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In Situ Rainwater Collection and Infiltration System Alleviates the Negative Effects of Drought on Plant-Available Water, Fine Root Distribution and Plant Hydraulic Conductivity

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Abstract: Soil water status and fine-root characteristics are the foundation for implementing forest water-management strategies in semiarid forest plantations, where rainwater is always the sole source of water for plant growth. Rainwater management and utilization are effective strategies to alleviate water scarcity in semiarid areas as ground water is always inaccessible there. Through the implementation of an in situ rainwater collection and infiltration system (IRCIS), we investigated the effects of IRCIS on soil water and fine-root distributions in the 0–5 m soil profile in a wet (2015, 815 mm) and a dry year (2016, 468 mm) in rainfed *Robinia pseudoacacia* forests in the Loess Plateau region of China. The results showed drought significantly decreased plant water availability and hydraulic conductivity of roots and branches, but strongly increased soil moisture deficits and fine-root (<2 mm diameter) biomass. With the implementation of IRCIS, soil profile available water and plant hydraulic conductivity can be significantly increased, but soil moisture deficits and fine-root (<2 mm diameter) biomass can be significantly decreased. Drought also significantly influenced the root distribution of *Robinia pseudoacacia*. The maximum depth of *Robinia pseudoacacia* roots in the dry year was significantly greater than in the wet year. Therefore, *Robinia pseudoacacia* can absorb shallow (0–1.5 m) soil water in wet years, while utilizing deep (>1.5 m) soil water in dry years to maintain normal growth and resist drought stress. The results of this study will contribute to the formulation of appropriate strategies for planning and managing rainwater resources in forest plantations.

Keywords: fine-root distribution; plant-available water; hydraulic characteristics; *Robinia pseudoacacia*; Loess Plateau

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1. Introduction

In drylands, large-scale afforestation and reforestation activities have been implemented to combat desertification, biodiversity loss and poverty, as forests are vital to preventing desertification and providing local residents with wood [1,2]. For instance, approximately 49 billion hectares of dryland were reforested between 2000 and 2010, resulting in a 0.8% increase in forest cover worldwide [3,4]. As forest plantation area increases, the amount of water consumed by these planted trees will also increase [5]. Then there may also be an increase in soil moisture deficits and a decrease in soil availability for plants. A severe soil moisture deficit will inhibit plants from growing normally (e.g., fine roots, hydraulic conductivity, etc.), and even result in the death of plants and the degradation of forest plantations [6]. Therefore, the development of these large-scale afforestation and reforestation projects will only be sustainable if adequate water resources are available. In these water-limited arid and semiarid regions, however, discrete rainfall is always the only source of soil water replenishment; therefore, regulating and utilizing rainwater rationally may be the only effective way to combat drought and alleviate forest degradation [6].

When it rains, some rainwater enters the shallow soil and is absorbed subsequently by the roots of the plants, while another part of the rainwater infiltrates into the deep soil and is stored and finally utilized by the deep roots, particularly during dry conditions in semiarid regions. Plant roots, especially fine roots, are important organs for absorbing water and nutrients from the soil [7]. Therefore, understanding the distribution of fine roots is fundamental to understanding the soil water-use pattern [8]. As a water deficiency detection sensor, fine roots are influenced by a variety of external factors, among which drought stress is the most significant. Recently, the response of fine roots of trees to drought stress has received much attention [9–13], but research on rainfed forest trees in semiarid regions is still lacking [8]. A better understanding of the distribution characteristics of rainfed plant roots, as well as their response to drought stress, is essential to understanding the water-use patterns of plants and is also important to address a number of fundamental problems in forest ecosystems, particularly in areas affected by severe droughts.

Water transfer in the roots and branches is one of the most critical aspects for ensuring plant survival. Studies have indicated that water transport within the roots and branches of plants is affected by a variety of factors, with drought stress being one of the most significant ones. When plants are subjected to drought, hydraulic failure can occur, which negatively impacts the growth and photosynthesis of plants and may lead to plant mortality as the drought persists [14,15]. In the past few decades, many studies have been conducted to determine the mechanisms causing drought-related tree mortality, and several mechanisms have been proposed [14,16], among which hydraulic failure of plants has been widely acknowledged. The hydraulic failure hypothesis states that high xylem tension induced by drought can cause air bubbles to enter the xylem and block the transport of water through the it, resulting in the plant's inability to move water and eventual desiccation [16]. Studies have been conducted to test the hydraulic failure hypothesis, and a comprehensive understanding of the water-transport characteristics of plants from the roots to the leaves has been formalized, but the roots are lagging behind compared to the branches. A better understanding of how plants adjust their water-transfer characteristics through their root systems, especially under drought conditions, will be helpful for us to adequately understand the hydraulic characteristics of plants, as well as to formulate reasonable management strategies.

In recent years, in situ rainwater collection and infiltration systems (IRCIS) have been developed and applied by farmers to harvest rainwater for sustainable plant growth, especially for orchards, in the semiarid Loess Plateau region of China [6,8]. These systems are designed to increase soil water quantity during the dry season by reducing surface runoff as well as improving rainwater-harvesting efficiency. In many studies, the effects of IRCIS have been discussed in relation to orchards [8,17]; however, very few studies have examined the effects of IRCIS on soil water content and root distribution for commonly planted trees on the Loess Plateau. However, understanding the effects of in situ rainwater collection and infiltration systems on soil moisture and vegetation growth (such as root distribution characteristics, plant hydraulic conductivity, etc.) of forest plantations under drought stress is of significant importance to develop reasonable plantation management measures and promote the healthy and sustainable development of these plantations.

The objectives of this study were (i) to determine the effects of drought on the distribution of soil moisture and fine roots (0–5 m) as well as plant hydraulic conductivity of a commonly planted tree species in the semiarid region of the Loess Plateau and (ii) to explore the effects of IRCIS on soil moisture, fine root distribution and plant hydraulic conductivity of a commonly planted tree species under drought. In order to investigate the effects of drought on soil moisture and plant growth (fine roots and plant hydraulic conductivity), a wet year with higher-than-average rainfall (2015) and a dry year with lower-than-average rainfall (2016) were chosen. The tree species *Robinia pseudoacacia*, which has been widely planted on the Loess Plateau to control soil and water erosion, prevent desertification and produce timber and fuel wood, was selected for this study.

2. Materials and Methods

2.1. Site Description

The study was conducted at Yeheshan Forestry Station (YFS; 34°33′ N, 107°54′ E, 1090 m a.s.l) in the National Natural Reserve of Fufeng County in Shaanxi Province, China. The area has a semiarid continental monsoon climate that is characterized by hot, humid summers (June–August) and cold, dry winters (December–February). According to the Fufeng meteorological station (which is located <10 km from the study area), average annual precipitation and air temperature are 580 mm and 12.7 °C, respectively. The precipitation mainly falls from May–October (~80% of annual precipitation). The main soil type in the region is silt loam, with a homogeneous texture along the 0–500 cm soil profile and mean sand, silt and clay contents of 5.8%, 73.4% and 20.9%, respectively [18]. The mean soil bulk density (BD), field capacity (FC) and permanent wilting point (PWP) of the silt loam are 1.30 g cm^{-3}, 0.304 cm^3 cm^{-3} and 0.072 cm^3 cm^{-3}, respectively [19].

YFS is a hilly-gully region with an elevation range of 449–1662 m a.s.l and area of 110 km^2. Forest cover in the region is ~90% and is dominated by *Robinia pseudoacacia* planted since the 1980s to control soil erosion. *Robinia pseudoacacia* plantation covers an area of 86.7 km^2 and has a dense understory that is a mix of *Stipa bungeana*, *Humulus scandens* and *A. codonocephala*.

2.2. Experimental Plot

Six *Robinia pseudoacacia* experimental plots (20 × 20 m^2) with an age of 13 years and density of 2000 trees/ha were selected and established on hills with slopes of 5–10° (middle slope facing south) where rainfed crops (such as maize and winter wheat) were previously cultivated. Three experimental plots (treated plots) were randomly chosen to install the in situ rainwater collection and infiltration systems (IRCIS), and another three experimental plots were used as the control plots (without IRCIS). Each plot was constructed with an aluminum composite panel ridge of 30 cm above the ground around the borders and an H-flume applied to measure surface runoff. Previous cropland (predominantly maize and winter wheat) that had been abandoned for 13 years was used as a control site for monitoring soil moisture changes.

In the treated experimental plots, IRCIS was constructed upslope of individual trees and consisted of a semi-circular ridge of radius 1.0 m and height 0.2 m. During the construction of the ridge, soil was excavated and moved in such a manner that the tree trunk formed the apex of the semicircular ridge and the soil surface within the semicircle area was relatively level. From above, the ridges formed an upslope pattern resembling a fish scale along each row in the *Robinia pseudoacacia* forest plots. Within the semicircular ridge, an 80 cm × 80 cm × 80 cm soil pit was dug. In this pit, the down-slope wall was 100 cm away from the tree trunk. This storage pit was lined with permeable geotextiles and filled with soil, weeds, branches and forest debris. The surface of this storage pit was then covered with black plastic film and a 3 cm diameter hole was drilled in the center of the plastic film. Rainwater collected from the fish-scale ridge would infiltrate into the filled material through the hole in the plastic film. Rainwater collected in the pit could then be directed laterally and downward into the surrounding soil. The design slows the flow of runoff, resulting in a reduction in sedimentation and loss of soil-pit storage capacity.

The experimental plots treated with IRCIS in 2015 and 2016 were designated, respectively, as RC2015 and RC2016. The control plots without IRCIS in 2015 and 2016 were designated as WT2015 and DT2016, respectively.

2.3. Fine-Root Measurement

The vertical distribution of fine roots in the controlled and treated *Robinia pseudoacacia* stands was investigated using the soil auger method [20]. In each plot, soil core samples were collected using a cylindrical metal corer (9 cm wide and 10 cm long) with one sharp edge. A total of 8 sample points was selected in each forest stand. Samples were taken between 10 and 20 May, 10 and 20 July, and 10 and 20 September at the beginning, middle and end of the growing season. Soil cores were collected at 20 cm intervals to a depth of 100 cm and then at 40 cm intervals to a depth of 500 cm where fine roots were not observed, and the width of the tree canopy. The collected soil samples were stored in polythene plastic bags at 4 °C for later analyses. In the laboratory, the root samples were separated from the soil by a two-stage process. In the first stage, soil samples were washed carefully over a sieve (5 mm). Then grass roots and other organic debris were discarded and tree roots were placed with tweezers into petri dishes containing water. In the second stage, the tree roots were separated by physiological status and diameter classes (d > 2 mm and d ≤ 2 mm). Then separation was performed using a microscope (10–40 × magnification). The *Robinia pseudoacacia* tree roots were identified based on color and morphology. The root samples were then digitally scanned using an Epson Perfection v700 photo scanner at 600 dpi (Seiko Epson Corporation, Naga-no-ken, Japan). Root lengths were measured using the WinRhizo image analysis software (pro 2009c, Regent Instruments Inc., Quebec City, QC, Canada). The fine-root (<2 mm) length density (FRLD, cm dm^{-3}) was calculated as:

$$\mathrm{FRLD} = \frac{\mathrm{L}}{\mathrm{Vs}} \tag{1}$$

where L is fine-root length and Vs is soil volume. We also calculated the cumulative fine-root length density (CFRLD, % of total) for each experiment plot in each soil layer.

2.4. Soil Water Content and Rainfall Measurement

Volumetric soil water content was automatically measured using soil water probes. At each forest stand, 10 Hydra-Probes (Stevensons Water Monitoring Systems, Portland, OR, USA) were installed at soil depths of 5, 15, 30, 50, 80, 120, 180, 250, 350 and 500 cm below the ground surface. Soil water content was sampled every 10 min and recorded by a CR1000 datalogger (Campbell Scientific Inc., Logan, UT, USA). Before the study, all soil water probes were calibrated.

Plant-available water storage (PAMS) is the amount of water storage that can be released into the root zone at any point in time. It is defined as the difference between in situ field water content and permanent wilting point (PWP) and is calculated as:

$$\mathrm{PAMS}_{i,j} = (\mathrm{SWC}_{i,j} - \mathrm{PWP}) \times \mathrm{BD}_{i,j} \times \Delta \mathrm{Z}_{i,j} \tag{2}$$

where $SWC_{i,j}$ is soil water content of the jth soil layer under the ith treatment (stand age); PWP is permanent wilting point; $BD_{i,j}$ is soil bulk density at depth j and sampling site i; and $\Delta Z_{i,j}$ is soil depth increment.

Soil moisture storage deficit (SMSD), relative to the values of the abandoned cropland, was used to assess the feasibility of ecological restoration [8]:

$$\mathrm{SMSD}_{t,i} = \frac{\mathrm{SWS}_{t,i} - \mathrm{SMS}_{c,i}}{\mathrm{SMS}_{c,i}} \tag{3}$$

where $SMS_{t,i}$ and $SMS_{c,i}$ are soil moisture storage in the ith soil layer in the treated experimental plot and the abandoned cropland, respectively. SMSD ≥ 0 indicates no soil moisture storage deficit, while SMSD < 0 represents soil moisture storage deficit in the specified soil layers, where the magnitude of the value is indicative of the severity of the deficit.

Rainfall was measured using both automatic and manual rain gauges. Three manual funnel-type rain gauges (30 cm orifice diameter) were installed near (<30 m away) each forest stand at a sufficiently open place. Due to financial limitations, only one T-200B weighing bucket rain gauge (Geonor, Eiksmarka, Norway) was used in this study. The automatic rain gauge was connected to a CR1000 data logger (Campbell Scientific Inc., Logan, UT, USA) and installed in a sufficiently exposed nearby place (<30 m) in the middle of the watershed. The manual rain gauges were read immediately after each rainfall event. Using the long-term yearly rainfall data (1958–2016), we constructed a rainfall frequency curve. Each year was categorized as either a wet year, a normal year or a dry year, depending on the frequency of gross rainfall (<25% are wet years; >75% are dry years; remainder are normal years) [21].

To exclude the effect of rainfall on soil water movement, seven successive days without rainfall (rain-free period) were set in this study as the investigation period. Moreover, leaves were completely unfolded and canopies remained stable during summer and therefore 6 rain-free periods (8–14 June, 25–31 July and 25–31 August in 2015 and 16–22 June, 2–8 July and 10–16 August in 2016) were ultimately used for investigation (Figure 1).

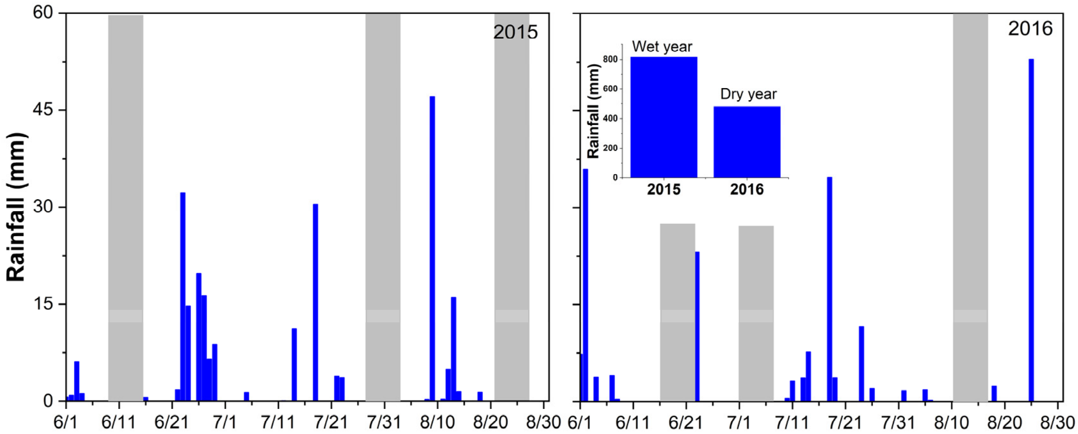

Figure 1. Gross rainfall distribution and the six selected investigation times during the experimental periods in 2015 and 2016. Gray rectangles indicate the periods during which the study was carried out.

2.5. The Percent Loss of Hydraulic Conductivity (PLC)

In this study, one-year-old branches at the middle-upper canopy on the sunny side (the south side) of the plant, as well as roots from shallow soil layers (0–100 cm), were used to determine the percent loss of hydraulic conductivity (PLC). To measure the PLC, a low-pressure flow meter was used following the approach proposed by Sperry et al. [22]. During the dawn or noon period of the fine-root collection, approximately 30–40 cm long samples of branches with a basal diameter of approximately 1.0 cm and roots in soil depths of 50 cm were collected. To avoid embolisms induced by cutting, all plant samples were cut under water. Afterwards, all the samples were wrapped in plastic bags and taken back to the lab for PLC analysis. The PLC was determined by averaging three segments (4 cm long) across three biological replicates. To determine the flow rate through the segment, the solution was collected and weighed using a balance. By measuring the flow rate of the KCl solution at a pressure differential of 4 kPa, the initial hydraulic conductivity (Ki) was determined gravimetrically. The stem segment was flushed for a period of 10 min at a pressure of 0.175 MPa in order to remove any air embolisms. Afterwards, the hydraulic conductivity of the fluid was determined again at a pressure differential of 4 kPa and was set as the maximum hydraulic conductivity (Kmax). The PLC was then calculated as PLC (%) = (1 − Ki/Kmax).

2.6. Statistical Analysis

The data were analyzed using a one-way analysis of variance (ANOVA) using SPSS Version 25.0 (Chicago, IL, USA) after verifying the assumptions of normality and homogeneity. Ducan's multiple range tests were performed at $p < 0.05$ and $p < 0.01$ for significant differences between the treatments for PAMS, SMSD, FRLD and PLC between treated and control forest plots: WT2015, RC2015, DT2016 and RC2016. Origin software 2022 (OriginLab Corporation, Hampton, MA, USA) and Excel 2022 (Microsoft Corporation, Redmond, WA, USA) were used to fit curves and plot graphs.

3. Results

3.1. Plant-Available Moisture Storage (PAMS)

Plant-available moisture storage (PAMS) in *Robinia pseudoacacia* forest stands was significantly affected by the in situ rainwater collection and infiltration system (IRCIS) in both wet and dry years (Figure 2). In general, the average PAMS profile decreased with increasing soil profile, but the decrease under the treatment of IRCIS was relatively gradual, whereas it was relatively rapid under the control treatment (Figure 2A). Furthermore, IRCIS increased the average PAMS in soil profiles (0–5 m) of *Robinia pseudoacacia* forest stands in both study years, but the increase was greater in the dry year 2016 than in the wet year 2015. IRCIS increased average PAMS in soil profiles by 4.6% in the wet year 2015 and 10.0% in the dry year 2016 (Figure 2B).

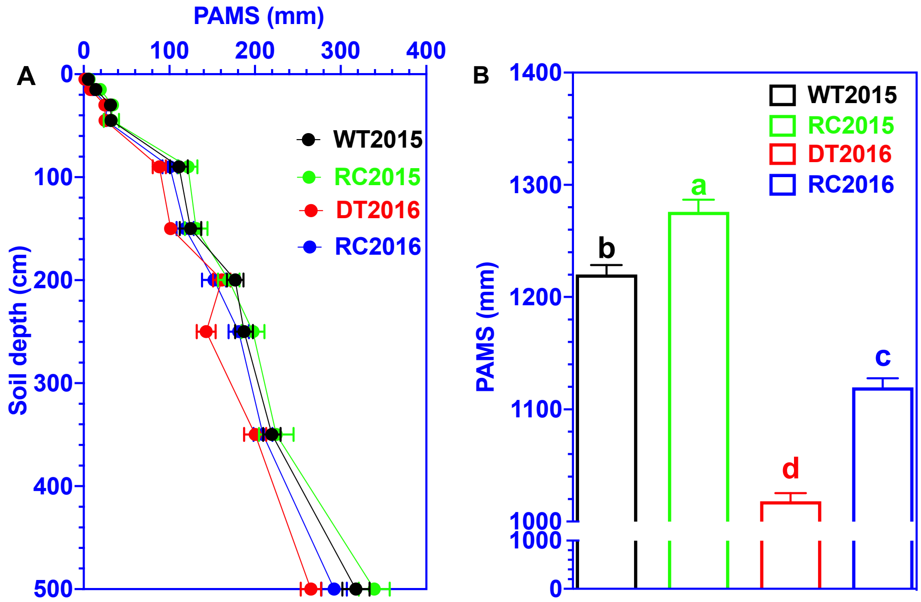

Figure 2. Vertical distribution (0–5 m, **A**) and the content (**B**) of plant-available moisture storage (PAMS) in a wet year of higher-than-average rainfall (2015) and a dry year of lower-than-average rainfall (2016) in *Robinia pseudoacacia* forest stands of different treatments. WT2015 is wet year of 2015 without in situ rainwater collection and infiltration system; RC2015 is wet year of 2015 with in situ rainwater collection and infiltration system; DT2016 is dry year of 2016 without in situ rainwater collection and infiltration system and RC2016 is wet year of 2016 with in situ rainwater collection and infiltration system. Different letters indicate a statistically significant difference at $p < 0.05$ between treatments. Error bars represent ±1 SD.

3.2. Soil Moisture Storage Deficit (SMSD)

The soil profile SMSD is shown in Figure 3. Overall, shallow soil profiles (0–1.5 m) suffered greater soil moisture deficits during the dry year of 2016, but little or no deficit during the wet year of 2015 relative to abandoned cropland (Figure 3A,B). In deep soils (>1.5 m), almost all forest treatments displayed soil moisture deficits. The vertical distribution of the profile soil moisture deficits was significantly affected by IRCIS treatment (Figure 3C). On the whole, IRCIS treatment alleviated the soil profile deficit, but the alleviation in the shallow soil (0–1.5 m) was much greater than that in the deep soil profile (>1.5 m) (Figure 3A,B). In the two study years, the amount of alleviation was similar, but slightly higher in the dry year of 2016 (decreased by 0.06) than in the wet year of 2015 (decreased by 0.05).

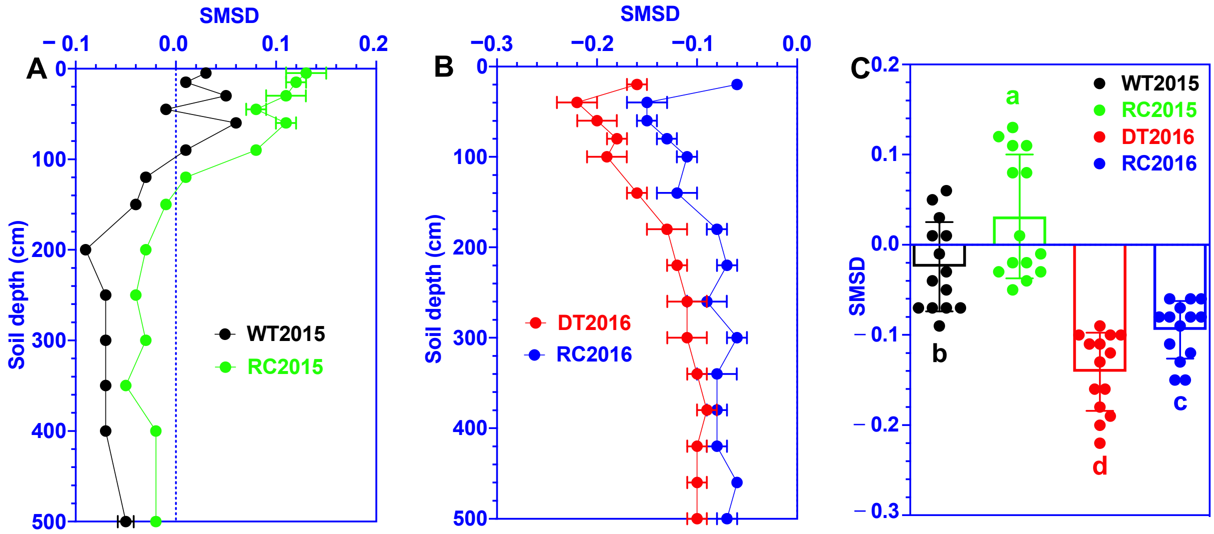

Figure 3. Vertical distribution (0–5 m, **A**,**B**) and content (**C**) of soil moisture storage deficit (SMSD) in a wet year of higher-than-average rainfall (2015, **A**) and a dry year of lower-than-average rainfall (2016, **B**) in *Robinia pseudoacacia* forest stands of different treatments. Negative and positive values represent, respectively, a negative and positive soil moisture deficit relative to the control (abandoned cropland). Different letters indicate a statistically significant difference at $p < 0.05$ between treatments. Error bars represent ±1 SD. WT2015 is wet year of 2015 without in situ rainwater collection and infiltration system; RC2015 is wet year of 2015 with in situ rainwater collection and infiltration system; DT2016 is dry year of 2016 without in situ rainwater collection and infiltration system and RC2016 is wet year of 2016 with in situ rainwater collection and infiltration system.

3.3. Fine-Root Distribution (FRLD)

The vertical distribution of fine-root length density (FRLD) is shown in Figure 4. In general, the FRLD decreases with increasing soil depth, primarily in the 0–1.5 m soil profile (Figure 4A). Fine roots were mainly concentrated in the top 0–1.5 m soil: WT2015 and RC2015 had 82.9% and 93.9% of total FRLD, respectively, in the wet year of 2015; DT2016 and RC2016 had 67.4% and 75.3% of total FRLD, respectively, in the dry year of 2016. Drought strongly increased the amount of FRLD: DT2016 and RC2016 had 31.1% and 23.8% higher total FRLD, respectively, than WT2015 and RC2015 (Figure 4B). IRCIS significantly reduced the FRLD: RC2015 and RC2016 had 7.4% and 12.7% lower total FRLD, respectively, than WT2015 and DT2016 (Figure 4B).

Over both study years, the cumulative FRLD (CFRLD) was higher in the shallow soil layer than in the deeper soil layer (Figure 5). IRCIS treatment significantly affected the distribution of cumulative fine-root length density in *Robinia pseudoacacia* forests. IRCIS tended to decrease CFRLD profiles gradually, but control treatment caused them to decline profoundly (Figure 5), especially in the 0–1.5 m soil layer. IRCIS-treated forest stands tended to have shallower D_{95} (the depth above which 95% of the root mass is present) than the control forest stands, with respective values of 1.2 m for RC2015, 1.8 m for WT2015, 2.8 m for RC2016 and 3.3 m for DT2016.

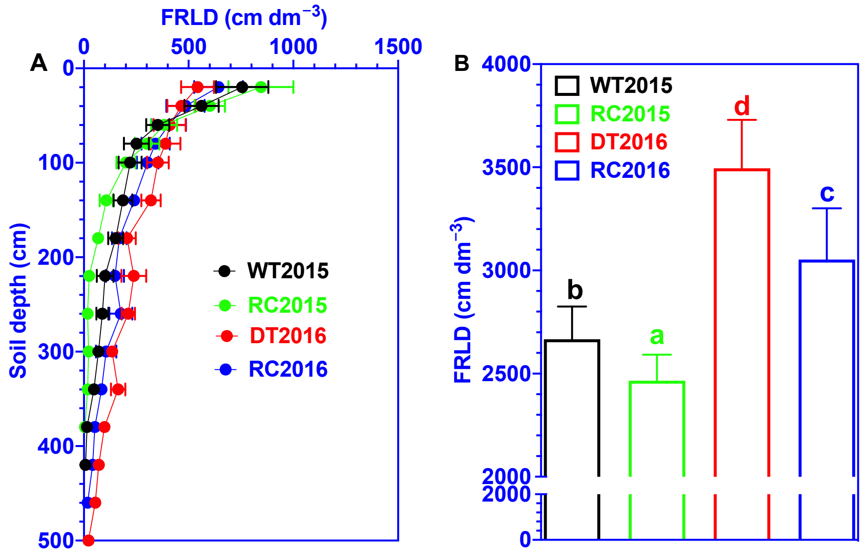

Figure 4. Vertical distribution (0–5 m, **A**) and content (**B**) of fine-root length density (FRLD, cm/dm^3) in a wet year of higher-than-average rainfall (2015) and a dry year of lower-than-average rainfall (2016) in *Robinia pseudoacacia* forest stands of different treatments. Different letters indicate a statistically significant difference at $p < 0.05$ between treatments. Error bars represent $\pm$1 SD. WT2015 is wet year of 2015 without in situ rainwater collection and infiltration system; RC2015 is wet year of 2015 with in situ rainwater collection and infiltration system; DT2016 is dry year of 2016 without in situ rainwater collection and infiltration system and RC2016 is wet year of 2016 with in situ rainwater collection and infiltration system.

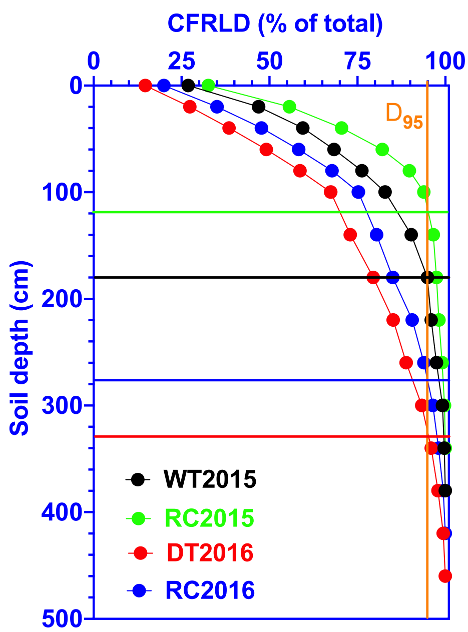

Figure 5. Comparison of cumulative fine-root length density in *Robinia pseudoacacia* forest stands of different treatments in a wet year of higher-than-average rainfall (2015) and a dry year of lower-than-average rainfall (2016). Data points represent average fine-root length densities in the indicated soil layers. The intersection of horizontal lines (with different colors) and vertical lines D_{95} indicates soil depth above which 95% of fine-root length density occur. WT2015 is wet year of 2015 without in situ rainwater collection and infiltration system; RC2015 is wet year of 2015 with in situ rainwater collection and infiltration system; DT2016 is dry year of 2016 without in situ rainwater collection and infiltration system and RC2016 is wet year of 2016 with in situ rainwater collection and infiltration system.

3.4. The Percentage Loss of Hydraulic Conductivity (PLC)

IRCIS strongly affected the percentage loss of hydraulic conductivity (PLC) in branches and roots of *Robinia pseudoacacia* forest (Figure 6). Over the two study years, IRCIS reduced the PLC for all forest stands. In branches, RC2015 and RC2016, were, respectively, 35.6% and 24.3% lower than WT2015 and DT2016 (Figure 6A). In roots, RC2015 and RC2016, were, respectively, 35.6% and 24.3% lower than WT2015 and DT2016 (Figure 6B). In general, IRCIS had a greater impact on the root PLC than on the branch PLC (Figure 6A,B). This shows that roots have a higher sensitivity to external factors, such as drought and IRCIS, than branches when it comes to hydraulic conductivity.

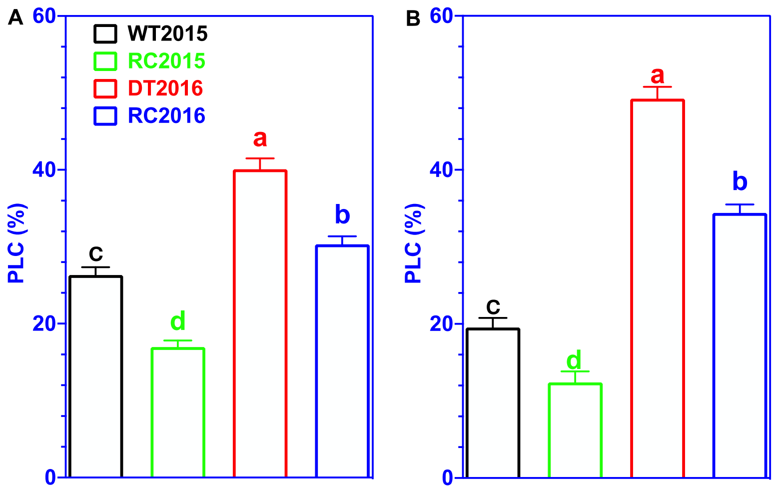

Figure 6. The percentage loss of hydraulic conductivity (PLC) in branches (**A**) and roots (**B**) of *Robinia pseudoacacia* under different treatments. Different letters indicate a statistically significant difference at $p < 0.05$ between stand age treatments. Error bars represent ±1 SD. WT2015 is wet year of 2015 without in situ rainwater collection and infiltration system; RC2015 is wet year of 2015 with in situ rainwater collection and infiltration system; DT2016 is dry year of 2016 without in situ rainwater collection and infiltration system and RC2016 is wet year of 2016 with in situ rainwater collection and infiltration system.

4. Discussion

4.1. Soil Moisture Profile

Over the last few decades, large-scale afforestation efforts have increased forest cover by 7.6% from 2001 to 2016 in the semiarid Loess Plateau region of China [23]. Due to the large amount of soil water required by forest vegetation, plant-available soil water is likely to decline dramatically, and the soil water deficit will be exacerbated, especially in drought years (Figures 2 and 3). As a result, this will negatively impact the health and stability of the forest vegetation ecosystem in the semiarid Loess Plateau region, resulting in a reduction in the normal growth of forest vegetation and even death of forest vegetation [19,24]. As the climatic and environmental conditions experienced by the forest plots are similar in our study, rainfall in different years and forest management measures (with or without IRCIS treatment) are the primary factors determining soil water balance and how soil water is distributed in the soil profile of *Robinia pseudoacacia* forests.

This study highlights the importance of IRCIS for rainfall harvesting in afforestation planting and management because it can significantly increase the availability of soil water to the plants and decrease soil water deficits (relative to the abandoned cropland). In line with our findings, Song et al. (2020) also found that IRCIS treatment can significantly increase the soil profile water content of orchard plants [8]. It has been shown that shallow (0–1.5 m) soil moisture is primarily affected by rainfall and vegetation utilization [17,25]; thus, shallow soil (0–1.5 m) has significantly wider variations in soil water content than deep soil, particularly during dry seasons or years (Figure 2). Our study also found that the effect of IRCIS on shallow soil moisture content (0–1.5 m) was greater than it was on deep soil moisture (>1.5 m), which could be attributed to the fact that the soil moisture increased by IRCIS was mainly retained and consumed by the shallow (0–1.5 m) root system of *Robinia pseudoacacia* (Figures 4 and 5), but could not be substantially replenished in the deep soils (>1.5 m). As a consequence, the shallow soil moisture content (0–1.5 m) is highly variable with the implementation of IRCIS, whereas the deep (>1.5 m) soil moisture content is relatively stable. Additionally, this suggests that deep soil profiles may serve as an important water source for forest vegetation during extremely dry years [8,26,27].

4.2. Root Distribution Pattern

Fine roots are essential to the growth and development of plants as they extract the majority of the water and nutrients from the soil. In this study, it was found that *Robinia pseudoacacia* increased its biomass of fine roots as well as its distribution depth during dry years, demonstrating that *Robinia pseudoacacia* is able to absorb and utilize large amounts of deep soil water during dry periods. These findings are similar to those of Brunner et al. 2015 [26] and Song et al., 2020 [8]. When *Robinia pseudoacacia* was treated with IRCIS, its fine-root biomass and fine-root depth decreased significantly in comparison to the control group. This may be because IRCIS can increase the water content of the shallow soil in both dry and wet years (Figure 2), making it easier for *Robinia pseudoacacia* to absorb water from the shallow soil instead of allocating more carbon for growing deeper roots to absorb deep soil water to support its growth and development. Similar results were also found by Li et al. (2022) [28] and Song et al. (2020) [8].

Additionally, this study demonstrated that the FRLD content in the surface (0–1.5 m) soil of *Robinia pseudoacacia* forests was the highest in both dry and wet years, accounting for more than 80.0% of the total fine-root biomass, among which WT2015, RC2015, DT2016 and CR2016 each had a content of 82.9%, 93.9%, 67.4% and 75.3%, respectively. The results demonstrated that this structure facilitates the efficient uptake of water from shallow soil layers, where soil water is greatly affected by rainfall and replenished rapidly [8,17,29]. Although the FRLD content in deep soil (>1.5 m) is relatively low, this part of the fine roots is critical to the growth of plants. Particularly in drought years, this part of the fine roots can absorb deep soil moisture in order to aid plants in resisting drought conditions. There is also evidence from Song et al. (2020) [8] that apple trees in semiarid regions will increase their water consumption from deep soil in drought years in order to resist drought stress [8].

A deep root system is one of the most important adaptations for plants in arid and semiarid environments. Generally, rooting depth determines how much water can be accessed by plants through transpiration from the soil [30]. In this study, it was found that, in comparison with the wet year of 2015, the growth of *Robinia pseudoacacia* fine roots (maximum depth and D_{95}) was deeper in the dry year of 2016, which may enable them to switch between shallow and deep water sources, depending on soil water availability. These findings agree well with reports by [8,25,31]. In addition, this study found that IRCIS treatment increased plant water availability and reduced soil water deficit, reducing the risk of plants suffering from drought stress. Similar results were also reported by Song et al. (2020) [8].

4.3. PLC

Xylem water transport is essential for maintaining canopy gas exchange and cell expansion and, therefore, for plant growth and survival. Studies have shown that xylem conduits with larger diameters always have greater water transport ability, but are also more vulnerable to hydraulic failure [16]. This is due to the structural characteristics of the xylem network: plants are faced with the challenge of transporting as much water as possible while minimizing the risk of drought-induced embolisms during dry periods [32]. This was also evident in the present study, where the loss of hydraulic conductivity during drought years was larger in roots (with a larger xylem diameter) than it was in branches (with a small xylem diameter). The loss of hydraulic conductivity will affect the growth processes of plants, such as photosynthesis and transpiration, resulting in slow growth and possibly even death [32]. In addition, our study found that after the application of IRCIS treatment, the PLC of the branches and roots decreased in both wet and dry years. This may indicate that IRCIS treatment plays a significant role in improving plant resistance to drought and preventing the loss of hydraulic conductivity, especially during drought conditions.

4.4. Implications for Afforest Management

In this study, we provided evidence that PAMS in shallow soil layers (0–1.5 m) was low during the rainy season of the dry year 2016, and soil water deficits were observed in most deep soil layers (>1.5 m) in both 2015 and 2016. This was mainly due to the lower rainfall and higher water consumption of *Robinia pseudoacacia* trees in dry years, which eventually reduced soil water content, increasing soil moisture deficits [19]. Severe soil moisture deficits in turn resulted in lower hydraulic conductivity, hindered *Robinia pseudoacacia* growth and even caused branch dieback and tree mortality [32]. Therefore, for the healthy development of artificial forests and sustainable ecological construction, effective water-saving management with the potential to control soil erosion without endangering further soil water availability should be implemented in the semiarid Loess Plateau region.

A rational collection, management and utilization of rainfall, the only water resource available for the growth of vegetation in this region, can result in an increase in soil water content (Figure 2), a reduction in soil water deficit (Figure 3) and an improvement in artificial forests' growth (fine roots and plant hydraulic conductivity, Figures 4–6). Diverse afforestation management strategies for the effective utilization of rainwater to increase sustainable forest development in the Loess Plateau region are well documented [6,8]. All these strategies, including engineering measures (e.g., creation of fish-scale pits and mini-catchments), level furrowing and agronomic measures (e.g., mulching with straw or stone, application of water-retaining chemicals), have all been tested and are well implemented [6]. In situ rainwater collection and infiltration systems (IRCIS) that divert rainwater and runoff to deeper soils have been introduced into orchards to optimize rainwater utilization on the Loess Plateau [8,17,33]. The results of our study also indicate that IRCIS can be used for the sustainable development of artificial forests to increase the availability of soil moisture for plants and decrease soil moisture deficits.

5. Conclusions

Afforestation is an effective measure to control soil and water erosion for sustainable ecological construction in the Loess Plateau of China. However, due to huge water requirements, forest land, such as *Robinia pseudoacacia* forests in our study, had significantly lower plant-available water than abandoned cropland, resulting in higher soil moisture deficits, especially in low rainfall years. The presence of a significant water deficit in soil will reduce the hydraulic conductivity of the roots and branches of plants, inhibiting the normal growth of plants and even resulting in their death. Our results indicated that IRCIS can increase soil water content, decrease soil moisture deficits and increase the hydraulic conductivity of plants. Moreover, our results revealed that drought significantly influenced the root distribution of *Robinia pseudoacacia.* The biomass and maximum depth of *Robinia pseudoacacia* roots in dry years were significantly greater than those in wet years, suggesting that *Robinia pseudoacacia* can absorb shallow soil water in wet years, while absorbing deep soil water in dry years to maintain normal growth and resist drought stress. The results of this study will contribute to the formulation of appropriate strategies for planning and managing rainwater resources. The use of all these strategies, such as in situ rainwater collection and infiltration systems, would help counteract the degradation of forest plantations caused by droughts, not only on the Loess Plateau, but also in other similar regions around the world.

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