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Intensification of water storage deficit in topsoil but not deep soil in a semi-humid forest after excluding precipitation for two years

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ABSTRACT

Deep-rooted forest trees can potentially utilize moisture in deep soil to tolerate periods when growth is water limited. Black locust (*R. pseudoacacia*) is a deep-rooted forest species but the benefits of deep roots for water uptake under drought conditions are unclear. In this study, we assessed the effects of drought on water storage and the hydrological properties of soil at different depths. We performed a precipitation manipulation experiment continuously from June 2015 to November 2016 using mature *R. pseudoacacia* in the Loess Plateau region of China. The soil volumetric water contents were measured in the 0–4 m soil layer, as well as the soil hydrological properties comprising the soil bulk density (BD), total porosity, saturated hydraulic conductivity (Ks), and aggregate-associated organic carbon (OC) concentration in the 0–20 cm soil layer. The results showed that soil water storage deficit mainly occurred in the 0–1 m soil layer rather than in the 1–4 m layer after excluding precipitation for two years. Compared with the control, excluding precipitation for two years decreased the soil water storage in the 0–1 m soil layer by 18%. Precipitation exclusion also significantly decreased the soil Ks by 28% and total porosity by 17%, but increased BD by 20% in the 0–10 cm soil layer. In addition, precipitation exclusion significantly decreased the total soil OC concentration and macro- and micro-associated OC concentrations. Our results indicate that excluding precipitation for two years could potentially degrade the water conditions in the topsoil layer but not the deeper soil. These findings provide insights into water management and sustainability in semi-humid afforestation areas of the Loess Plateau region in China.

1. Introduction

Increased water stress in semi-humid regions is becoming a major concern as global warming progresses (Arnell, 1999; Ostad-Ali-Askar et al., 2018). This problem is demonstrated by the drying trend in the Loess Plateau region of China, which is facing increasing water shortages (Deng et al., 2016; Deng et al., 2017; Liu et al., 2015; Wang et al., 2011). The soil water content is the key factor that limits ecological restoration in the Loess Plateau region. High water consumption by vegetation aggravates the dryness of the soil and leads to declines in plant productivity (Brookshire and Weaver, 2015). The soil water dynamics are vital components of the hydrological cycle and they can be affected by various factors, including precipitation (Seneviratne et al., 2010), soil organic carbon (OC) (Breuer et al., 2006), porosity, and saturated hydraulic conductivity (Ks) (Wang et al., 2012), as well as the soil depth (Wang et al., 2012). Therefore, understanding the hydrological properties and water processes in soil is critical for effectively managing water resources, and thus successful revegetation in this semi-humid region.

Understanding the distribution and characteristic variations in the soil water content is necessary for sustainable revegetation, and hydrology and climate modeling (Ostad-Ali-Askari et al., 2021). Assessments of the benefits of revegetation may be facilitated by considering the soil hydrological properties (Wei et al., 2009; Qiu et al., 2010; Wang

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et al., 2012) and soil water contents in different soil layers (Zhang and Shangguan 2016; Jia et al., 2017). For example, afforestation in cropland areas is usually accompanied by increases in the soil OC and nutrient contents (Hazlett et al., 2007; Wei et al., 2013; Zhang et al., 2018), as well as improvements in the soil structure due to the accumulation of residues in soils under the plant canopy (Menyailo et al., 2002; Wei et al., 2013). Revegetation can restore the integrity of disturbed ecosystems by reducing the soil bulk density (BD) (Breuer et al., 2006; Zhang et al., 2013) as well as increasing the soil infiltration rate (Wu et al., 2016), saturated soil hydraulic conductivity (Ks) (Wu et al., 2013; Zhang et al., 2013), and soil water retention (Montalvo et al., 2008), thereby improving the soil hydrological properties. These soil properties then influence the soil volumetric water content and soil water storage (Zhang and Shangguan, 2016). The soil depth is strongly associated with the physiology and respiration rates of tree roots. In general, the moisture in soil surface layers is greatly influenced by rainfall infiltration or evapotranspiration, and it provides a source of water to support the growth of vegetation (Xue et al., 2017). However, the soil moisture in deeper layers remains relatively stable during the growth of vegetation due to the insulating effect of the upper soil (Rasmussen et al., 2020; Nakhforoosh et al., 2021). Yang et al. (2017) found that deep soil water may contribute significantly to avoiding the effects of drought over the dry period, but the shallow soil water available to the fine roots during the dry season may determine tree growth. Therefore, the relationship between the growth of vegetation and water at different soil depths is fundamental for determining the availability of water and nutrients to plants, and it may be important for sustainable revegetation as well as hydrology and climate modeling (Sardans and Penuelas, 2014; Ostad-Ali-Askari et al., 2021).

R. pseudoacacia is considered a promising tree for use in reforestation because of its rapid growth and ability to resist drought, and thus it has been planted in the Loess Plateau region (Wei et al., 2009; Qiu et al., 2010; Mantovani et al., 2015). However, during the last 30 years, dramatic climate change has occurred in the dryland regions that dominate north China, where soil moisture is a significant component of the overall terrestrial water resources (Nemani et al., 2003). Furthermore, plants affect soil water storage by forming a pathway for the transport of soil water to the atmosphere via their root systems (Wang et al., 2010). As a consequence, the soil water content has decreased dramatically after the restoration of vegetation in this region (Jia et al., 2017). Thus, it is necessary to understand the changes in the soil water storage under drought conditions and the most important associated factors in soil layers at different depths.

In the present study, we performed a continuous precipitation manipulation experiment from June 2015 to November 2016 using mature *R. pseudoacacia* in the Loess Plateau region of China. We measured the soil volumetric water content in the 0–400 cm soil layer and the soil hydrological properties in the 0–20 cm soil layer, including the soil BD, total porosity, Ks, and aggregate-associated OC concentrations. We hypothesized that: (i) excluding precipitation for two years would lead to a decrease in the soil water storage in the topsoil layer but not in the deeper layer due to the root distribution; and (ii) precipitation exclusion would have negative effects on the hydrological properties of the topsoil layer. Our main objectives were to assess the effects of drought on the soil water storage and soil hydrological properties at different soil depths. The results obtained in this study provide new insights that may facilitate land water management and sustainability in semi-humid afforestation areas in the Loess Plateau region of China.

2. Materials and methods

2.1. Study area

A single stand containing black locust trees was selected at Yehe National Forestry Center located in Fufeng County (34.55°N, 107.90°E) in the southern Loess Plateau region of China at 1080 m above sea level. The region has a temperate climate with mean annual precipitation of 592 mm during 1989–2019. During the summer period from June to September, the mean precipitation was 414 mm. The mean annual temperature was 11.5 °C, ranging from a mean of –2°C in January to 26 °C in July. The soil in the area is classified as Gleyic Phaeozems according to the World Reference Base for Soil Resources, with 11% sand, 20% clay, and 69% silt (Zhang et al., 2020). *R. pseudoacacia* (Linn.), and *Pinus tabuliformis* (Carr.) communities dominate the forests produced by artificial afforestation throughout this region, with a forest canopy density ranging between 80 and 95%. *R. pseudoacacia* is a fast-growing tree with high water requirements and it is an important introduced plantation forest species in the southern Loess Plateau region. *Stipa bungeana* (Trin.) and *Artemisia argyi* (H.) are the dominant plants in the understory vegetation, where they cover 80% to 90% of the ground area.

2.2. Experimental design and sampling

In this study, we focused on the first two years of a large-scale precipitation manipulation experiment established at the site in spring 2015 (for details of the precipitation manipulation installation, see Zhang et al., 2018). We selected a 10-year-old black locust stand with a south-facing aspect after an initial survey in March 2015. The slopes facing the sun exhibited no vertical climatic variations. Two treatments comprising precipitation exclusion and control were applied in plots with dimensions of 20 × 20 m, which each contained 20 target trees (Table 1). The two treatments were replicated in three random blocks with a total of six experimental plots. The soil type and topography were similar in the three blocks. The initial physical and chemical properties in the 0–20 cm soil layer were measured in May 2015 (Table 2). In the precipitation exclusion treatment, precipitation was reduced by about 40% relative to the control using interceptors (Zhang et al., 2018) and it was close to the minimum ecological water requirement for *R. pseudoacacia* forest trees (Jiao et al., 2014).

In November 2016, three disturbed soil samples were randomly collected from two soil layers (0–10 cm and 10–20 cm) in each plot using a tube auger with a diameter of 5.0 cm. These samples were used to measure the aggregate-associated OC and total soil OC concentrations. In addition, three undisturbed soil cores were randomly collected from each plot in two soil layers using a soil bulk sampler with a diameter of 5.0 cm and a stainless steel cutting ring with a height of 5.0 cm (six replicates). These samples were used to measure the soil BD, total porosity, and Ks. In total, 72 samples were collected: three soil replicates × two treatments × three blocks × two soil layers × two samples for BD and composite variables.

2.3. Rainfall and soil water content

The throughfall was measured in all of the stands before the experiment and it could account for 85% of the precipitation. In addition, precipitation outside of the forest canopy was measured using a tipping

Table 1
Mean stand characteristics comprising the number of individuals in each plot, stand age, mean diameter at breast height, mean tree height, and leaf area index in July 2015. Ind. = individuals in each plot; SA = stand age; DBH = diameter at breast height; TH = tree height; BA = basal area; LAI = leaf area index. The LAI was calculated for July 2015 by processing digital hemispherical photographs using CAN-EYE (Demarez et al., 2008). The characteristics of the trees were measured in the six stands for all trees in May 2015.

Stand	Ind.	SA	DBH (cm)	TH (m)	BA (m^{-2} ha^{-1})	LAI
Control	20	10	11.2 ± 0.4	9.0 ± 1.1	24.3	2.29
Precipitation exclusion	20	10	11.3 ± 0.5	9.1 ± 0.9	24.6	2.35

Table 2
Physical and chemical properties of the initial soil in May 2015 (0–20 cm layer). Samples were collected from each of the three blocks. Values represent the mean ± standard error and the sample size was n = 6. Abbreviations: BD, bulk density; Ks, saturated hydraulic conductivity; Soil OC, soil organic carbon concentration; TN, total nitrogen concentration.

Soil layer (cm)	Plots	Total porosity (%)	Ks (mm min^{-1})	BD (g cm^{-3})	Soil OC (g kg^{-1})	TN (g kg^{-1})
0–10	Precipitation exclusion	47.2 ± 2.9	1.21 ± 0.2	1.18 ± 0.1	14.5 ± 1.2	0.85 ± 0.1
	Control	48.9 ± 3.5	1.15 ± 0.1	1.20 ± 0.1	14.9 ± 1.5	0.81 ± 0.2
10–20	Precipitation exclusion	41.8 ± 4.5	0.82 ± 0.1	1.39 ± 0.2	9.13 ± 1.1	0.54 ± 0.1
	Control	41.1 ± 1.9	0.87 ± 0.2	1.41 ± 0.1	8.74 ± 0.8	0.62 ± 0.1

bucket rainfall gauge (CS700-L; Campbell Scientific, Logan, UT, USA) with a resolution of 0.2 mm. In 2015, the annual precipitation amount (815 mm) was larger than the long-term mean, whereas the amount in 2016 (556 mm) was smaller than the long-term mean (Fig. 1a).

In order to monitor the temporal variations in the moisture contents of the upper soil layer under the control and precipitation exclusion treatments, the soil volumetric water contents were measured from June 2015 to November 2016 using 12 electrically conductive sensors (EC-5, Decagon, USA), which were installed around the trees at depths of 10, 20, 40, 60, 80, and 100 cm (for details of the EC-5 sensors, see Zhang et al., 2018).

In addition, three aluminum neutron-probe access tubes (each with a length of 420 cm) were randomly installed in each plot. The soil volumetric water contents were measured in the growing season once each month to a depth of 400 cm at intervals of 20 cm using a calibrated neutron probe (CNC 503DR Hydro probe, Beijing Super Power

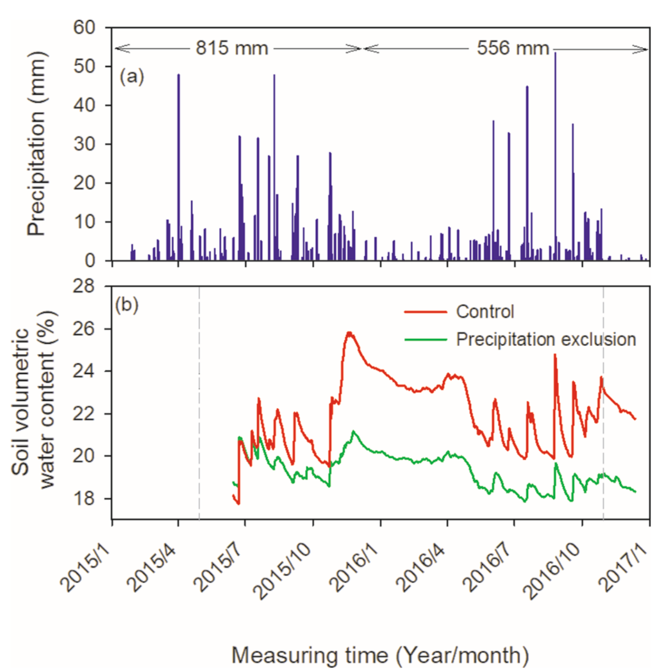

Fig. 1. (a) Temporal variations in precipitation measured at the study site and (b) soil volumetric water content (measured using EC-5 sensors in the 0–1 m soil depth) under the control and precipitation exclusion treatments from June 2015 to November 2016. The values represent means over the depth range. The two gray dotted lines indicate the initial measurement period and after excluding precipitation for two years.

Company, Beijing, China). In total, 18 sites were sampled 11 times from June 2015 to October 2016. The soil water storage was calculated as follows:

$$SWS = \theta\hat{A}\cdot h\hat{A}\cdot BD\hat{A}\cdot 10^{-1}$$

where SWS is the soil water storage (mm), h is the soil depth (cm), BD is the soil bulk density (g cm^{-3}), and θ is the soil volumetric water content (%).

The soil water storage deficit degree (DSW) was calculated as follows (Huang et al., 2018):

$$DSW = Ds/Fc\hat{A}\cdot 100\%$$

$$Ds = Fc - SWS$$

where Ds is the soil water storage deficit (mm) and Fc is the field capacity (mm).

2.4. Soil hydrological properties

Ks was determined using the constant head method (Kanwar et al., 1989) and the sample was then oven dried at 105 °C before weighing to determine the soil BD. The soil total porosity was calculated using the soil particle density (2.65 g cm^{-3}) and BD. The macro-aggregate (>0.25 mm), micro-aggregate (0.25–0.053 mm), and silt + clay fractions (<0.053 mm) were measured by wet sieving according to the procedures described by Kemper and Rosenau (1986). All of the soil aggregates were oven dried to a constant weight at 70 °C and weighed. Undisturbed soil from each plot was ground using a pestle and mortar until it passed through a 2-mm sieve in order to measure the total soil OC concentration. The OC concentrations were analyzed in both the total soil and individual aggregate fractions using a VARIO EL III CHON analyzer (Elementar, Germany).

2.5. Statistical analysis

Due to the non-Gaussian distributions of the results because of the small sample size, we used nonparametric methods to compare the findings obtained for the control and treatment sites. The effects of precipitation exclusion on the soil volumetric water content and soil water storage in the 0–400 cm soil depth, as well as the soil hydrological properties (BD, Ks, total porosity, and soil OC) in the 0–20 cm soil depth were evaluated using one-way analysis of variance followed by least significant difference tests ($p < 0.05$). The mean and standard deviations of the water storage data for the soil profiles under the two treatments were analyzed at various soil depths (n = 6). Data preprocessing was performed using Microsoft Excel 2016. Statistical analyses were performed using the SPSS statistical package version 18.0 (SPSS 18.0; SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Vertical distribution of soil water content

The soil volumetric water contents in the 0–1 m soil layer were measured using EC-5 sensors (Fig. 1b). The soil volumetric water content in the 0–1 m soil depth was significantly lower during 2016 due to precipitation exclusion ($p < 0.05$). Furthermore, the distributions of the soil volumetric water contents in the 0–4 m soil layer under the two treatments during 2015 and 2016 are shown in Fig. 2. Precipitation exclusion significantly affected the soil volumetric water content and the values were lower than those under the control (Fig. 2). In particular, precipitation exclusion had a pronounced effect on the soil volumetric water content in the 0–1 m soil layer during 2016, but not in the soil layer from 1 m to 4 m ($p < 0.05$, Fig. 2).

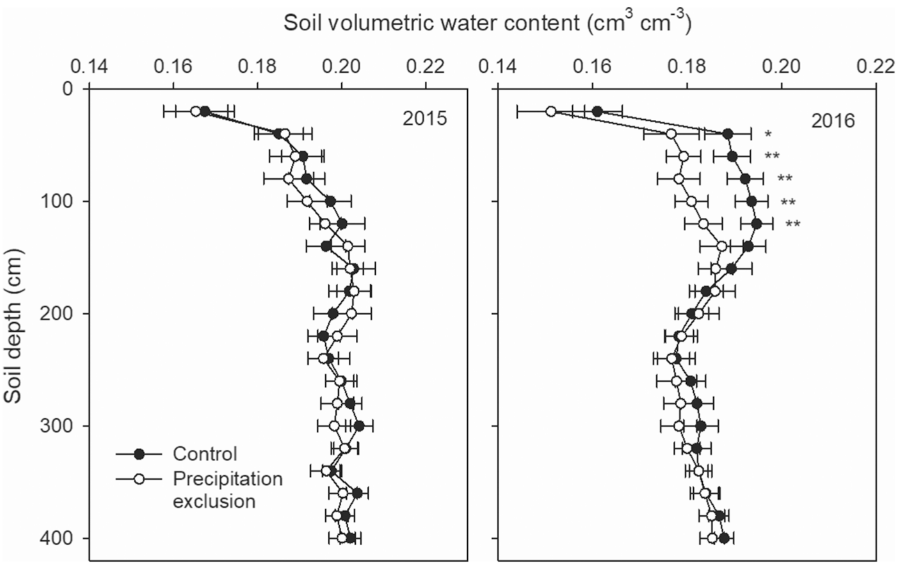

Fig. 2. Average volumetric water contents determined in the soil profile using a calibrated neutron probe in the 0–400 cm soil depth during 2015 and 2016 under the control and precipitation exclusion treatments. Error bars represent the standard error of the mean (n = 6 sampling sites). The soil water storage values in 2015 or 2016 represent the average values on different measurement dates in each year. * and ** indicate that the soil volumetric water contents differed significantly between the control and precipitation exclusion treatments at $p < 0.05$ and $p < 0.01$, respectively.

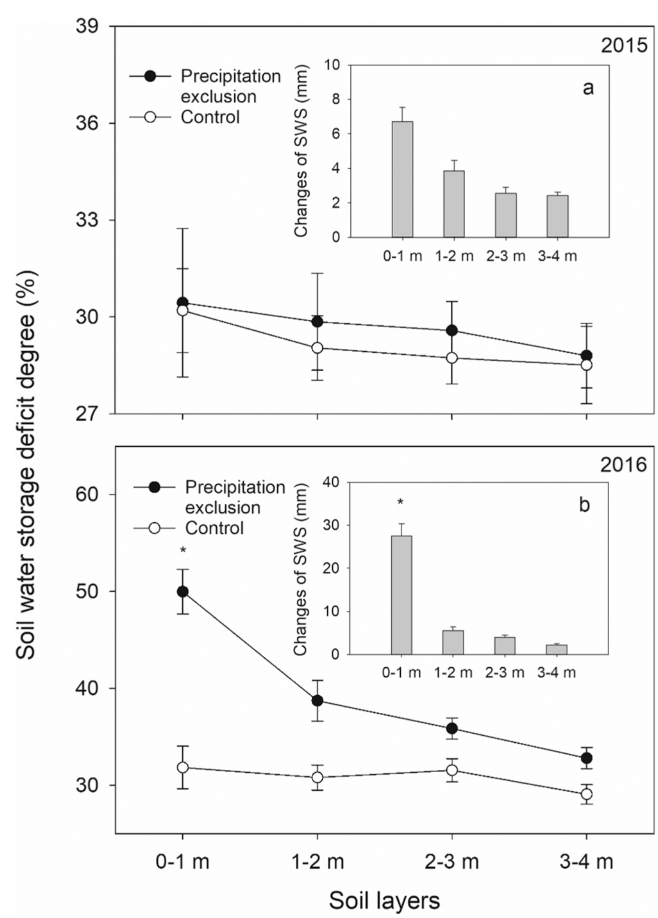

Fig. 3. Soil water storage and deficit degree in different soil layers under the control and precipitation exclusion treatments during 2015 and 2016. Error bars represent the standard error of the mean (n = 6 sampling sites). The soil water storage values in 2015 or 2016 are the average values on different measurement dates in each year. * indicates that the soil water storage or deficit degree differed significantly between the control and precipitation exclusion treatments at $p < 0.05$.

3.2. Soil water storage and deficit

The changes in soil water storage in each soil layer after excluding precipitation for two years are shown in Fig. 3. In the 0–4 m soil depth, the changes in the soil water storage under precipitation exclusion were more obvious during 2016 than 2015. In addition, the soil water storage in the 0–4 m soil depth was lower under precipitation exclusion compared with the control during 2016, especially in the topsoil layer (0–1 m) ($p < 0.01$). In general, precipitation exclusion significantly decreased the soil water storage in the 0–1 m soil layer.

Soil water storage deficit occurred under the control, with a range from 27.2% to 32.8% (Fig. 3a). After excluding precipitation for two years, the soil water storage deficit in the 0–1 m soil depth was significantly higher during 2016 than 2015 ($p < 0.05$, Fig. 3b). Throughout the soil profile, the soil water storage deficit during 2016 was greatest (50.5%) in the 0–1 m soil depth and it decreased as the soil depth increased (Fig. 3b). Below a soil depth of 1 m, the soil water storage deficit during 2016 was<40% but it was still higher than that in 2015.

3.3. Soil hydrological properties

In general, the soil BD, total porosity, and Ks changed significantly during the precipitation exclusion process (Fig. 4). In the surface soil layer (0–10 cm), BD increased significantly ($p < 0.05$) from 1.18 g cm^{-3} to 1.32 g cm^{-3} after precipitation exclusion (Fig. 4a). The total porosity and Ks values in the 0–10 cm soil layer were significantly lower under precipitation exclusion compared with the control ($p < 0.05$) (Fig. 4b, 4c). The soil BD, total porosity, and Ks in the 10–20 cm soil layer did not differ significantly between the two treatments.

The aggregate-associated OC concentration was generally higher under the control than precipitation exclusion (Fig. 5). In both the 0–10 and 10–20 cm soil layers, the aggregate-associated OC concentration decreased as the aggregate size decreased according to the following order: macro-aggregates > micro-aggregates > silt + clay. In the 0–10 cm soil layer, the OC concentration was significantly lower under precipitation exclusion for the macro- and micro-aggregate classes, i.e., 25% lower in the macro-aggregates and 22% lower in the micro-aggregates ($p < 0.05$), whereas precipitation exclusion had not significant effect on the OC concentration in the silt + clay OC fraction (Fig. 5a). The aggregate-associated OC concentration in the 10–20 cm soil layer did not differ significantly between the two treatments (Fig. 5b).

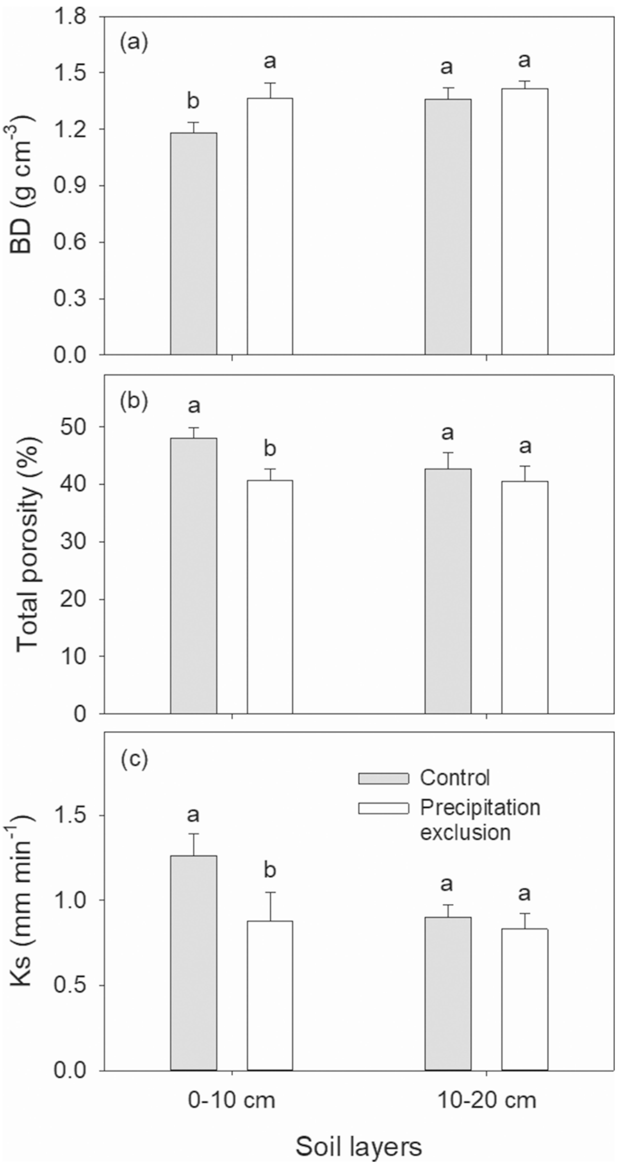

Fig. 4. Effects of precipitation exclusion on soil bulk density (BD), total porosity, and saturated hydraulic conductivity (Ks) in the 0–10 cm and 10–20 cm soil layers. Error bars represent the standard error of the mean (n = 6 sampling sites). Different lowercase letters indicate significant differences between the two treatments within each soil layer ($p < 0.05$).

4. Discussion

4.1. Effects of precipitation exclusion on soil water storage

Soil water is replenished by infiltration from rainfall or recharge from groundwater, and this water is removed from the soil by evaporation and root uptake for transpiration, or it is lost to deeper layers due to drainage and percolation into groundwater (Arnell, 1999; Dash et al., 2021). These inputs and outputs lead to the variable and continuous redistribution of water within soils (Shen et al., 2014). In our study region with a lack of surface water resources, rainfall is considered the sole source of soil water storage (Zeng et al., 2011). Thus, in the present study, *in-situ* soil moisture measurements indicated a significant decline in the moisture content of the topsoil layer after excluding precipitation for two years but not in the deep soil (Fig. 1b, 3, 4). Meerveld and McDonnell (2006) and Seneviratne et al. (2010) also found that the soil moisture content of the upper soil layers was influenced greatly by transpiration by plants and soil evaporation. In the upper layers, the combination of transpiration by vegetation and soil evaporation can consume as much as 60% of the total precipitation input (Oki and Kanae, 2006). In an extreme example, Wang et al. (2011) found that transpiration and evaporation consumed 90% of the total precipitation in a study conducted on the Loess Plateau. In the present study, the combination of low precipitation and high evapotranspiration mainly explain the decrease in the soil water content of the topsoil layer. Therefore, the different responses of the topsoil and deep soil layer to drought conditions may be explained by: (i) greater evapotranspiration affecting the topsoil layer, and (ii) low infiltration due to the decrease in the capillary force as the soil depth increases (Nakhforoosh et al., 2021). Thus, *R. pseudoacacia* mainly acquired water from the 0–1 m depth during drought conditions. Our results highlight the benefit of deep root growth for water uptake in forests, but they also suggest that the uptake of water from the deep soil is limited under prolonged drought conditions when little water is available in the topsoil.

4.2. Changes in soil hydrological properties

Determining the soil hydrological properties is important for understanding the movement of soil water and predicting parameters that might affect agronomic and environmental projects in the study region (Zhang et al., 2006). Our results showed that excluding 40% of the precipitation for two years had negative effects on the soil hydrological properties investigated in this study, such as reductions in the total porosity and Ks in the 0–10 cm soil layer, but an increase in BD (Fig. 4). In particular, precipitation exclusion increased the BD in the 0–10 cm soil layer (Fig. 4a), possibly due to the lower fine root biomass and porosity of the surface soil layer (Zhang et al., 2019b). Similarly, a previous study showed that drought negatively affected the properties of the surface soil (Yuksek, 2009). In the 10–20 cm soil layer, the BD did not differ significantly after excluding 40% of the precipitation for two years, thereby suggesting that excluding precipitation for two years had no obvious effects on the BD in the deeper soil layers.

The total porosity of soil is a highly dynamic property that is affected by numerous natural and human-related factors, and thus assessing its temporal variability is essential for accurately understanding soil processes during restoration (Bodner et al., 2013). In the present study, the total porosity decreased in the 0–10 cm soil layer after excluding 40% of the precipitation for two years (Fig. 4b), mainly because the porosity might have been decreased by the lower input of litter from the aboveground biomass and its incorporation into the soil was reduced after precipitation exclusion commenced (Wu et al., 2016; Yang et al., 2017; Rasmussen et al., 2020). Furthermore, these findings indicate that the proportion of macro-pore spaces in the drought-treated soil decreased as the total porosity decreased (Wang et al., 2012). This decrease in the macro-pore volume implies that Ks and the water-holding capacity also decreased, thereby preventing the effective infiltration of precipitation and aeration of the deeper soil layers to hinder plant root growth and vegetation development (Wang et al., 2008).

In general, Ks is a parameter that integrates several physical characteristics, such as the BD, porosity, and mechanical composition (Wu et al., 2016). The mean Ks value for all of the soil samples was significantly higher than the values reported previously (0.05–0.58 mm min^{-1}) for soils in the central and southern regions of the Loess Plateau, mainly due to differences in soil parent materials in this region (Wang et al., 2008). The Ks values in the 0–10 cm soil layer were significantly higher for the control soil than the soil under precipitation exclusion ($p < 0.05$), but the differences were not significant in the 10–20 cm soil layer (Fig. 4c), thereby indicating that excluding precipitation for two years reduced the Ks value in the surface soil layer.

Under both the control and precipitation exclusion treatments, we found that the macro-aggregate and micro-aggregate associated OC concentrations were higher than the soil OC concentrations, and also greater than those in the silt + clay fractions in all soil layers (Fig. 5;

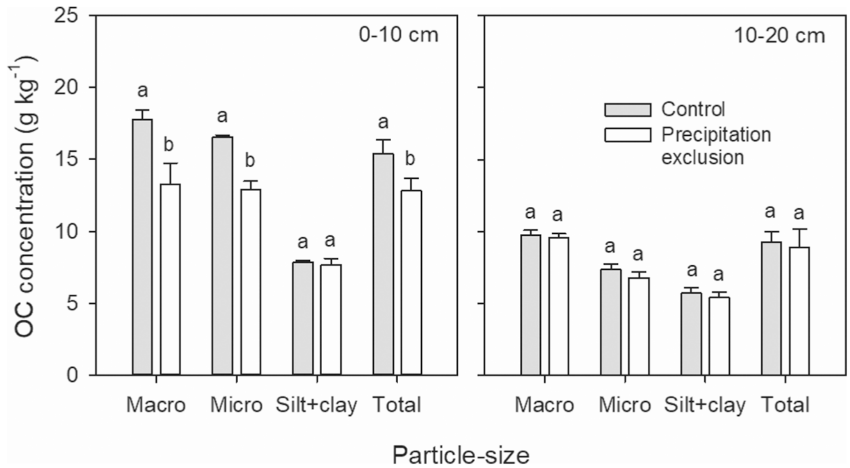

Fig. 5. Effects of precipitation exclusion on aggregate-associated OC concentrations in the 0–10 cm and 10–20 cm soil layers. The size fractions comprise macro-aggregates (>0.25 mm), micro-aggregates (0.25–0.053 mm), and silt + clay (<0.053 mm). Error bars represent the standard error of the mean (n = 6 sampling sites). Different lowercase letters indicate significant differences between treatments within aggregate size classes ($p < 0.05$).

Zhang et al., 2019a). In general, the soil OC concentrations were higher in the macro-aggregates than micro-aggregates under both treatments. These results agree with the aggregate hierarchy concept where micro-aggregates are bound together into macro-aggregates by transient and temporary binding agents (Tisdall and Oades, 1982). This aggregate hierarchy and the important role of organic matter in soil aggregation have been demonstrated in temperate forest land (Kabiri et al., 2015). In agreement with our hypothesis, excluding precipitation for two years had significant negative effects on the soil OC concentrations in macro-aggregates and micro-aggregates (Fig. 5). This negative effect of drought on the aggregate-associated OC concentration is similar to the results obtained in temperate forests (Su et al., 2020). These results demonstrate that changes in the OC concentrations in macro-aggregates or micro-aggregates can be used as sensitive indicators of the effects of management (Six et al., 2002). In the present study, we found that excluding precipitation for two years significantly decreased the above- and below-ground biomass of the understory vegetation (Zhang et al., 2019a). In general, the transfer of nutrients between soils and plants can lead to the rapid stabilization of C (in days to weeks) (He et al., 2006) due to the presence of fresh plant litter on the soil surface, as well as the input of residues from understory vegetation into the surface soil layer (Li et al., 2021). Consequently, excluding precipitation for two years significantly decreased the soil aggregate-associated OC concentrations in the 0–10 cm soil layer. We also observed that the 10–20 cm soil layer had a lower aggregate-associated OC concentration than the 0–10 cm soil layer (Fig. 5), possibly because the fine root biomass was greater in the 0–10 cm soil depth (Cheng et al., 2006; Zhang et al., 2019b), and thus more organic matter was incorporated into the surface soil. These results are consistent with those reported by by Six and Jastrow (2002) and they indicate that the OC concentration was more stable in the 10–20 cm soil layer than the 0–10 cm soil layer despite excluding precipitation for two years.

5. Conclusions

In this study, we found that excluding precipitation for two years modified the soil water storage in different soil layers. In the 0–400 cm soil depth, the soil water storage in the surface layer (0–100 cm) decreased after excluding precipitation for two years, but this was not the case in the deeper soil (100–400 cm). Excluding 40% of the precipitation for two years led to significantly lower Ks and total porosity values, but the BD was higher in the 0–10 cm soil layer. Precipitation exclusion also significantly decreased the total soil OC concentrations and macro-and micro-associated OC concentrations in the 0–10 cm soil layer after two years. In addition, excluding precipitation for two years mainly affected the soil hydrological properties and OC concentrations down to a depth of 10 cm. Based on these results, we conclude that the shallow soil water is probably highly vulnerable to the effects of drought in dry periods. Our results highlight the importance of considering the differences in the extraction of water from shallow and deep soil layers when trying to explain the variations in evapotranspiration in ecosystems.

CRediT authorship contribution statement

Qingyin Zhang: Conceptualization, Methodology, Software, Data curation, Writing – original draft. **Xiaoxu Jia:** Investigation, Visualization. **Tongchuan Li:** Investigation, Visualization. **Mingan Shao:** Supervision. **Qiang Yu:** Writing – review & editing. **Xiaorong Wei:** Conceptualization, Methodology, Software.

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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