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Severe depletion of available deep soil water induced by revegetation on the arid and semiarid Loess Plateau

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ABSTRACT

Revegetation-induced water deficits in the deep soil (>100 cm) on the arid and semiarid Loess Plateau threaten the sustainability of its ecosystems. However, quantifying changes in deep-soil water status at the regional scale remains challenging. This study represents the first attempt to integrate *meta*-analysis with the digitization of map data from previous research to evaluate the effects of revegetation on the deep soil water status. A total of 4906 observations from 94 peer-reviewed publications related to soil water changes to a depth of 500 cm in planted forests, planted shrublands, natural grasslands and croplands were synthesized, and two regional-scale evaluation criteria, the stable field capacity (SFC) and the permanent wilting point (PWP), were developed by digitizing the map data. The results indicated that (1) compared with cropland, revegetation more severely depleted the deep soil water availability, and planted forest revegetation resulted in the most serious depletion; (2) the extent of soil water changes was influenced significantly by the tree species planted; *Platycladus orientalis* was better able to maintain the deep soil water availability than *Robinia pseudoacacia* and *Pinus tabuliformis*; (3) the soil water status worsened with time after restoration, particularly at 20 years after restoration; (4) contrary to expectations, deep soil water depletion in forests and shrublands even increased in areas of high rainfall zones (>550 mm) compared to drier zones.; and (5) natural restoration (i.e., grasslands) was a better option than revegetation due to the resultant higher, more stable soil water availability. These results indicate that changes in deep soil water availability must be considered when planning revegetation initiatives.

1. Introduction

In water-limited regions, the soil water status is the foundation of many hydrological and biogeochemical processes and plays a decisive role in sustaining ecological functions and services (Huang and Shao, 2019). The arid and semiarid Chinese Loess Plateau is characterized by thick loess deposits (the average thickness of loess coverage is 105.7 m (Zhu et al., 2018)), limited annual precipitation (<600 mm) and strong evapotranspiration (1400–2000 mm) (Wang et al., 2010b). Due to unreasonable land use, the Loess Plateau has become one of the areas in the world with the most serious soil erosion (Wen and Zhen, 2020). To counteract soil erosion and other environmental problems, a large-scale revegetation effort known as the "Grain for Green" project has been widely implemented on the Loess Plateau (Cao et al., 2009). Although the initial goal of the "Grain for Green" was to curb soil erosion, it resulted in a severe decline in soil water content (SWC), which threatens ecological sustainability on the Loess Plateau (Wang et al., 2010a; Huang and Shao, 2019). Despite a growing interest in soil water research on the Loess Plateau (Wang et al., 2015b; Zhu et al., 2019; Zhang et al., 2020), the regional effects of revegetation on deep SWC and soil water availability remain unclear.

According to a literature review that included 148 studies of how revegetation affects deep soil water (>100 cm) on the Loess Plateau (Supplementary Table 1), more than 80% of studies focused on soil water changes at the field or small-watershed scale. Only 20 cases addressed deep soil water (>100 cm) at the regional scale, 19 of which

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came from the same dataset (Supplementary Table 1). Recent quantitative reviews have discussed the impact of revegetation on soil water at the regional scale (Deng et al., 2016; Yu et al., 2018); however, the depth of these reviews was limited to within the upper 100 cm of soil. To the best of our knowledge, the regional effects of revegetation on the deep soil water status and its dynamics remain essentially lacking due to the high costs of sampling and labor.

The soil water status at different depths is usually related to various hydrological or ecological functions (Yang et al., 2012; Fang et al., 2016). Shallow soil water (<100 cm) is usually strongly affected by precipitation infiltration or evapotranspiration and is a direct water source for plant growth (Fang et al., 2016), while deep soil water, which is relatively insensitive to environmental changes, functions as a "soil reservoir". In years of heavy rainfall, precipitation can supplement the deep soil water (Cao et al., 2018). In dry years, deep soil can provide the water necessary for plant growth, and it is essential for plant growth in dry seasons (Wang et al., 2010a). This relationship is especially crucial in water-limited regions, such as the Loess Plateau, where water resources are extremely scarce (Wang et al., 2015b). In these areas, deep soil water has become a major constraint on plant productivity and ecosystem sustainability (Wang et al., 2012b; Huang and Shao, 2019).

Revegetation on the Loess Plateau, e.g., converting cropland to forestland, shrubland, or grassland, changes the vertical distribution profile of plant roots (Wang et al., 2010a). For example, the root depth of traditional crops grown in this area (e.g., millet or wheat) is usually within 50 cm. After the implementation of revegetation, the introduced forest species (e.g., *Robinia pseudoacacia* or *Pinus tabuliformis*) and shrub species (e.g., *Caragana microphylla*) have developed extensive root systems that have been reported to reach a depth of more than 1000 cm (Gao et al., 2018). Compared with crop species, the tree species introduced during revegetation consume more water; therefore, an ecological problem occurs because the regional precipitation cannot meet the evapotranspirative demand of the introduced vegetation (Feng et al., 2016; Li et al., 2018). It has been reported that deep-rooted plants such as forest trees not only absorb and use contemporaneous precipitation in shallow soils but also use deep soil water (>100 cm) that has accumulated over the long term (Pierret et al., 2016). Li (2019) showed that natural precipitation on the Loess Plateau could not meet the water consumption needs of mature forests, leading to the continuous use of deep soil water. Although the absorption of deep soil water through roots and its utilization by plants can help alleviate water stress in plants (Nepstad et al., 1994; Markewitz et al., 2010), the excessive consumption of deep soil water on the Loess Plateau has weakened the ecological function of the soil reservoirs and has gradually resulted in soil desiccation, reduced groundwater replenishment rates, and a series of new ecological and hydrological problems, such as wizened, old trees (Wang et al., 2010a; Wang et al., 2010b). This has greatly exacerbated the water crisis in the region and has directly affected regional water security and ecological restoration sustainability. Therefore, quantifying the impact of revegetation on the soil water profile at a regional scale is essential for guiding ecological restoration on the Loess Plateau.

The availability of soil water is the predominant factor limiting vegetation and ecosystem productivity on the arid and semiarid Loess Plateau (Huang and Shao, 2019). The available soil water refers to the difference in the root zone SWC between the field capacity and the permanent wilting point (PWP) (Wang et al., 2010b). The field capacity refers to a relatively stable SWC that can be maintained in the soil profile for a certain period after the soil water is fully replenished by irrigation or precipitation under conditions of deep groundwater and good drainage. At field capacity, water can freely and completely infiltrate the soil, and water evaporation is prevented. The PWP is the SWC level at which plants permanently wilt because their roots cannot absorb water. It is the lower limit below which plants cannot access the soil water. According to previous studies on the Loess Plateau (Wang et al., 2010a; Wang et al., 2010b), the widely accepted range of soil water contents in severe soil desiccation is from the permanent wilting point to the stable field capacity (SFC) (upper limit). Generally, 60% of field capacity has been taken to be the SFC and thus a soil layer with a SWC lower than the SFC could be considered as a dried soil layer (Wang et al., 2010a). The existence of a dried soil layer prevents or slows the exchange of soil water between the shallow and deep soil layers, leading to the "soil reservoir" function being weakened, ecosystem degradation and even large-scale plant death (Wang et al., 2010a; Wang et al., 2012a). It has been reported that the large-scale distribution of "little old man trees" whose ecological benefits such as soil and water conservation were not obvious or even lost, which was largely related to the occurrence of soil desiccation on almost 2/5 of the area of the Loess Plateau is largely caused by insufficient water, which is related to the existence of dried soil layers (Wang, 2010). Quantifying the "gap" between the SWC and the SFC and PWP at the regional scale has highly practical guidance value. Nevertheless, limited by the high costs of sampling and labor, identifying the changes in deep soil water and their driving factors remains challenging.

The present study tries to quantify deep soil water changes at the regional scale on the Loess Plateau based on the spatial reference established by Wang (2010) (Fig. 1 C, D) and the large dataset related to soil water after revegetation combined with the method of unweighted *meta*-analysis (Deng et al., 2016). Then, the effects of vegetation type, soil depth, precipitation, and time since revegetation on soil water are discussed. We hypothesize that at the regional scale, revegetation, especially with deep-rooted plants (e.g., forest trees and shrubs), significantly reduces the soil water availability in deep soil and that the changes in deep soil water are impacted by the vegetation type or tree species, time since revegetation and rainfall zone. The objectives of this study are to 1) identify the changes in deep soil water and its availability after revegetation and 2) detect the effects of different vegetation types, restoration periods and climatic zones on deep soil water changes.

2. Materials and methods

2.1. Data compilation

The peer-reviewed publications included in this study investigated the effect of revegetation on SWC changes on the Loess Plateau. Online databases, including Web of Science (http://www.webofknowledge.com/) and China National Knowledge Infrastructure (CNKI) (https://www.cnki.net/), were used to search peer-reviewed publications that were published before July 2020. The following keywords were used to select related studies: revegetation, restoration, soil water, soil moisture, "Grain for Green" and Loess Plateau. In addition, to avoid bias, the following criteria were used to select publications for the data analysis:

(1) The SWC was determined volumetrically or gravimetrically using an auger or neutron probe in the field (laboratory experiments excluded);
(2) The SWC was determined to a depth of at least 100 cm; the SWC data were grouped into the following depth classes: 0–100 cm, 100–200 cm, 200–300 cm, 300–400 cm and 400–500 cm;
(3) The changes in SWC during revegetation with planted forests, planted shrublands or natural grasslands (e.g., abandoned croplands) on the Loess Plateau were reported;
(4) The data were collected at the field scale (studies with data at the regional scale were excluded); and
(5) The location, precipitation amount, and vegetation type were clearly provided, and the number of years since revegetation was either provided or directly ascertainable.

In total, 4906 observations from 94 peer-reviewed publications since 2000 at 55 sites on the Loess Plateau were compiled (Fig. 1 A); of these, 3052 observations had a clear chronosequence. The raw data were extracted either from tables directly or from figures with Getdata Graph

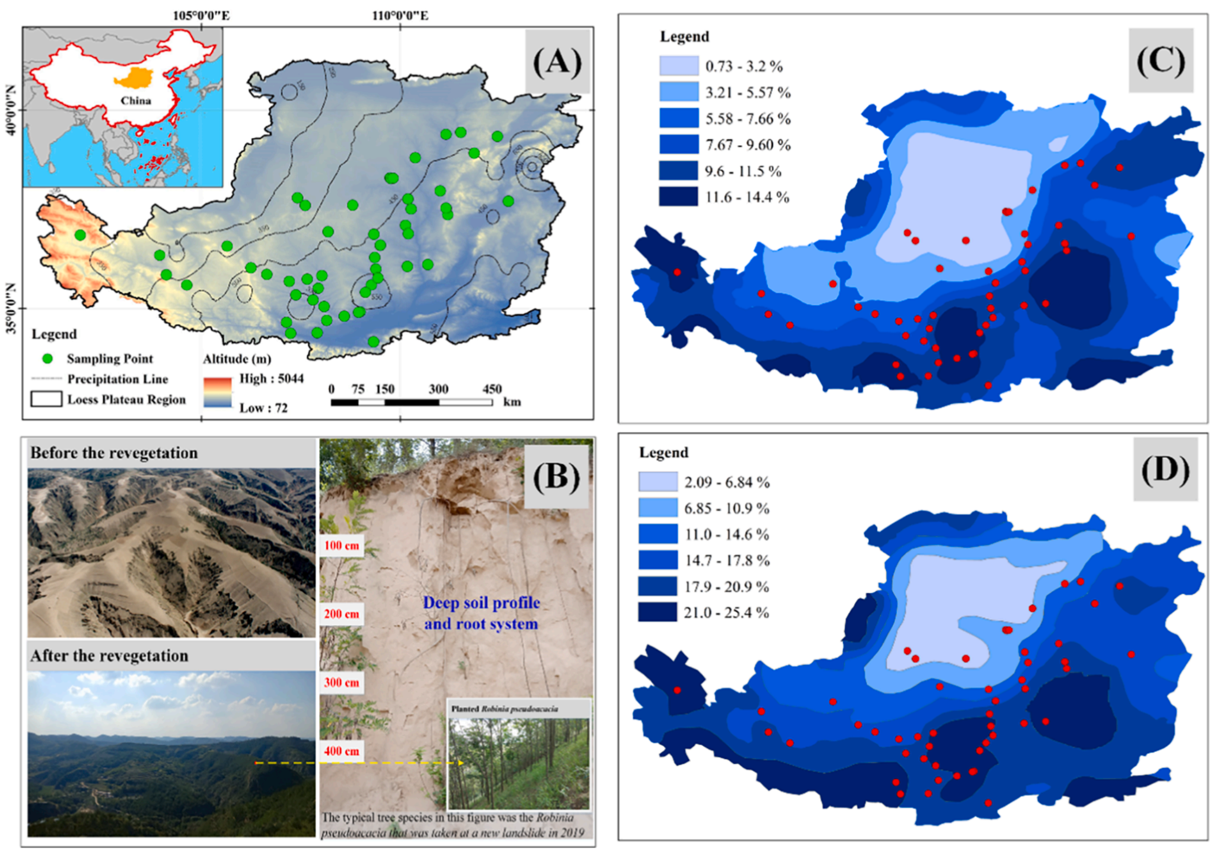

Fig. 1. (A) The distribution of sampling sites, (B) deep root systems, (C) the spatial distributions of the permanent wilting point (D) and field capacity on the Loess Plateau. Note: The figures of the deep root systems in a landslide area and under different vegetation types were taken in the Zhifanggou watershed during a 2019 field survey. The spatial distributions of the permanent wilting point (C) and field water capacity (D) are digitized from Wang (2010).

Digitizer (version 2.24, Russian Federation). The following information was compiled: data source (title, authors, and year published), site location (longitude and latitude), climatic information (mean annual precipitation (MAP) and temperature), vegetation type (cropland, grassland, shrubland (*C. microphylla*, *Hippophae rhamnoides* and other shrub species) and forest (*R. pseudoacacia, Pinus tabuliformis, Platycladus orientalis* and other tree species)), soil depth, and SWC. In this study, part of the database in Deng et al. (2016) (117 pieces of data, accounting for 2.4% of the final database) and Su and Shangguan (2019) (1058 pieces of data, accounting for 21.5% of the final database) were incorporated into the final database as independent observations. According to previous studies in this region (Wang et al., 2012b; Zhao et al., 2017), the soil depths of 0–500 cm were grouped into five levels: 0–100 cm, 100–200 cm, 200–300 cm, 300–400 cm, and 400–500 cm. When more than one depth was sampled (e.g., at an interval of 20 cm or 10 cm), the mean SWC every 100 cm was calculated. The volumetric SWC and gravimetric SWC were transformed based on the formula proposed by Jia et al. (2017b) and Bai (2009) for the Loess Plateau.

2.2. The selection of references at the regional scale for assessing soil water availability

In this study, we selected two parameters, the SFC (equal to 60% of the field capacity) and the PWP, to evaluate changes in the SWC, which are commonly accepted parameters for the Loess Plateau (Wang et al., 2010a; Wang et al., 2010b; Zhang et al., 2020). The basis for the selection of these two parameters is provided in the Introduction. Previous studies that used the SFC and PWP to assess the soil water status have usually been performed at the field scale (Wang et al., 2010a) or the small-watershed scale (Yu and Jiao, 2018). It remains a challenge to derive these parameters at the regional scale. However, Y. Wang has performed several noteworthy studies on this topic (e.g., Wang (2010)). In 2009, Wang et al. quantified the spatial distribution of SFC and PWP (Fig. 1 C, D) at 382 sampling points on the Loess Plateau (Wang et al., 2015a). They also quantified the spatial distribution of other soil parameters (e.g., soil texture, saturated water content, and bulk density) in this region (Wang et al., 2013). These studies provide a good foundation for soil water research on the Loess Plateau. In this study, we digitized a map of the spatial distribution of field capacity and PWP (Fig. 1 C, D). The tool box in ArcGIS 10.3 was used to extract field capacity and PWP with the *Spatial Analyst-Extract Analysis-Extract Values to Points* tools based on the digitized map of field capacity and PWP and our sampling sites (Fig. 1 C, D). The SFC could then be calculated directly from the field capacity.

2.3. Quantification of soil water changes at the regional scale

After calculating the SFC and PWP, the next step was to quantify the changes in the SWC. To achieve this goal, the unweighted *meta*-analysis approach was used (Deng et al., 2016; Li et al., 2020). The degree of change in the SWC compared with the SFC and PWP was calculated as the response size with Eqs. (1) and (2):

$$R_{PWP} = SWC/PWP - 1 \quad (1)$$

$$R_{SFC} = SWC/SFC - 1 \quad (2)$$

where SWC is the soil water content (%); PWP and SFC are the permanent wilting point and the stable field capacity, respectively; R_{PWP} is the relative change in SWC compared to PWP; and R_{SFC} is the degree of change in SWC compared to SFC.

In a traditional *meta*-analysis, the mean values of the treatment and control with their standard deviations or standard errors should be extracted from the publications. However, most published papers selected for this study reported their mean values without standard deviations. To maximize the number of observations, unweighted *meta*-analysis was adopted. In this study, we regarded the SFC and PWP as the control values and calculated the response size (R_{PWP} and R_{SFC}) of the changes in SWC after revegetation. This operation not only evaluates the changes in SWC based on a large dataset but also avoids the uncertainty caused by the spatial variability in SFC and PWP at the regional scale.

To test the significance of differences between SWC and SFC or PWP, a 95% confidence interval was used. A previously described method (Luo et al., 2006; Deng et al., 2016) was used to calculate the 95% confidence intervals (CIs) of the R_{PWP} and R_{SFC} for SWC, as shown in Eqs. (3) and (4):

$$SE_{total} = \sqrt{\frac{Vs}{N}} \quad (3)$$

$$95\%CI = 1.96 \times SE_{total} \quad (4)$$

where SE_{total} is the standard error of R_{PWP} or R_{SFC} for SWC and Vs and N are the variances of R_{PWP} or R_{SFC} and the number of observations, respectively. In this study, the differences between SWC and R_{PWP} or R_{SFC} were considered significant if the 95% CIs did not include zero, and the differences were not considered significant if the 95% CIs did not include zero.

2.4. Statistical analysis

The Kruskal-Wallis test was used to test the difference in R_{PWP} or R_{SFC} among different vegetation types, soil depths, restoration periods and

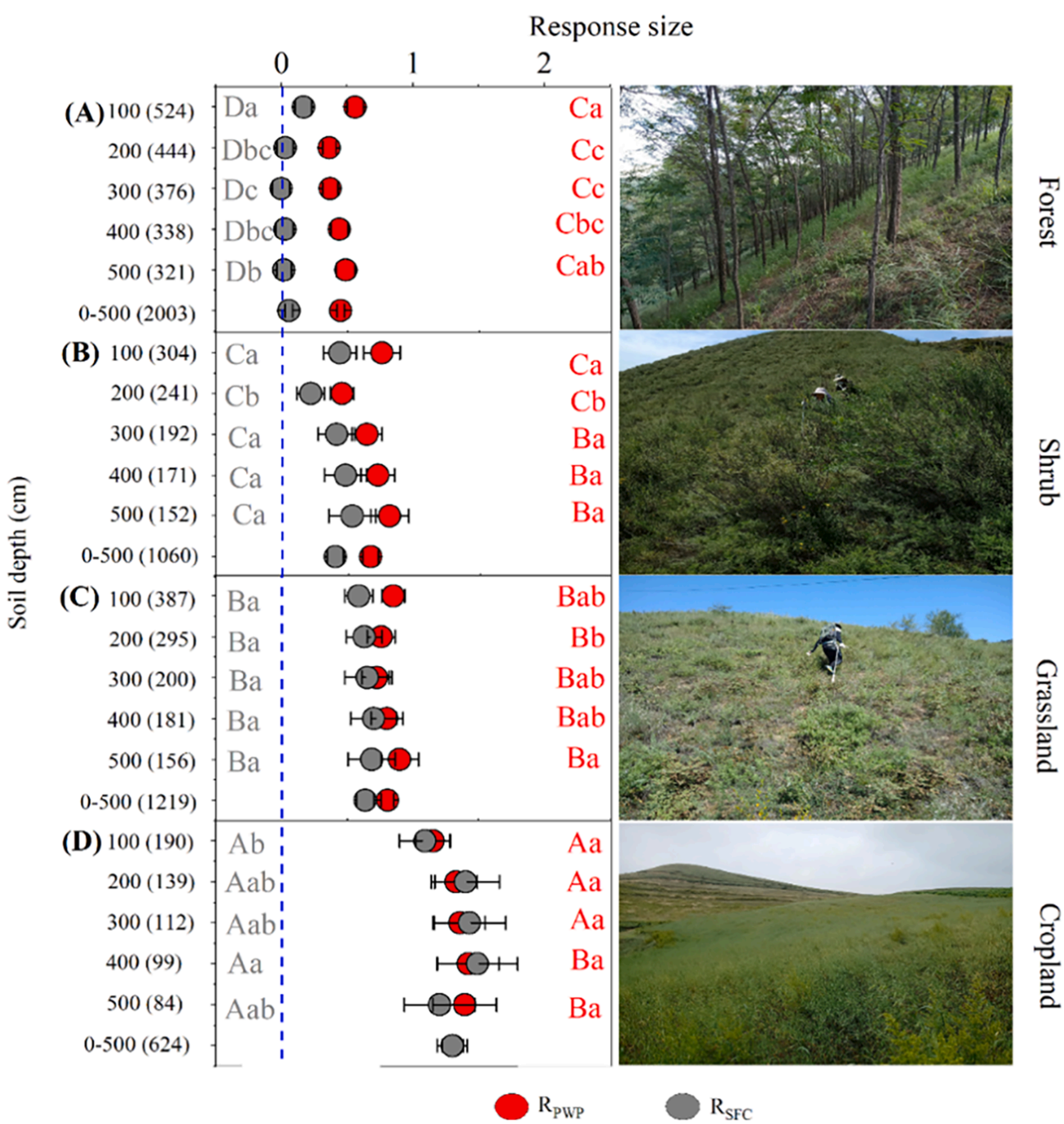

Fig. 2. The overall effects of revegetation on the soil water content at different depths on the Loess Plateau. Note: (A) Forest; (B) Shrub; (C) Grassland; (D) Cropland. Dots with error bars denote the overall mean values and 95% CIs, and the number of observations is in parentheses. Different uppercase letters indicate significant differences among the different vegetation types within the same soil layer ($P < 0.05$). Different lowercase letters indicate significant differences among the different soil layers within the same vegetation type ($P < 0.05$). The dashed line indicates $x = 0$. The red and gray letters represent the statistical tests for the R_{SFC} and R_{PWP}, respectively. The figures of the different typical vegetation types were taken in the Zhifanggou watershed during a 2019 field survey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

climatic zones. A Kruskal-Wallis test is typically performed to test for differences between three or more treatments or conditions; in this way, it is similar to a one-way ANOVA. However, the Kruskal-Wallis test is robust to nonnormally distributed variables, and is often considered a nonparametric alternative to one-way ANOVA. In this study, the *kruskal* function in the R package *agricolae* was used to perform the Kruskal-Wallis test (https://cran.r-project.org/web/packages/agricolae/index.html). Linear regression was used to test the relationship between the changes in SWC (R_{PWP} and R_{SFC}) and the restoration time and precipitation gradients. The *lm* function in R was used to perform the linear regression.

3. Results

3.1. Soil water depletion by vegetation type

When an area was revegetated with any type of perennial vegetation (forest, shrubland, or grassland), the SWC across the 0–500 cm profile was depleted compared with that under cropland (Fig. 2). Overall, the depletion of SWC in terms of both the R_{PWP} and R_{SFC} decreased in the order forest > shrubland > grassland > cropland (Fig. 2). Specifically, forests exhibited more severe deep SWC depletion (>100 cm) than the other three vegetation types, in which there was no significant difference between the SWC and the SFC (Fig. 2 A).

In lands that were restored to forests and shrublands, the overall SWC depletion was also influenced significantly by species, although the differences between specific soil layers were not significant (Fig. 3). In terms of the R_{PWP} and R_{SFC}, the tree species *R. pseudoacacia* and *Pinus tabuliformis* depleted the SWC the most (A2, D2; A3, D3), while *Platycladus orientalis* was better able to maintain the deep SWC (>300 cm) (Fig. 3 A1, D1). In particular, the deep SWC under *R. pseudoacacia* was significantly lower than the SFC (Fig. 3 D2), and the deep SWC under *Pinus tabuliformis* was the same as the SFC (Fig. 3 D3). Shrub species also had a significant effect on the SWC (Fig. 3 B1-B2, D1-D2); the SWC depletion was significantly greater under *H. rhamnoides* (Fig. 3 D2) than under *C. korshinskii* (Fig. 3 D1).

3.2. Temporal changes in soil water content due to vegetation types

Overall, the time since revegetation had significant effects on the changes in SWC in terms of both the R_{SFC} and R_{PWP} (Fig. 4). In forests, the R_{PWP} showed similar trends at different soil depths, declining slightly between 0 and 20 years, declining significantly between 20 and 30 years, and then remaining relatively stable (red points in Fig. 4 A1-A6). In contrast, the R_{SFC} in forests decreased significantly and continuously in the first 30 years and then remained relatively stable (gray points in Fig. 4 A1-A6). When the restoration time was greater than 20 years, the R_{SFC} of the deep SWC was significantly lower than that of the SFC (Fig. 4 A2-A4). In the case of shrublands, the changes in deep SWC (>100 cm) in terms of the R_{SFC} and R_{PWP} were similar to those in forests (Fig. 4 B2-B5). Specifically, we noticed that the R_{SFC} exhibited significant recovery trends > 30 years after restoration (gray points in Fig. 4 B1-B6). In grasslands, the R_{PWP} showed an increasing trend during the first 30 years across the whole profile (red points in Fig. 4 C1-C6), while the R_{SFC} showed first a decline and then an increase in the first 30 years after restoration (gray points in Fig. 4 C1-C6).

3.3. Changes in soil water content in the different climatic zones

The three climatic zones, which were categorized on the basis of MAP (<450 mm, 450–550 mm and > 550 mm), differed in the extent of the changes in the R_{PWP} and R_{SFC} during revegetation (Fig. 5; Fig. 6). In each zone, the R_{PWP} and R_{SFC} were significantly affected by the vegetation type, generally following the order cropland > grassland > shrubland > forest (Fig. 5). The R_{PWP} decreased the most in the > 550 mm zone (Fig. 5 A), while the R_{SFC} decreased the most in the 450–550 mm and > 550 mm zones (Fig. 5 B). The R_{PWP} and R_{SFC} also changed significantly during the different restoration periods in the different climatic zones (Fig. 6). Specifically, the R_{SFC} and R_{PWP} both decreased significantly with increasing restoration time (Fig. 6). In terms of the R_{SFC} and R_{PWP}, the SWC in the relatively high-rainfall zones (450–550 mm or > 550 mm) exhibited a severe decrease over time, particularly in the later period (>20 years after restoration) (Fig. 6).

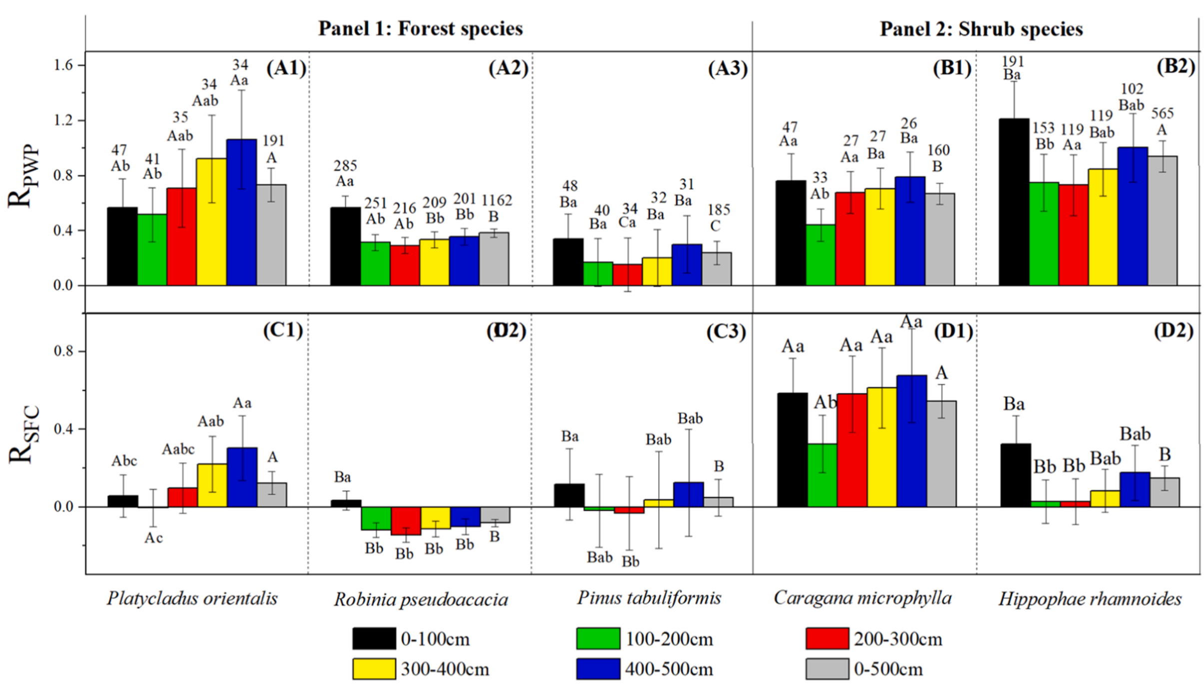

Fig. 3. The effects of forest/shrub species on soil water content in different soil layers. Note: The bars are the means ±95% CIs, and the number of observations is above the letters. Different lowercase letters indicate significant differences among the different layers (P < 0.05); different uppercase letters indicate significant differences among different species within the same layer in each panel (P < 0.05); and the same lowercase or uppercase letters indicate nonsignificant differences (P > 0.05). The gray bar indicates the average value of the five soil layers.

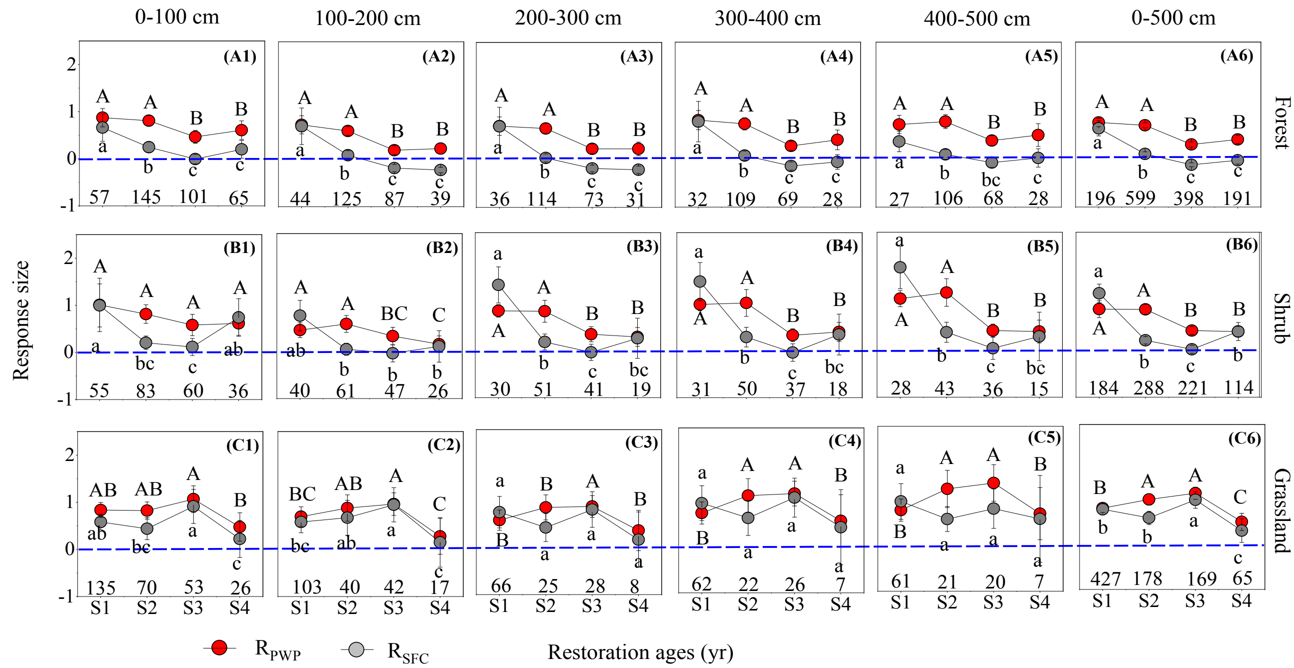

Fig. 4. The effects of the restoration period on the soil water content in the different soil layers. Note: S1, S2, S3 and S4 indicate the 0–10, 10–20, 20–30 and > 30 yr restoration periods, respectively. Dots with error bars denote the overall mean values and 95% CIs. Different lowercase and uppercase letters indicate significant differences in the R_{PWP} and R_{SFC} in different restoration periods within the same soil layer, respectively ($P < 0.05$). The dashed line indicates $\times = 0$. The number of observations is shown at the bottom of each panel. The R_{PWP} and R_{SFC} have the same number of observations.

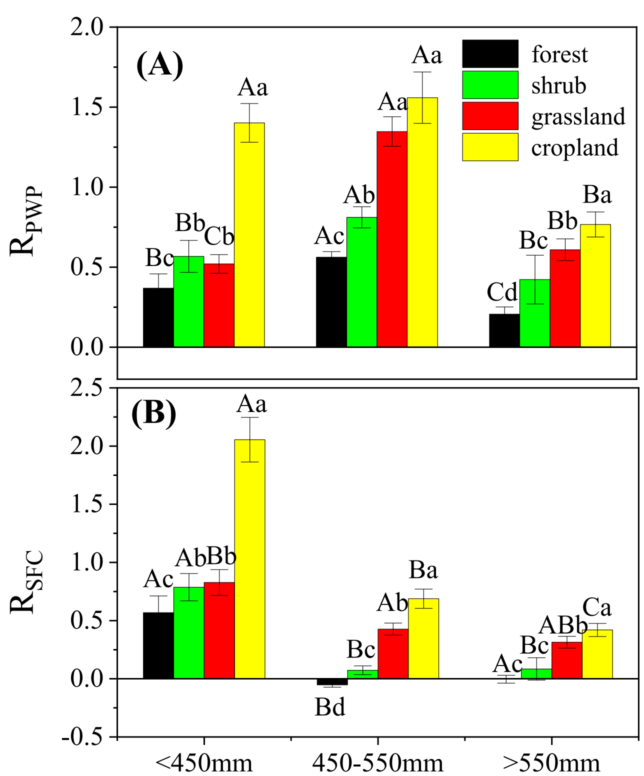

Fig. 5. The effects of the different climatic zones and vegetation types on the soil water content throughout the entire soil profile. Note: The error bars in the charts denote the overall mean values and 95% CIs. Different uppercase letters indicate significant differences among the different climatic zones for the same vegetation type ($P < 0.05$), and different lowercase letters indicate significant differences among the different vegetation types for the same climatic zone ($P < 0.05$). The number of observations is shown above the letters. The R_{PWP} and R_{SFC} have the same number of observations.

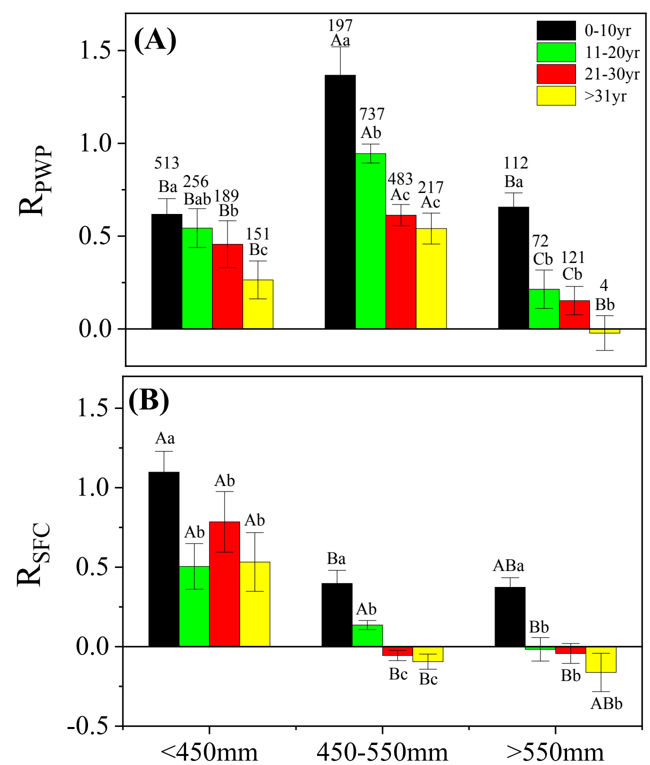

Fig. 6. The effects of the different climatic zones and restoration periods on the soil water content throughout the entire soil profile. Note: The error bars in the charts denote the overall mean values and 95% CIs. Different uppercase letters indicate significant differences among the different climatic zones for the same restoration period ($P < 0.05$), and different lowercase letters indicate significant differences among the different restoration periods for the same climatic zone ($P < 0.05$). The number of observations is shown above the letters. The R_{PWP} and R_{SFC} have the same number of observations.

3.4. Soil water changes along the precipitation and restoration time gradients

Overall, the changes in soil water were significantly correlated with the precipitation and restoration time gradients (Fig. 7 D1-D4). In forests, both the R_{PWP} and R_{SFC} were negatively correlated with MAP (Fig. 7 A1-A2), while in shrublands, they had opposite correlations with MAP (Fig. 7 B1-B2). In grasslands, both the R_{PWP} and R_{SFC} were significantly and positively correlated with MAP (Fig. 7 C1-C2). The time since revegetation had significant negative effects on soil water in all vegetation types (Fig. 7 A3-C3; A4-C4). In terms of the slope values, grasslands had a higher increase rate along the precipitation gradient than forests and shrublands (Fig. 7 C1, C2). Furthermore, along the temporal gradient, grasslands also exhibited a lower decrease rate than forests and shrublands (Fig. 7 C3, C4).

4. Discussion

4.1. Changes in soil water content as affected by vegetation type

Different vegetation types differentially impact the SWC primarily due to their different water consumption characteristics (Xiao et al., 2014). Previous studies have reported that revegetation on the arid and semiarid Loess Plateau resulted in severe declines in SWC locally (Wang et al., 2010a; Jin et al., 2018) and regionally (Wang et al., 2012b). In the present study, the depletion of soil water throughout the soil profile in terms of the R_{PWP} and R_{SFC} decreased in the order forest > shrubland > grassland > cropland (Fig. 2); this result is supported by those of previous studies (Yu and Jiao, 2018; Zhang et al., 2020). Generally, perennial vegetation (e.g., forests, shrublands or grasslands) in water-limited regions consumes excessive soil water compared with crops because of the extensive root systems and higher water demands of perennial plants (Wang et al., 2012c; Xiao et al., 2014; Jia et al., 2017a). It has been reported that plant roots on the Loess Plateau can penetrate to depths of more than 1000 cm due to the limited precipitation (Gao et al., 2017) and thick loess deposits (Zhu et al., 2018). Moreover, forest trees and shrubs usually have greater root biomass and depth than crop plants and thus have higher water demands (Gao et al., 2018).

Severe soil desiccation occurred in the revegetated forestland, where there was no significant difference between the deep SWC (>100 cm) and SFC (gray points in Fig. 2 A). Soil desiccation is, to a certain extent, the result of soil water deficits, and the existence of dried soil layers can prevent or slow the exchange of soil water between shallow and deep soil layers (Wang et al., 2010a); this weakens the ecological functioning of the soil reservoir, leading to vegetation degradation and even large-scale vegetation death (Wang et al., 2010b; Wang et al., 2012b; Wang et al., 2015c). Our results indicate that on a broad scale, the deep SWC depletion in planted forests threatens their sustainability, especially under extreme drought conditions. When lands are restored to forest in the Loess Plateau region, large quantities of water are lost through transpiration from the deeply rooted woody vegetation; this lowers the water table and makes it harder for other plant species to survive (Deng

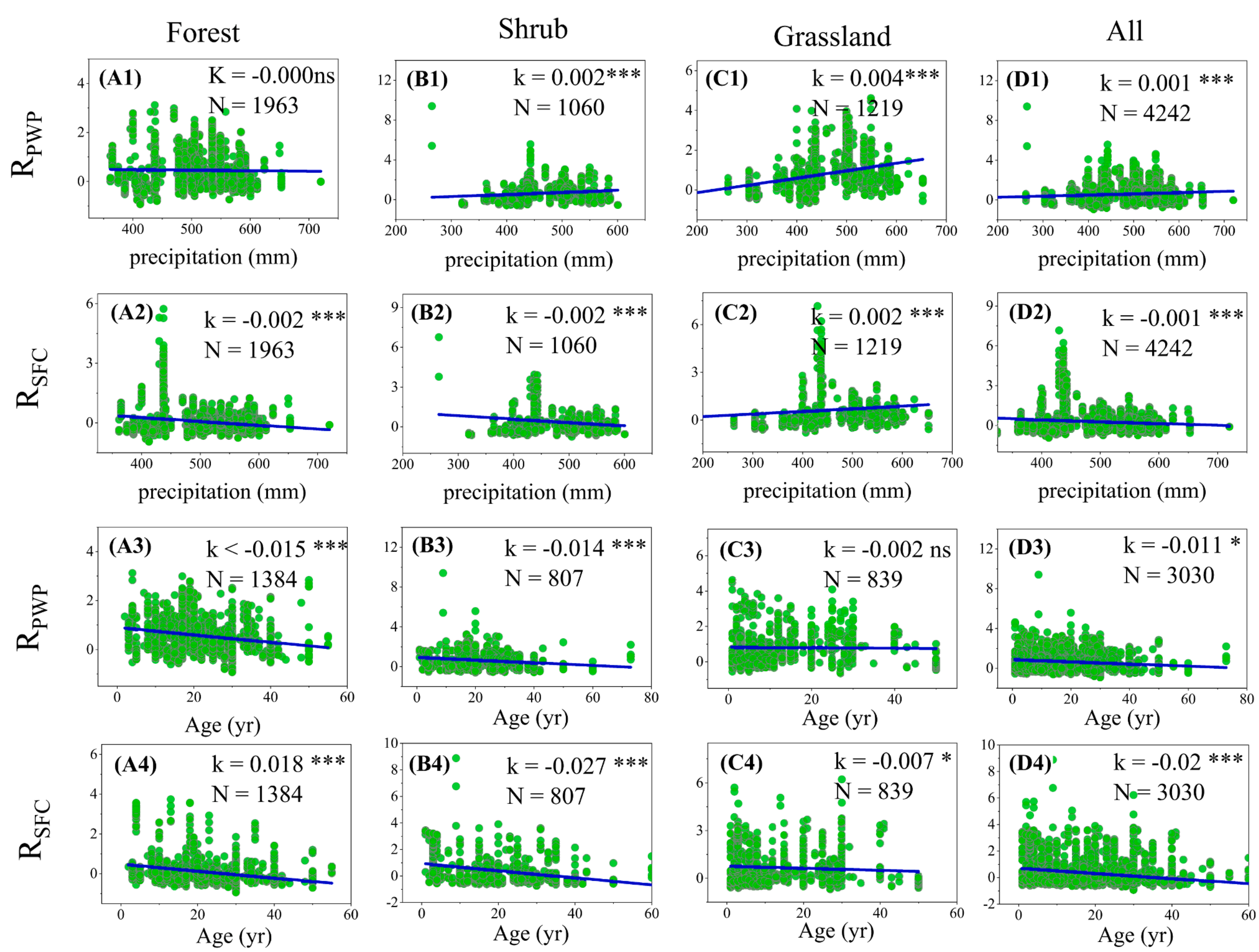

Fig. 7. The relationship between response size and time since restoration and mean annual precipitation throughout the entire soil profile. Note: "***", "**", "*" and "ns" indicate significance at P < 0.001, P < 0.01, P < 0.05 and P > 0.05, respectively. N means the number of observations.

et al., 2016). Therefore, effective practices should be adopted to manage the existing forests, for example, growing different forest species together (Gong et al., 2020) or thinning the forest trees (Gokbulak et al., 2016), to alleviate water stress.

In contrast, in grassland, both the R_{PWP} and R_{SFC} revealed higher SWC values than in all vegetation types except cropland. Compared with forests and shrublands, grasslands have shorter periods of water use and deeper precipitation recharge depths (Fan et al., 2016). Moreover, the roots of grasslands are concentrated at shallow soil depths (Zhang et al., 2016), which reduces their consumption of deep soil water. Deng et al. (2016) also recommended natural grassland restoration as a sustainable method for water-limited regions due to its relatively low water demands. Furthermore, one additional advantage of grassland, at least at the global scale, is that it generally showed a higher albedo than forests which contributes to the water saving (Hollinger et al., 2010). A recent study revealed that grassland was the best choice for optimizing the tradeoff between water yield and soil conservation in the implementation of ecological restoration programs in semiarid regions (Liu et al., 2020a). Overall, we suggest that restoring degraded areas to grassland may be a sustainable and highly beneficial restoration practice on the Loess Plateau.

Forest and shrub species exerted significant influences on the changes in SWC in terms of both the R_{PWP} and R_{SFC} (Fig. 3). In general, the forest community characteristics (e.g., canopy evapotranspiration, root biomass or depth, and tree growth rate) and human activities (e.g., forest thinning) can account for the differences in deep soil water levels under different tree species (Gazal et al., 2006; Gao et al., 2018; Li et al., 2018; Li, 2019). In the present study, *R. pseudoacacia* and *Pinus tabuliformis* resulted in a severely low soil water status throughout the entire soil profile, while *Platycladus orientalis* was better able to maintain the deep SWC. On the Loess Plateau, *Platycladus orientalis* is usually planted at relatively low densities (Gao et al., 2018). In addition, this species is relatively low in height (Gao et al., 2018) and has a low sap flow density (Wu et al., 2015). Moreover, the water use strategy of *Platycladus orientalis* may also contribute to its ability to maintain the SWC; *Platycladus orientalis* absorbs water from mostly the middle and deep soil layers during the dry season and changes to absorbing water from the surface layers during the wet season (Liu et al., 2018). In contrast, the density, tree height and soil water consumption of *R. pseudoacacia* and *Pinus tabuliformis* were much higher than those of *Platycladus orientalis* on the Loess Plateau. The results of this study showed that *C. microphylla* had higher soil water availability (in terms of the R_{PWP} and R_{SFC}) than *H. rhamnoides* L. This is not in agreement with the results of previous studies. For example, Xiao et al. (2014) reported that *H. rhamnoides* L. on the Loess Plateau had a higher SWC due to its shallower root depth and higher infiltration rate. The absolute SWC in this study (shown in Supplementary Fig. S1) is in line with that in previous studies; however, the available SWC (in terms of the R_{SFC} and R_{PWP}) is different. We attribute this phenomenon to the uneven distribution of *C. microphylla* and *H. rhamnoides* on the Loess Plateau. In this study, 57% and 40% of *C. microphylla* points were distributed in the < 450 mm and 450–550 mm rainfall zones, respectively, while more than 81% of *H. rhamnoides* L. were located in the > 450 mm rainfall zone. According to Fig. 1 (A, C, D), the higher the precipitation is, the higher the PWP and SFC; this relationship may explain the contradictory results. Due to the relatively large sample size and uniform distribution, the effects of uneven distribution for forest species may reduce. Overall, from the perspective of soil water availability, the choice of tree species is an important consideration for revegetation, and *Platycladus orientalis* is considered to be better for maintaining the deep SWC than *R. pseudoacacia* and *Pinus tabuliformis*.

4.2. Temporal changes in soil water content during vegetation restoration

In the present study, both the R_{PWP} and R_{SFC} differed significantly among the various restoration stages and showed an overall decreasing trend with the time since restoration (Fig. 4). In forests, the R_{PWP} changed relatively little in the first 20 years but decreased significantly from 20 to 30 years and remained stable thereafter; the R_{SFC} continued to decrease and was significantly lower than the SFC after 20 years. This phenomenon can be explained by different growth stages of planted forests on the Loess Plateau (Li and Huang, 2008; Duan et al., 2011; Wang et al., 2012c). In the early stage of forest growth, the trees usually grow quickly, as the soil water is sufficient to support their growth (Chen et al., 2007). However, soil water in both the shallow and deep soil layers is depleted during the stage when the trees reach maturity due to the excessive water consumption induced by the extensive root systems of the trees (Wang et al., 2011). Our results confirm that 0–20 years may be the optimal growth stage for forests on the Loess Plateau; beyond this time period, forests may cause a significant decrease in soil water availability (relative to both SFC and PWP). Therefore, to maintain a high SWC, forests that are more than 20 years old should be carefully managed.

Although the overall trends of the R_{PWP} and R_{SFC} in shrublands were similar to those in forests, we found a specific turning point for the R_{SFC} in shrublands in the present study; this finding is both interesting and logical. Wang et al. (2012c) identified five stages of soil water changes and plant growth: (1) in the initial stage, the water supply is sufficient, and the plants grow well; (2) in the second stage, deep soil water is extracted and utilized by the plants due to the increasing demands for water to support transpiration; (3) in the third stage, plants continue to utilize deep soil water, and the soil water status worsens; (4) in the fourth stage, plant growth stabilizes at a certain level; and (5) in the fifth stage, forest or shrub vigour decreased and therefore its water use; thus, excess rainfall can replenish the deep soil water deficits. In this study, soil water recovery in shrublands, but not in forests, was observed in the > 30-year stage (Fig. 4 B1-B6). This is in partial agreement with the results of Wang et al. (2012c), who observed that both forests and shrublands on the Loess Plateau exhibited recovery trends at the field scale. However, at the regional scale, deep soil water recovery is strictly limited by precipitation, vegetation type and restoration time (Fan et al., 2016; Liang et al., 2018). In our opinion, on the Loess Plateau, the deep soil water recovery phenomenon still needs further validation, and more attention should be paid to forest management.

Natural grasslands exhibited a better soil water status than forests and shrublands (Fig. 4 C1-C6) despite the reduction in soil water at > 30 years, which is supported by the results of Su and Shangguan (2019). The roots of grassland plants are concentrated mainly in shallow soil layers, and grassland communities in the initial stage of succession are usually herbaceous, with relatively low water demands (Jiao et al., 2011). However, in the later stages of succession, subshrub grasses with deep roots and higher water demands begin to grow (e.g., *Artemisia sacrorum* Ledeb and *Lespedeza daurica*) (Jiao et al., 2011). The fluctuating trends of the R_{SFC} in grasslands can be explained by the different community compositions at different stages of grassland succession; these different communities have varying capabilities for root water uptake and precipitation interception (Ferreira et al., 2007; Wang et al., 2017). Notably, the R_{PWP} increased with time in grasslands, which can be explained by the improved soil quality (e.g., lower bulk density and higher porosity and infiltration) and thus the increased soil water penetration from shallow to deep soil layers (Xu et al., 2006; An et al., 2010). Previous studies have revealed that grasslands on the Loess Plateau are more able to maintain runoff (Liu et al., 2020a), inhibit soil erosion (Liu et al., 2020b) and sequester carbon (Deng et al., 2014) than other vegetation types. Consequently, in terms of the R_{PWP} and R_{SFC}, natural grassland restoration may be a better way than other restoration methods to sustain ecological functions and services on the Loess Plateau.

4.3. Effects of rainfall zones on changes in soil water content

In the different rainfall zones, the overall trends of SWC depletion in terms of the R_{PWP} and R_{SFC} generally decrease in the order forest > shrubland > grassland > cropland (Fig. 5). In terms of restoration time, the SWC became depleted gradually with the time since restoration in all rainfall zones. These findings are consistent with the results described above. Surprisingly, our results showed that the higher the rainfall was, the lower the available soil water, indicating that in areas with higher precipitation, revegetation induced substantial water losses. This finding contradicts the findings of previous studies in this region. For example, Deng et al. (2016) suggested that revegetation could not have negative impacts on the soil water deficit in areas that received more than 600 mm of annual precipitation in northern China. Zhang et al. (2019) encouraged afforestation in areas that receive more than 520 mm of precipitation annually. Other values (e.g., 400 mm, 500 mm and 450 mm) have also been proposed as thresholds above which tree planting should be encouraged (Wang et al., 2017; Cao et al., 2018). However, most of the conclusions in previous studies are based on SWC rather than on soil water availability. The contradictory conclusions in this study can be attributed to the following factors: (1) the higher SFC and PWP in higher-rainfall zones (Fig. 1 A, C, D). On the Loess Plateau, the soil texture (clay, silt and sand), rainfall, SFC, PWP, and effective water capacity showed a clear zonal distribution in which the higher the precipitation is, the higher the SWC, but the stronger the soil water holding capacity due to the fine soil texture; (2) the adaptability of vegetation to drought. In areas with low precipitation (e.g., <450 mm), plants usually adapt to low-water conditions by adjusting their stomatal opening, extending their root depth, and improving their water use efficiency (Germon et al., 2020; Thorup-Kristensen et al., 2020). With increasing precipitation (450–550 mm and > 550 mm), plant transpiration and photosynthesis increase, and thus, water consumption also increases. It is worth mentioning that precipitation on the Loess Plateau generally ranges from 200 to 600 mm, and even in areas with higher precipitation, it may still be more challenging to maintain sustainable tree and shrub growth than to maintain grasslands. Therefore, we call for greater caution in restoring vegetation on the Loess Plateau in relatively high-rainfall zones.

4.4. Implications for ecological management

The initial goal of the “Grain for Green” project was to control severe soil erosion on the Loess Plateau. However, erosion control initiatives also exert significant impacts on SWC dynamics. In arid and semiarid regions, the available soil water plays a central role in sustaining ecological functions and services (Huang and Shao, 2019). In this study, we demonstrated that revegetation severely decreased the soil water availability on the Loess Plateau. The soil water availability in forests decreased the most and approached the SFC (Fig. 2 A), which indicates a severely low soil water status. Generally, introduced tree species (e.g., *R. pseudoacacia* and *Pinus tabuliformis*) are popular for restoring degraded lands, but such restoration efforts may fail if the corresponding management practices (e.g., planting density) or local conditions (e.g., soil, climate and topography) are inappropriate. Therefore, the government’s overemphasis on revegetation using introduced tree species seems likely to induce ecological risks on the Loess Plateau. In addition, at 20 years after planting, restoration forests should be managed manually, for example, by thinning; this time frame was selected according to the temporal changes in the R_{PWP} and R_{SFC} observed in this study.

Our study also indicates that natural restoration is better than the other restoration approaches at maintaining deep soil water availability on the arid and semiarid Loess Plateau (Fig. 8). This finding is supported by several recent studies (Deng et al., 2016; Huang and Shao, 2019; Su and Shangguan, 2019; Yu et al., 2018). Specifically, Yu and Jiao (2018) showed that the soil water status of natural restoration areas and former croplands were similar in the 500 cm profile in this region, indicating there was no severe water depletion. According to recent research and our results, natural restoration, e.g., allowing degraded areas to return to natural grasslands, should more seriously considered for the ecological restoration of the arid and semiarid Loess Plateau.

The consensus in the research community is that precipitation has strong impacts on soil water, and previous scholars have suggested planting trees in relatively high-rainfall zones (Deng et al., 2016; Zhang et al., 2019) based on the SWC rather than on the soil water availability. In contrast, we strongly recommend that revegetation in the relatively

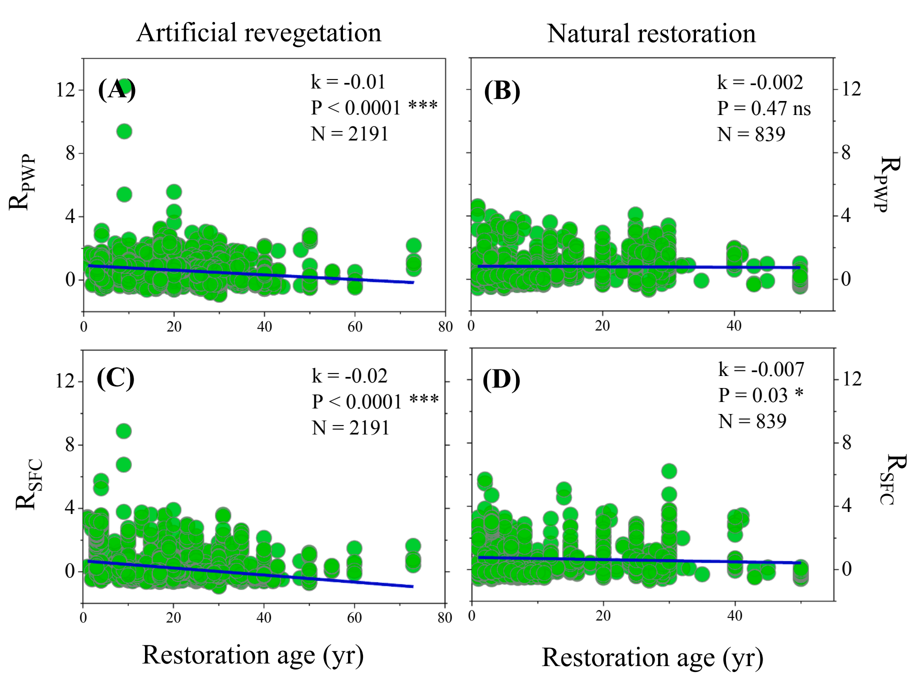

Fig. 8. Changes in the soil water content under natural and artificial restoration methods. Note: (A) and (C) indicate artificial revegetation; (B) and (D) indicate natural restoration. “***”, “**”, “*” and “ns” indicate significance at $P < 0.001$, $P < 0.01$, $P < 0.05$ and $P > 0.05$, respectively. N means the number of observations. k denotes the change rate of the R_{PWP} or R_{SFC}.

high-rainfall zones of the Loess Plateau should be implemented with more caution and with the careful selection of appropriate tree species. Future research should focus on the spatial distribution of soil water availability, especially in deep soils on the Loess Plateau.

5. Conclusions

Revegetation under the “Grain for Green” program has severely depleted the available soil water in deep soils on the arid and semiarid Loess Plateau. With the passage of time since revegetation, the soil water deficit has worsened. The vegetation type and climatic zone both profoundly impact the SWC. Certain management practices, for example, forest thinning, need to be adopted in forests at 20 years after revegetation in this region to alleviate water depletion. On the basis of the changes in the deep SWC after revegetation, we strongly argue that revegetation in zones with relatively high precipitation (e.g., >550 mm) must be performed with extreme caution. Overall, the introduced tree and shrub species significantly decreased the deep SWC, and natural restoration performed better in terms of maintaining the deep soil water; these results indicate that natural restoration to grasslands is a better approach than other restoration practices for the Loess Plateau.

6. Author statement

B.L. and M.X conceived the study. B.L., M.X. and G.L. designed the study. W.Z., S.L. and J.W. collected the data, 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.

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Author contributions

B.L. and M.X conceived the study. B.L., M.X. and G.L. designed the study. W.Z., S.L. and J.W. collected the data, all authors wrote and edited the manuscript.

Appendix A. Supplementary material

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