than that in the upper three layers (−0.12 at 0–100 cm, −0.17 at 100–200 cm, −0.21 at 200–300 cm) (Fig. 2a and Table 1).

For mixed-species plantations, the decrease in the response size of soil moisture in the upper four layers (−0.10 at 0–100 cm, −0.17 at 100–200 cm, −0.19 at 200–300 cm, −0.20 at 300–400 cm) was not significant, while the response size of soil moisture in the deep layer (400–500 cm, −0.28) was significantly lower than that in the surface layer (0–100 cm, −0.10) and the sub-surface layer (100–200 cm, −0.17) (Fig. 2b and Table 1). For monoculture plantations, significant differences were not observed in the response size of soil moisture between the surface layer (0–100 cm, −0.14) and the sub-surface layer (100–200 cm, −0.17). Additionally, the response sizes of soil moisture in 200–500 cm (−0.22 at 200–300 cm, −0.27 at 300–400 cm, −0.28 at 400–500 cm) were significantly lower than that in the surface layer (0–100 cm, −0.14) (Fig. 2c and Table 1). In addition, the response size of soil moisture in the surface layer (0–100 cm) showed higher variability (CV) than that of the other soil layers (Appendix Table B).

The extent of soil moisture reduction was also significantly affected by species (Table 1). The change of the response size of soil moisture for vegetation species was not significant, except mixed arbors and pure arbors (Table 1). Specifically, the response size of soil moisture in the deep layer (400–500 cm) of the mixed arbors and pure arbors was significantly lower than that of the surface layer (0–100 cm) and the sub-surface layer (100–200 cm) (Table 1). In addition, the response size of soil moisture at 0–500 cm of the arbors mixed with shrubs (−0.16) was slightly higher than that of the mixed arbors (−0.18), and the response size of soil moisture of the pure arbors (−0.19) was slightly

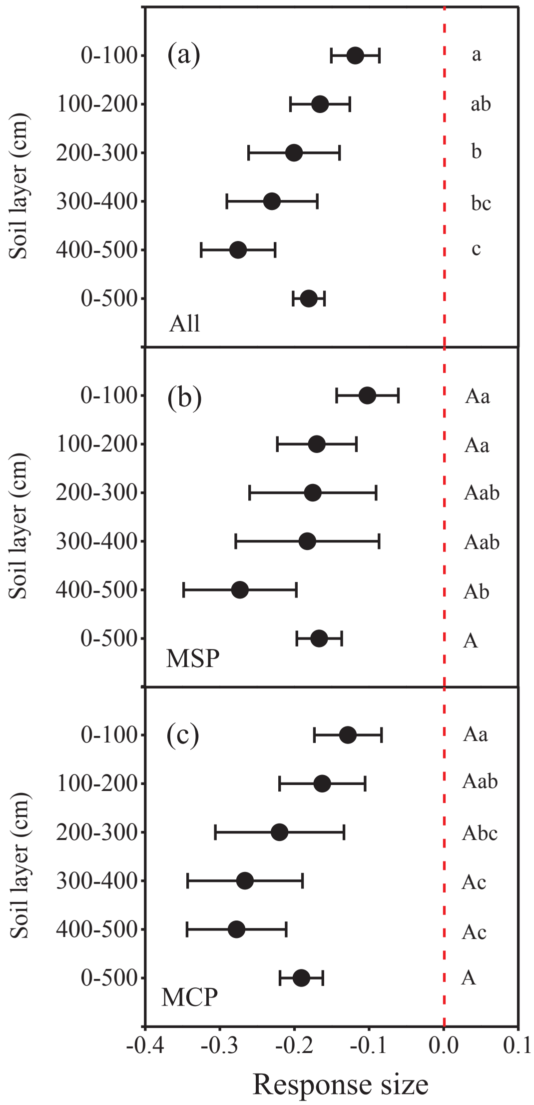

Fig. 2. The response size of soil moisture in different vegetation patterns and soil depths. Note: a, all plantations (All); b, mixed-species plantations (MSP); and c, monoculture plantations (MCP). Dots with error bars denote the overall mean values and the 95% CIs. Different upper-case letters indicate significant differences among different vegetation types ($P < 0.05$), and different lower-case letters indicate significant differences among different soil layers ($P < 0.05$). The total includes data from five soil layers. The dashed line indicates x = 0.

higher than that of the pure shrubs (−0.20). However, the differences in the response size of soil moisture at 0–500 cm between different species were not significant (Table 1).

For different precipitation zones, the response size of soil moisture for different vegetation species was the lowest in the zone with the lowest precipitation (< 400 mm), followed by the 400–500 mm zone, and that of the > 500 mm zone was the highest (Fig. 3a). For different vegetation species, the pure shrubs in the < 400 mm (−0.32) and the 400–500 mm zone (−0.33) had the lowest response sizes of soil moisture. However, the pure shrubs in the > 500 mm zone (−0.07) had the highest response size of soil moisture, which was significantly higher than that of the pure arbors (−0.14) and the arbors mixed with shrubs (−0.16) (Fig. 3a).

For different temperature zones, the response size of soil moisture was the lowest in the zone with the highest temperature (> 9 °C), followed by that in the < 7 °C zone and the 7–9 °C zone (Fig. 3b). Significant differences in the response size of soil moisture for difference species were not observed in the < 7 °C and > 9 °C zones. The response size of soil moisture of the pure shrubs in the 7–9 °C zone (−0.21) was significantly lower than that of the arbors mixed with shrubs (−0.03) and the pure arbors (−0.02) (Fig. 3b).

Topographic factors (slope angle, slope aspect, slope position, and elevation) had different effects on the response size of soil moisture for different vegetation species (Fig. 4). For the mixed-species plantation and monoculture plantation, the response size of soil moisture on shady slopes was higher than that on sunny slopes, although the difference was not significant for different vegetation species (Fig. 4a). The response size of soil moisture for the vegetation species on the upper slope position was higher than that on the middle slope position, but there was no significant difference found for different vegetation species on the upper slope position (Fig. 4b). For different slope angles, the response size of soil moisture for vegetation species on the middle slope (20-30°) was the highest (Fig. 4 c). The response size of soil moisture at middle-elevation area (1200–1600 m) was the highest (Fig. 4d). In addition, significant differences were not observed in soil moisture reduction among the vegetation species at middle-elevation area (1200–1600 m).

In general, all vegetation species consumed soil moisture content at different age stages (Fig. 5). For the mixed arbors, the response size of soil moisture decreased to some extent with time, but there was no significant difference in the response size of soil moisture between these two stages (Fig. 5a). For the arbors mixed with shrubs, the response size of soil moisture was significantly decreased with increasing planting age (Fig. 5b). For the pure arbors, the response size of soil moisture during the growth phase (20-30a, −0.44) was significantly lower than that during the young (< 20 a, −0.14) and mature phases (> 30 a, −0.18) (Fig. 5c). In the case of shrubs, the response size of soil moisture initially increased and then decreased with planting age, and the response size of soil moisture at the mature stage (> 20 a) was the lowest

Table 1
The response size of soil moisture in different vegetation species.

Land use types	Species	Soil layer (cm)					Total
		0–100	100–200	200–300	300–400	400–500	
Mixed-species plantations	MA	−0.09 ± 0.06Aa (n = 34)	−0.15 ± 0.08Aab (n = 19)	−0.25 ± 0.09Abc (n = 12)	−0.27 ± 0.08Abc (n = 12)	−0.30 ± 0.07Ac (n = 12)	−0.18 ± 0.04A (n = 89)
	AS	−0.11 ± 0.06Aa (n = 24)	−0.19 ± 0.07Aa (n = 20)	−0.13 ± 0.12Aa (n = 19)	−0.13 ± 0.15Aa (n = 19)	−0.25 ± 0.12Aa (n = 15)	−0.16 ± 0.05A (n = 97)
Monoculture plantations	PA	−0.12 ± 0.05Aa (n = 68)	−0.17 ± 0.07Aab (n = 32)	−0.23 ± 0.13Aabc (n = 21)	−0.26 ± 0.11Abc (n = 21)	−0.30 ± 0.07Ac (n = 20)	−0.19 ± 0.04A (n = 162)
	PS	−0.15 ± 0.09Aa (n = 30)	−0.16 ± 0.09Aa (n = 21)	−0.21 ± 0.12Aa (n = 20)	−0.27 ± 0.11Aa (n = 20)	−0.25 ± 0.11Aa (n = 18)	−0.20 ± 0.05A (n = 109)

Note: MA: mixed arbors; AS: arbors mixed with shrubs; PA: pure arbors; and PS: pure shrubs. The values representing the response size are the mean ± 95% CIs, and the numbers of observations are displayed in parentheses. Different upper-case letters indicate significant differences among different vegetation species ($P < 0.05$), and different lower-case letters indicate significant differences among different soil layers ($P < 0.05$).

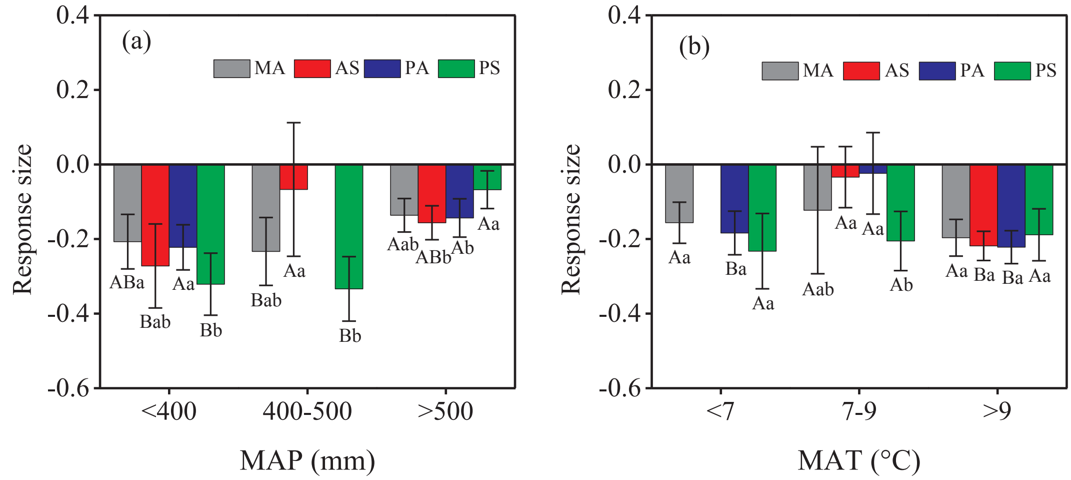

Fig. 3. The response size of soil moisture in different climatic zones. Note: MA: mixed arbors; AS: arbors mixed with shrubs; PA: pure arbors; and PS: pure shrubs. The charts with error bars denote the overall mean values and the 95% CIs. Different lower-case letters indicate significant differences among different vegetation species ($P < 0.05$), and different upper-case letters indicate significant differences among different climatic zones ($P < 0.05$).

(−0.33) and significantly lower than that at the middle stage (10–20 a, −0.08). However, the difference was not significant compared with the young stage (< 10 a, −0.24) (Fig. 5 d).

Overall, the response size of soil moisture was negatively correlated with the initial soil moisture content (Fig. 6). For different vegetation species, the response size of soil moisture was significantly and negatively correlated with the initial soil moisture content in the case of the arbors mixed with shrubs and the pure shrubs (Fig. 6b, d). However, the interaction was nonsignificant in the case of the mixed arbors and the pure arbors (Fig. 6a, c).

4. Discussion

Frequent and intense droughts will greatly affect the regional water cycle and increase regional water stress (Breshears et al., 2005). Water stress is considered to be highly correlated with forest ecosystem dynamics (Rennenberg et al., 2006). However, the ecological strategies that vegetation species use to deal with water stress vary widely

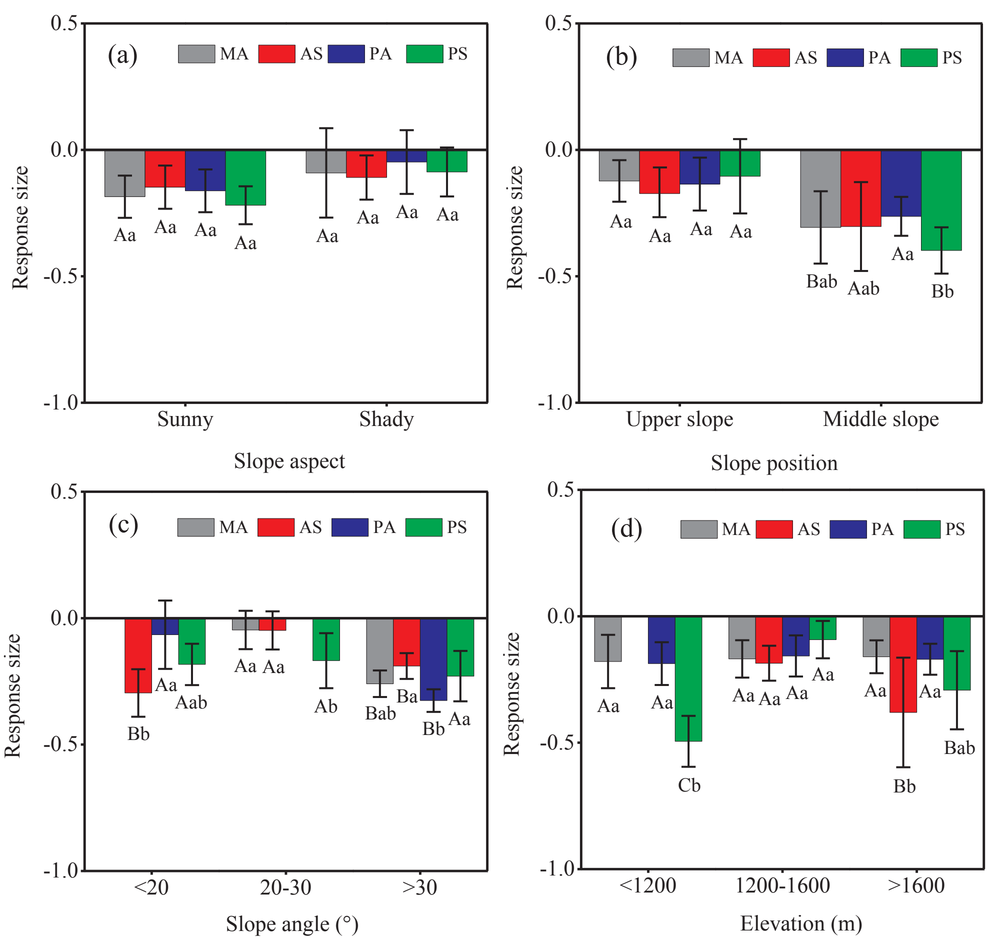

Fig. 4. The response size of soil moisture by different topographic factors. Note: MA: mixed arbors; AS: arbors mixed with shrubs; PA: pure arbors; and PS: pure shrubs. The charts with error bars denote the overall mean values and the 95% CIs. Different lower-case letters indicate significant differences among different vegetation species ($P < 0.05$), and different upper-case letters indicate significant differences among different topographic factors ($P < 0.05$).

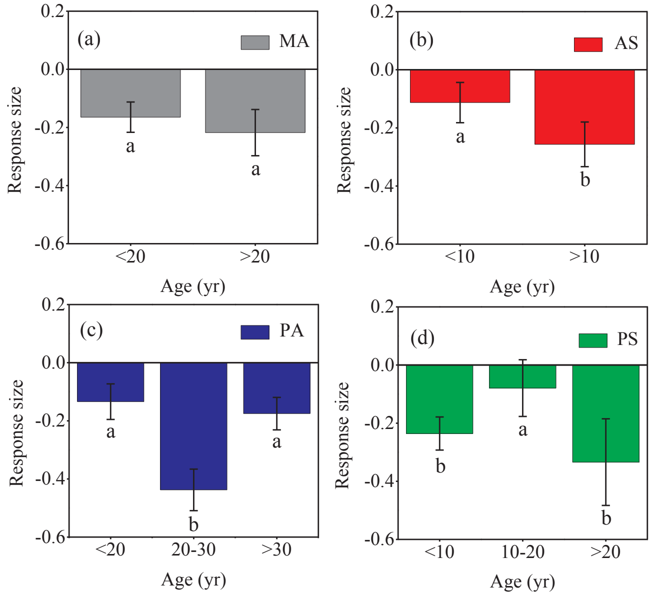

Fig. 5. The response size of soil moisture at different planting age. Note: MA: mixed arbors; AS: arbors mixed with shrubs; PA: pure arbors; PS: pure shrubs. The charts with error bars denote the overall mean values and the 95% CIs. Different lower-case letters indicate significant differences among different planting age ($P < 0.05$).

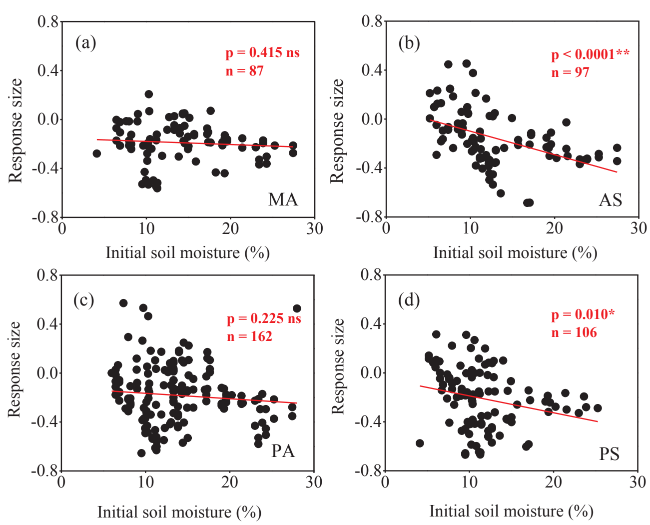

Fig. 6. The relationship between the response size of soil moisture and the initial soil moisture. Note: MA: mixed arbors; AS: arbors mixed with shrubs; PA: pure arbors; and PS: pure shrubs. * significant at $P < 0.05$, ** significant at $P < 0.01$.

(Forrester and Bauhus, 2016). In addition, due to differences in research areas and subjects, available research results are inconsistent and may even have opposite conclusions (Lebourgeois et al., 2013; Grossiord et al., 2014). Therefore, there is an urgent need to raise awareness of the characteristics of soil moisture changes in different planting patterns in arid environments to propose sustainable management options. Our results showed that mixed-species plantations, especially arbor mixed with shrubs, are more conducive to maintaining the soil moisture content. However, this effect also varies by topography, climate and planting age. This study determined the general rules and influencing factors of soil moisture change in mixed-species and monoculture plantations, and provided suggestions for the scientific planning and sustainable development of forest in the future.

4.1. Effects of different vegetation patterns and types on soil moisture

Our study found that the response size of soil moisture of the soil profile (0–500 cm) decreased significantly in both monoculture plantations and mixed-species plantations (Fig. 2 and Table 1). Although previous studies have yielded similar results (Shangguan, 2007; Yang et al., 2012; Duan et al., 2017), these studies were based on different land use types and ignored the variation characteristics of soil moisture content in different planting patterns (mixed-species plantations and monoculture plantations). By comparing the changes in soil moisture content between monoculture plantations and mixed-species plantations, we found that the response size of soil moisture in the surface layer (0–100 cm) was the highest (Fig. 2b, c), probably as a result of rainfall recharge (Chen et al., 2008; Tan et al., 2016). However, both planting patterns consumed substantial deep water (400–500 cm) (Fig. 2b, c), this phenomenon was probably due to the water stress and the subsequent transport of deeper soil moisture content to shallower soil layers by roots to meet the needs of vegetation growth (Lee et al., 2005; Wang et al., 2011b). We also found that mixed-species plantations did not show significant the response size of soil moisture reductions in the 0–400 cm layer (Fig. 2b), which may be attributed to the stand structural heterogeneity of the mixed-species plantation (Zeller et al., 2017). The structure could adjust the evapotranspiration of vegetation and the redistribution of rainfall to improve the microclimate and light transmittance between forests (Barbier et al., 2008; Cavanaugh et al., 2011; Edwards et al., 2014). In addition, mixed-species plantations can increase the hydraulic conductivity of the surface soil layer by increasing the buffering and interception capacity of the leaves and the litter layer to increase the soil moisture content (Robichaud, 2000; Jin et al., 2011).

Interestingly, we found no significant difference in the response size of soil moisture at the same soil layer between monoculture plantations and mixed-species plantations (Fig. 2b, c and Table 1). Similarly, Su and Shangguan (2019) showed that there was no significant difference in the response size of soil moisture among different vegetation species on the Loess Plateau. This phenomenon was attributable to the sampling season, especially in the surface soil layer (0–100 cm); the soil moisture content at the surface layer may temporarily increase due to precipitation. Moreover, the soil layers were divided by 100 cm in this study and ignored some details of the changes in soil moisture content. In addition, many of the integrated studies lacked long-term observations, which may have increased the uncertainty of this study (Appendix Dataset A).

Our study also found that various combinations of different vegetation species have large variations in their ecological strategies for dealing with water stress. In this study, we found that significant differences were not observed in the response size of soil moisture at 0–500 cm in the case of the pure shrubs and the arbors mixed with shrubs (Table 1), this may be due to shrubs (such as *Caragana korshinskii*) need more water to maintain their rapid growth; when water supply in the shallow layer (0–100 cm) is in short, the plantations will use the deep-water resources and then release the absorbed water into the shallow layer (Prieto and Ryel, 2014; Deng et al., 2016). The response sizes of soil moisture among the mixed arbors and the pure arbors at the deep layer (400–500 cm) were significantly lower than that at the surface layer (0–100 cm) (Table 1), probably because *Robinia pseudoacacia* and *Pinus tabulaeformis* were widely planted on the Loess Plateau (Appendix Dataset A), both of which had two types of roots: lateral roots that absorb surface water mainly during the wet season and main roots that absorb the deep water during the dry season (Dawson and Pate, 1996; Zhang et al., 2014). This structure led to substantial water consumption in the deep soil layer.

4.2. Analysis of factors affecting soil moisture

In addition to the influence of vegetation species and planting patterns, the soil moisture content was affected by various factors such as climate, topography and planting age. Among them, temperature and rainfall could directly affect soil moisture content through evapotranspiration and recharge in the affected area. This meta-analysis showed that areas with abundant rainfall and low evapotranspiration were more suitable for afforestation (Fig. 3a, b). Previous researches had also proven this point (Jian et al., 2015; Yan et al., 2017; Ren et al., 2018). For topographic factors, previous studies generally thought that the soil moisture content on shady slopes was generally better than that on sunny slopes on the Loess Plateau (Wang et al., 2011a). However, in our study, we found that the slope aspect did not significantly affect the response size of soil moisture (Fig. 4a), indicating that the slope aspect was not the main factor affecting the soil moisture content on the Loess Plateau (Yu and Jiao, 2018). Additionally, we found that the response size of soil moisture on the upper slope position was higher than that on the middle slope position (Fig. 4b). Although some studies have shown that the soil moisture moved laterally from top to bottom due to topography/gravity and eventually accumulated in the lower region (Newman et al., 1998), there were also studies suggesting that vegetation species could play a greater role in the movement of soil moisture, because plantations could drive soil moisture accumulation by affecting the initial soil moisture content, soil infiltration patterns and rain interception on slopes (Wilcox, 2002; Zhao et al., 2017). In addition, we found that the steep slope and the high elevation were not conducive to soil moisture retention (Fig. 4c, d). Previous studies have also demonstrated this. For example, Feng et al. (2013) and Yang et al. (2017) indicated that soil moisture content was inversely correlated with elevation and slope angle. Li et al. (2008) showed that when the slope angle was > 25°, the soil moisture content dropped sharply.

Similarly, because the water use efficiency of vegetation differs at different growth stages, the difference in soil moisture content between different plantations was obvious. The pure arbors significantly consumed the response size of soil moisture at 20–30 a (Fig. 5c), this may be due to the increased transpiration and large water demand in this stage (Chen et al., 2007). However, the water consumption of the pure arbors decreased after 30 years, which may be attributed to the maturity of the arbors after 30 years, and the gradual cessation of vegetation growth, which reduced the consumption of soil moisture (Jia et al., 2017; Yu and Jiao, 2018). For the pure shrubs, the response size of soil moisture in the moderate age (10–20a) stage was significantly higher than that at the young stage (< 10a) and the mature stage (> 20a) (Fig. 5d), which was probably due to the "transpiration pull" of the shrub root system and the "funnel effect" of the shrubs (Jian et al., 2014; Prieto and Ryel, 2014). In addition, shrubs were more morphologically conducive to the penetration of rainwater into the substrate than arbors (Yang et al., 2019). Our study also pointed out that with increasing planting age, the response size of soil moisture for the mixed-species plantations gradually decreased (Fig. 5a, b). However, the soil moisture content change of the arbors mixed with shrubs was more obvious (Fig. 5b), probably because the inconsistent use of soil moisture by arbors and shrubs at different life stages (Fig. 5c, d).

Our study also showed that the response size of soil moisture for different vegetation species was negatively correlated with the initial water content (Fig. 6), which was consistent with the results of Su and Shangguan. (2019). The response sizes of soil moisture for the arbors mixed with shrubs and pure shrubs were significantly negatively correlated with the initial soil moisture content (Fig. 6 b, d), indicating that these two vegetation species were more conducive to maintaining the soil moisture content. However, farmland ecosystems were relatively unstable due to human interventions, such as long-term irrigation and fertilization (Wang et al., 2009). Therefore, the selection of restored and control sites with similar site conditions made the results easier to compare (Chen et al., 2017). At the same time, before planting vegetation, the range of initial soil moisture content in the area should be completely understood to improve the effectiveness of ecological restoration measures.

In addition to the above factors, planting density was also a key factor that affects soil moisture content. In our research, there was no in-depth discussion of planting density due to the lack of data. However, previous studies have pointed out that the introduction of vegetation with high planting density will disturb the balance between soil moisture content and vegetation, thus consuming more soil moisture (Tan et al., 2011; del Campo et al., 2019). Additionally, due to the characteristics of loess, soil texture must be considered when assessing soil moisture conditions. Some studies have shown that the soil moisture content was positively correlated with the clay and the silt content and negatively correlated with the sand content (Fu et al., 2018; Li et al., 2018), which meant that the soil texture was also an important factor affecting the soil moisture content.

4.3. Implications for management

Afforestation usually required more water than native vegetation, and the annual rainfall in arid and semiarid regions generally did not meet these needs (Wang et al., 2010). Considerable evidence showed that the positive aspects of mixed-species plantations were highly influenced by the specific composition of the mixture, and further assessments of which species or combination of functions need to be promoted should be conducted to address regional water stress (Metz et al., 2016). Afforestation was not a useful choice for areas where the MAP was close to or below the potential evapotranspiration on the Loess Plateau (Deng et al., 2016). In addition to considering the influence of climatic factors, afforestation should also be adapted to local conditions. Areas with excessive slope and high elevation were not suitable for planting, and the initial soil moisture content was key for the normal growth and development of vegetation. In addition, inappropriate tree species and planting densities are often used, and the forest soil usually lacks moisture; thus, human intervention is needed (Jactel and Brockerhoff, 2007; Shi et al., 2016; Darmawan et al., 2017). Combined with relevant research, we suggested that the future ecological restoration of the Loess Plateau should be transformed from simple species-based measures to the best combination of high-yield vegetation with shallow root plants (Fan et al., 2016; Jiang et al., 2019).

In arid and semiarid regions, water limitation had become a key factor in the growth of regional mixed forests (Molnar, 2001). Although our study showed that mixed-species plantations did not significantly consume soil moisture at 0–400 cm soil depth, it was still debatable whether mixed-species plantations were conducive to alleviating regional soil moisture stress. Although our research could provide a reference for relevant research around the world, still requires additional supplemental evidence.

5. Conclusions

Returning farmland to forests has caused the depletion of soil moisture content on the Loess Plateau, especially in deep soil layers. Better stand structure and community characteristics of mixed-species plantations leads to maintenance of soil moisture content at 0–400 cm compared with that of monoculture plantations. In addition to considering the effects of vegetation species and climate, afforestation measures should also account for the effects of topography, planting age and initial soil moisture content. Specifically, afforestation is an inappropriate choice in areas with low MAP, steep slope and high elevation. These results also provide a reference for global vegetation restoration. In the context of global warming and frequent drought, mixed-species plantations are more conducive to alleviating water stress than monoculture plantations. For arid and semiarid regions, the stability of forest ecosystems should be optimized by increasing the species richness of trees and selecting the best combination of species. In addition, planners must realize that different environments support different vegetation species and patterns.

Author contributions

C.G., M.X. and G.L. conceived this study, C.G. and Q.T. conducted the experiment, C.G. analyzed the results, all authors wrote and edited the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (2017YFC0504601, 2017YFC0506503); the National Natural Science Foundation of China (Grant No. 41771318, 41830758). We express our gratitude to the anonymous reviewers and editors for their constructive comments and suggestions.

References

An, W.M., et al., 2017. Exploring the effects of the "Grain for Green" program on the differences in soil water in the semi-arid Loess Plateau of China. Ecol. Eng. 107, 144–151.
Barbier, S., Gosselin, F., Balandier, P., 2008. Influence of tree species on understory vegetation diversity and mechanisms involved–a critical review for temperate and boreal forests. For. Ecol. Manage. 254 (1), 1–15.
Breshears, D.D., et al., 2005. Regional vegetation die-off in response to global-change-type drought. Proc. Natl. Acad. Sci. U.S.A. 102 (42), 15144–15148.
Cao, S.X., 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. J. Appl. Ecol. 46 (3), 536–543.
Carnol, M., et al., 2014. Ecosystem services of mixed species forest stands and monocultures: comparing practitioners' and scientists' perceptions with formal scientific knowledge. Forestry 87 (5), 639–653.
Cavanaugh, M.L., Kurc, S.A., Scott, R.L., 2011. Evapotranspiration partitioning in semi-arid shrubland ecosystems: a two-site evaluation of soil moisture control on transpiration. Ecohydrology 4 (5), 671–681.
Chen, H.S., Shao, M.G., Li, Y.Y., 2008. The characteristics of soil water cycle and water balance on steep grassland under natural and simulated rainfall conditions in the Loess Plateau of China. J. Hydrol. 360 (1–4), 242–251.
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.
Chen, P.F., Shang, J.L., Qian, B.D., Jing, Q., Liu, J.G., 2017. A New Regionalization Scheme for Effective Ecological Restoration on the Loess Plateau in China. Remote Sens. 9 (12).
Chen, X.D., et al., 2018. Why does oriental arborvitae grow better when mixed with black locust: Insight on nutrient cycling? Ecol. Evol. 8 (1), 744–754.
Chen, Y.P., et al., 2015. Balancing green and grain trade. Nat. Geosci. 8 (10), 739–741.
D'Odorico, P., et al., 2010. Ecohydrology of Terrestrial Ecosystems. Bioscience 60 (11), 898–907.
Darmawan, A., Atmowidi, T., Manalu, W., Suryobroto, B., 2017. Land-use change on Mount Gede, Indonesia, reduced native earthworm populations and diversity. Aust. J. Zool. 65 (4), 217–225.
Dawson, T.E., Pate, J.S., 1996. Seasonal water uptake and movement in root systems of Australian phraeatophytic plants of dimorphic root morphology: A stable isotope investigation. Oecologia 107 (1), 13–20.
del Campo, A.D., et al., 2019. Effectiveness of water-oriented thinning in two semiarid forests: the redistribution of increased net rainfall into soil water, drainage and runoff. For. Ecol. Manage. 438, 163–175.
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. For. Ecol. Manage. 366, 1–10.
Duan, L.X., Huang, M.B., Li, Z.W., Zhang, Z.D., Zhang, L.D., 2017. Estimation of spatial mean soil water storage using temporal stability at the hillslope scale in black locust (Robinia pseudoacacia) stands. Catena 156, 51–61.
Edwards, D.P., Tobias, J.A., Sheil, D., Meijaard, E., Laurance, W.F., 2014. Maintaining ecosystem function and services in logged tropical forests. Trends Ecol. Evol. 29 (9), 511–520.
Fan, J., Wang, Q.J., Jones, S.B., Shao, M.G., 2016. Soil water depletion and recharge under different land cover in China's Loess Plateau. Ecohydrology 9 (3), 396–406.
Feng, Q., Zhao, W.W., Qiu, Y., Zhao, M.Y., Zhong, L.N., 2013. Spatial heterogeneity of soil moisture and the scale variability of its influencing factors: a case study in the loess plateau of China. Water 5 (3), 1226–1242.
Feng, X.M., et al., 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat. Clim. Chang. 6 (11), 1019-+.
Forrester, D.I., 2015. Transpiration and water-use efficiency in mixed-species forests versus monocultures: effects of tree size, stand density and season. Tree Physiol. 35 (3), 289–304.
Forrester, D.I., Bauhus, J., 2016. A Review of Processes Behind Diversity-Productivity Relationships in Forests. Curr. For. Rep. 2, 45–61.
Fu, C.F., Bian, Z.H., Xi, J.J., Zhao, J.B., 2018. Spatial distribution characteristics of soil moisture in different types of sand dune in the Mu Us Sandy Land, adjacent to north of Chinese Loess Plateau. Environ. Earth Sci. 77 (4).
Gao, G.Y., Ma, Y., Fu, B.J., 2016. Temporal Variations of Flow-sediment Relationships in a Highly Erodible Catchment of the Loess Plateau, China. Land Degrad Dev 27, 758–772.
Gao, X.D., Li, H.C., Zhao, X.N., Ma, W., Wu, P.T., 2018. Identifying a suitable revegetation technique for soil restoration on water-limited and degraded land: Considering both deep soil moisture deficit and soil organic carbon sequestration. Geoderma 319, 61–69.
Grossiord, C., Granier, A., Gessler, A., Jucker, T., Bonal, D., 2014. Does Drought Influence the Relationship Between Biodiversity and Ecosystem Functioning in Boreal Forests? Ecosystems 17, 394–404.
Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80 (4), 1150–1156.
Jactel, H., Brockerhoff, E.G., 2007. Tree diversity reduces herbivory by forest insects. Ecol. Lett. 10 (9), 835–848.
Jia, X.X., Shao, M.A., Zhu, Y.J., Luo, Y., 2017. Soil moisture decline due to afforestation across the Loess Plateau. China. J. Hydrol. 546, 113–122.
Jian, S.Q., Zhao, C.Y., Fang, S.M., Yu, K., 2014. Characteristics of Caragana korshinskii and Hippophae rhamnoides stemflow and their significance in soil moisture enhancement in Loess Plateau. China. J. Arid Land 6 (1), 105–116.
Jian, S.Q., Zhao, C.Y., Fang, S.M., Yu, K., 2015. Effects of different vegetation restoration on soil water storage and water balance in the Chinese Loess Plateau. Agric. For. Meteorol. 206, 85–96.
Jiang, C., Zhang, H.Y., Wang, X.C., Feng, Y.Q., Labzovskii, L., 2019. Challenging the land degradation in China's Loess Plateau: Benefits, limitations, sustainability, and adaptive strategies of soil and water conservation. Ecol. Eng. 127, 135–150.
Jiao, L., Lu, N., Sun, G., Ward, E.J., Fu, B.J., 2016. Biophysical controls on canopy transpiration in a black locust (Robinia pseudoacacia) plantation on the semi-arid Loess Plateau. China. Ecohydrology 9 (6), 1068–1081.
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. Hydrol. Earth Syst. Sci. 15 (8), 2519–2530.
Lebourgeois, F., Gomez, N., Pinto, P., Merian, P., 2013. Mixed stands reduce Abies alba tree-ring sensitivity to summer drought in the Vosges mountains, western Europe. For. Ecol. Manage. 303, 61–71.
Lee, J.E., Oliveira, R.S., Dawson, T.E., Fung, I., 2005. Root functioning modifies seasonal climate. Proc. Natl. Acad. Sci. U. S. A. 102 (49), 17576–17581.
Legates, D.R., et al., 2011. Soil moisture: A central and unifying theme in physical geography. Prog. Phys. Geogr. 35 (1), 65–86.
Li, J.X., et al., 2019. The synergistic effects of afforestation and the construction of check-dams on sediment trapping: Four decades of evolution on the Loess Plateau. China. Land Degrad. Dev. 30 (6), 622–635.
Li, T.C., Shao, M.A., Jia, Y.H., Jia, X.X., Huang, L.M., 2018. Profile distribution of soil moisture in the gully on the northern Loess Plateau, China. Catena 171, 460–468.
Li, W., Wang, Q.J., Wei, S.P., Shao, M.A., Yi, L., 2008. Soil desiccation for Loess soils on natural and regrown areas. For. Ecol. Manage. 255 (7), 2467–2477.
Loreau, M., et al., 2001. Biodiversity and ecosystem functioning: current knowledge and future challenges. Science 294 (5543), 804–808.
Luo, Y.Q., Hui, D.F., Zhang, D.Q., 2006. Elevated CO2 stimulates net accumulations of carbon and nitrogen in land ecosystems: A meta-analysis. Ecology 87 (1), 53–63.
Manson, D.G., Schmidt, S., Bristow, M., Erskine, P.D., Vanclay, J.K., 2013. Species-site matching in mixed species plantations of native trees in tropical Australia. Agrofor. Syst. 87 (1), 233–250.
Metz, J., et al., 2016. Site-adapted admixed tree species reduce drought susceptibility of mature European beech. Glob. Change Biol. 22 (2), 903–920.
Molnar, P., 2001. Climate change, flooding in arid environments, and erosion rates. Geology 29 (12), 1071–1074.
Montagnini, F., Ugalde, L., Navarro, C., 2003. Growth characteristics of some native tree species used in silvopastoral systems in the humid lowlands of Costa Rica. Agrofor. Syst. 59 (2), 163–170.
Newman, B.D., Campbell, A.R., Wilcox, B.P., 1998. Lateral subsurface flow pathways in a semiarid ponderosa pine hillslope. Water Resour. Res. 34 (12), 3485–3496.
Powers, J.S., Corre, M.D., Twine, T.E., Veldkamp, E., 2011. Geographic bias of field observations of soil carbon stocks with tropical land-use changes precludes spatial extrapolation. Proc. Natl. Acad. Sci. U. S. A. 108 (15), 6318–6322.
Pretzsch, H., Schutze, G., Uhl, E., 2013. Resistance of European tree species to drought stress in mixed versus pure forests: evidence of stress release by inter-specific facilitation. Plant Biology 15 (3), 483–495.
Prevosto, B., Gavinet, J., Monnier, Y., Corbani, A., Fernandez, C., 2016. Influence of neighbouring woody treatments on Mediterranean oak development in an experimental plantation: Better form but weaker growth. For. Ecol. Manage. 362, 89–98.
Prieto, I., Ryel, R.J., 2014. Internal hydraulic redistribution prevents the loss of root conductivity during drought. Tree Physiol. 34, 39–48.
Ren, Z.P., et al., 2018. Comparing watershed afforestation and natural revegetation impacts on soil moisture in the semiarid Loess Plateau of China. Sci Rep 8.
Rennenberg, H., et al., 2006. Physiological responses of forest trees to heat and drought. Plant Biology 8 (5), 556–571.
Richards, A.E., Forrester, D.I., Bauhus, J., Scherer-Lorenzen, M., 2010. The influence of mixed tree plantations on the nutrition of individual species: a review. Tree Physiol. 30 (9), 1192–1208.

Robichaud, P.R., 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests. USA. J. Hydrol. 231, 220–229.
Schwendenmann, L., Pendall, E., Sanchez-Bragado, R., Kunert, N., Holscher, D., 2015. Tree water uptake in a tropical plantation varying in tree diversity: interspecific differences, seasonal shifts and complementarity. Ecohydrology 8 (1), 1–12.
Shangguan, Z.P., 2007. Soil desiccation occurrence an its impact on forest vegetation in the Loess Plateau of China. Int. J. Sustain. Dev. World Ecol. 14 (3), 299–306.
Shi, H.J., Wen, Z.M., Paull, D., Jiao, F., 2016. Distribution of natural and planted forests in the Yanhe river catchment: have we planted trees on the right sites? Forests 7 (11).
Stocker, B.D., et al., 2019. Drought impacts on terrestrial primary production underestimated by satellite monitoring. Nat. Geosci. 12 (4), 264-+.
Su, B.Q., Shangguan, Z.P., 2019. Decline in soil moisture due to vegetation restoration on the Loess Plateau of China. Land Degrad. Dev. 30 (3), 290–299.
Sun, G., et al., 2006. Potential water yield reduction due to forestation across China. J. Hydrol. 328 (3–4), 548–558.
Tan, H.B., Wen, X.W., Rao, W.B., Bradd, J., Huang, J.Z., 2016. Temporal variation of stable isotopes in a precipitation-groundwater system: implications for determining the mechanism of groundwater recharge in high mountain-hills of the Loess Plateau. China. Hydrol. Process. 30 (10), 1491–1505.
Tang, Y.K., et al., 2018. Water use strategies for two dominant tree species in pure and mixed plantations of the semiarid Chinese Loess Plateau. Ecohydrology 11 (4).
Tan, Z.H., et al., 2011. Rubber plantations act as water pumps in tropical China. Geophys Res Lett 38.
van der Waal, C., et al., 2009. Water and nutrients alter herbaceous competitive effects on tree seedlings in a semi-arid savanna. J. Ecol. 97 (3), 430–439.
Vereecken, H., et al., 2014. On the spatio-temporal dynamics of soil moisture at the field scale. J. Hydrol. 516, 76–96.
Wang, C., Fu, B.J., Zhang, L., Xu, Z.H., 2019. Soil moisture-plant interactions: an eco-hydrological review. J. Soils Sediments 19 (1), 1–9.
Wang, L., Wei, S.P., Horton, R., Shao, M.A., 2011a. Effects of vegetation and slope aspect on water budget in the hill and gully region of the Loess Plateau of China. Catena 87 (1), 90–100.
Wang, Q.J., et al., 2009. Controlled traffic farming with no tillage for improved fallow water storage and crop yield on the Chinese Loess Plateau. Soil Tillage Res. 104 (1), 192–197.
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. J. Hydrol. 381 (1–2), 9–17.
Wang, Y.Q., Shao, M.A., Zhu, Y.J., Liu, Z.P., 2011b. Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China. Agric. For. Meteorol. 151 (4), 437–448.
Wilcox, B.P., 2002. Shrub control and streamflow on rangelands: A process based viewpoint. J Range Manage 55 (4), 318–326.
Yan, W.M., Zhong, Y.Q.W., Shangguan, Z.P., 2017. Responses of different physiological parameter thresholds to soil water availability in four plant species during prolonged drought. Agric. For. Meteorol. 247, 311–319.
Yang, L., Wei, W., Chen, L.D., Mo, B.R., 2012. Response of deep soil moisture to land use and afforestation in the semi-arid Loess Plateau. China. J. Hydrol. 475, 111–122.
Yang, X.L., Shao, M.A., Wei, X.R., 2019. Stemflow production differ significantly among tree and shrub species on the Chinese Loess Plateau. J. Hydrol. 568, 427–436.
Yang, Y., Dou, Y.X., Liu, D., An, S.S., 2017. Spatial pattern and heterogeneity of soil moisture along a transect in a small catchment on the Loess Plateau. J. Hydrol. 550, 466–477.
Yu, W.J., Jiao, J.Y., 2018. Sustainability of abandoned slopes in the hill and gully loess plateau region considering deep soil water. Sustainability 10 (7).
Zeller, L., Ammer, C., Annighofer, P., Biber, P., Marshall, J., Schutze, G., Gaztelurrutia, M.D., Pretzsch, H., 2017. Tree ring wood density of Scots pine and European beech lower in mixed-species stands compared with monocultures. Forest. Ecol. Manag. 400, 363–374.
Zhang, B.B., et al., 2019. Higher soil capacity of intercepting heavy rainfall in mixed stands than in pure stands in riparian forests. Sci. Total Environ. 658, 1514–1522.
Zhang, C.B., Chen, L.H., Jiang, J., 2014. Vertical root distribution and root cohesion of typical tree species on the Loess Plateau. China. J. Arid Land 6 (5), 601–611.
Zhao, C.L., Jia, X.X., Zhu, Y.J., Shao, M.A., 2017. Long-term temporal variations of soil water content under different vegetation types in the Loess Plateau, China. Catena 158, 55–62.
Zhao, G.J., Mu, X.M., Wen, Z.M., Wang, F., Gao, P., 2013. Soil erosion, conservation, and eco-environment changes in the loess plateau of China. Land. Degrad. Dev. 24, 499–510.