The ~~degree~~moisture and depth limitations of deep soil desiccation and its impact on xylem hydraulic conductivity in dryland tree plantations

Nana He[1], Xiaodong Gao[2,3,4*], Dagang Guo[1], Yabiao Wu[1], Dong Ge[1], Lianhao Zhao[2], Lei Tian[5], Xining Zhao[2,3,4]

[1]College of Water Resources and Architectural Engineering, Northwest A&F University, 712100 Yangling, Shannxi Province, China

[2]Institute of Soil and Water Conservation, Chinese Academy of Science & Ministry of Water Resources, 712100, Yangling, Shaanxi Province, China

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

[4]National Engineering Research Center of Water Saving and Irrigation Technology at Yangling, 712100, Shaanxi Province, China

[5]Institute of Green Development Yellow River Drainage Basin, Lanzhou University, 730000, Lanzhou, Gansu Province, China

Correspondence to: Xiaodong Gao (gao_xiaodong@nwafu.edu.cn)

Abstract. In water-limited areas, planted trees can abstract substantial amounts of soil water from deep layers (>200 cm) to meet their ~~high~~ high-water demand, resulting in deep soil desiccation, which influences not only regional water cycling but also the sustainability of trees *per se* in drylands. However, the limitation~~s~~ in relation to both ~~degree~~moisture and depth of deep ~~layer~~ soil ~~moisture (DSM)~~desiccation (DSD) beyond which root water uptake ceases remains unclear. Whether limitation depends on tree species and how it will affect tree's xylem hydraulic conductivity are also unclear, restricting our ability to predict the fate of dryland tree plantations. We, therefore, studied the spatiotemporal distribution of deep soil moisture deficit (DSMD~~, the relative difference in soil moisture for given trees and referenced cropland or grassland, to minimize the effect of climate differences in various sampling years~~) for two typical planted trees, apple (*Malus pumila* Mill.) and black locust (*Robinia pseudoacacia* L.), based on the published data and multiple field samplings on China's Loess Plateau. The results indicated that the lowest deep soil moisture (DSM)~~DSM~~ occurred under the planted trees aged 24-28 years at all sites. The lowest DSMD fluctuated around -0.6, which close to the DSMD at the permanent wilting point (PWP) irrespective of tree species and site, although shallow (<200 cm) soil moisture was not reduced to the point of limitation. This suggests that PWP is a good indicator of the ~~degree~~ moisture limitation of ~~DSM~~ DSD for the tree species examined. The corresponding maximum depth of soil moisture use reached 18.0-22.0 m for these old planted trees at different sites while it was more than 25 m for black locust in the drier site of Mizhi. Furthermore, when the ~~degree~~ moisture and depth limitations were reached, the percent loss of xylem hydraulic conductivity of planted trees' branches reached 74.9-96.5%, indicating that tree mortality may occur. The findings will help to predict the sustainability of planted trees in semiarid regions with thick vadose zone.

1 Introduction

Worldwide, tree planting is extensively advocated as a nature-based solution (NbS) to facilitate the realization of Sustainable

Development Goals (Griscom et al., 2020). China's Loess Plateau (LOP), the greatest loess deposits in the world with a thickness of ~~50~~30-200 m loess (Shao et al., 2018), has been one of the most active regions for tree planting during the last four

35 decades, with the aim of controlling severe soil erosion and improving rural lives ~~there~~ (Fu et al., 2016). Many trees of a variety of species (mostly exotic) have been planted during implementation of two large ecological projects: the Three-North Shelter Forest Program and the Grain-For-Green Program (~~Gao~~ Cao et al., 2021). So far, the area of tree plantations on the LOP has reached 7.47 million ha; the vegetation cover for this region increased from 31.6% in 1999 to 65.0% in 2017 (official data from the National Forestry and Grassland Administration, http://www.forestry.gov.cn). As a result, a number of ecosystem

40 services, including soil and water conservation, have been greatly improved on the LOP (Fu et al., 2016; Gao et al., 2021). In fact, the success of ecological restoration through tree planting on the LOP greatly depends on the presence of an abundant "soil reservoir" deposited in deep loess deposits (200-2000 cm) (Zhu, 2006).

However, inappropriate tree planting in drylands can incur other ecological issues, such as soil desiccation due to excessive water consumption ~~in drylands~~ (Wang et al., 2010; Jia et al., 2017; Wu et al., 2021), preventing the sustainable development

45 of revegetation and may even result in tree mortality (Breshears et al., 2013; Choat et al., 2018; Stovall et al., 2019). Considerable researches have shown that planted trees abstract substantial deep-layer soil moisture (DSM) by developing deep roots to maintain its normal growth on the LOP (e.g., Gao et al., 2018; Su and Shangguan, 2019; Shi et al., 2021). However, continuous use of DSM over a number of years leads to severe soil desiccation (Wang et al., 2011; Gao et al., 2018; Tao et al., 2021), because DSM below 200 cm is hardly recharged by precipitation under tree plantations. In fact, deep-layer soil

50 desiccation under tree plantations can occur at multiple degrees depending on tree age and local climate (Fang et al., 2016; Jia et al., 2017). Although soil desiccation of different degrees has been widely reported in the above citations, knowledge remains restricted about variation in the lowest ~~degree~~moisture of ~~soil moisture deficit~~deep soil desiccation (DSD) that limits growth (hereafter "~~degree~~ moisture limitation") and/or the maximum depth from which trees are able to extract water (hereafter "depth limitation") for different species and in different climate zones, which is critical to estimate the amount of available soil water

55 storage in deep soils and to predict the fate of planted trees based on soil water availability. Currently, permanent wilting point (PWP) is often used to represent the lowest limit of soil moisture available to plants according to the definition of available water capacity (Tormena et al., 2017). However, the PWP determined in the lab and/or field is often related to annual crops rather than perennial mature trees (Lucia et al., 2020). In the literature it is mainly estimated on the basis of overall soil properties and uses soil moisture at -15 bar as the surrogate without considering differences between plant species (Torres et

60 al., 2021). However, a recent synthesis indicated that the lowest soil moisture (~~degree~~ moisture limitation) under tree plantations can be lower than the average PWP on the LOP (Li et al., 2021a). Therefore, it remains unclear whether the PWP is a good indicator of the ~~degree~~ moisture limitation of ~~DSM~~ DSD for planted trees.

The occurrence of soil desiccation in deep layers can greatly affect the growth and eco-physiological traits of the aboveground

parts of planted trees. It has been widely observed that the aboveground growth of planted trees is greatly constrained due to deep soil drying, resulting in so-called "dwarf aged trees" on the LOP (Hou et al., 1991; Zhu, 2000; Fang et al., 2016). Recently, Li et al. (2021) found that when deep soil below 200 cm is dry, the canopy transpiration of apple trees with a rooting depth beyond 2000 cm is reduced by around 40% relative to that without deep soil desiccation on the LOP. Furthermore, Yang et al. (2022) conducted a deep-soil-and-root-partitioning experiment to quantify the effect of deep-layer (>200 cm) root uptake on the transpiration and physiological features of apple tree. They found that the canopy transpiration and the net photosynthetic rate of apple trees without deep-layer root water uptake was reduced, respectively, by 36% and 20% on average, compared with the trees with deep roots in a semiarid site on the LOP. ~~They found that the canopy transpiration and the net photosynthetic rate of apple trees was reduced, respectively, by 36% and 20% on average compared with the trees with deep roots in a semiarid site on the LOP.~~ Moreover, embolism resistance increases with a decrease in soil water availability, leading to a reduction in xylem hydraulic conductivity and even hydraulic failure of the plantation (Liu et al., 2020; Fuchs et al., 2021). ~~However, it remains unclear on t~~The effect of ~~deep-layer soil desiccation~~DSD on xylem hydraulic conductivity of planted trees, however, is still unclear, when ~~degree~~moisture limitation and depth limitation~~s~~ of ~~DSM~~DSD are reached.

To address the gaps, we built a dataset, including 11980 observations of ~~380~~258 soil profiles from 34 peer-reviewed publications and 4200 observations of 72 soil profiles in-situ sampling across the LOP. The main objectives of this study were (i) to identify the ~~degree~~moisture and depth limitation~~s~~ of ~~DSM~~DSD for different tree species and the influencing factors, and (ii) to ~~disentangle~~explore their impact on xylem hydraulic conductivity of planted trees in different climatic zones on the LOP. Our hypotheses were that the ~~degree~~moisture and depth limitation of ~~deep-layer soil desiccation~~DSD depends on tree species ~~because of~~, as ~~their~~they differ~~ent~~ in drought-resistance capacity, which relies on themselves water use strategy under drought stress (Gessler et al., 2020); and that the xylem hydraulic conductivity of planted trees is greatly reduced when ~~degree~~moisture and depth limitation~~s~~ are reached due to low soil water availability in deep layers.

2 Materials and methods

2.1 Data compilation

2.1.1 Data sources

Peer-reviewed research papers, published between 1999 and 2021 were extracted from the Web of Science (United States) and CNKI (China Knowledge Resource Integrated Database, China; 2000-2021) using the search terms ("Loess plateau" OR "Loess hilly region") AND ("artificial forest" OR "afforestation" OR "plantation") AND ("soil moisture" OR "soil water content" OR "soil water deficit"). To avoid ~~publication~~ bias in the literature selection, the following criteria were set to filtrate 718 articles obtained:

(1) Soil profiles for moisture extraction under deep-rooted artificial forests must exceed a depth of 500 cm at dense

sampling intervals (≤100 cm). The reason for the criteria is that 0-200 cm soil layer is greatly affected by rainfall, while the phenomenon of 200-500 cm dry soil layer is common (Jia et al., 2020), thus, data from a sampling depth greater than 500 cm were considered in this study in order to explore the state of DSM.

(2) Soil moisture was the gravimetric or volumetric moisture content measured by drying methods or moisture sensors. The volumetric moisture content was uniformly converted to gravimetric moisture content by means of the average soil bulk density in each study area.

(3) Experiments with only shrub and grass communities or experiments with irrigation, mulching, pruning and/or other measures were excluded.

(4) Experiments yielded paired data for DSM in apple orchards or black locust forests and that in cropland or grassland (control).

(5) Location, mean annual precipitation (mm), forest age, and vegetation types were clearly presented.

2.1.2 Data extraction and classification

~~Based on the above criteria~~Using the aforementioned criteria, we retrieved a total of 11980 observations from ~~380~~ 258 soil profiles, ~~which covered~~covering 83 sites ~~in~~ across ~~4~~ four provinces or municipalities (Fig. 1). These data were ~~and~~ extracted from 34 peer-reviewed publications ~~were retrieved~~, and the specific information is shown in Table 1. The original data were either clearly obtained from tables in the selected papers or ~~intuitively~~ directly extracted from the intuitive figures in those papers using GetData Graph Digitizer (version 2.24, http://getdata-graph-digitizer.com). Soil moisture data were collected at 200 cm intervals, with values averaged when multiple samples were obtained within a 200 cm interval (e.g., with an interval of 20 cm or 10 cm)~~All sampled soil layers were divided into 200 cm intervals, when more than one soil moisture data sample was obtained within 200 cm (e.g., with an interval of 20 cm or 10 cm), we averaged the values of all soil layers to convert them into a 200 cm interval~~. Soil moisture data for the same stand age collected in different sampling years were ~~treated~~ analyzed independently ~~when analyzing~~to assess the influence of forest age on soil moisture. To avoid random errors, data extracted ~~When analyzing~~for the ~~degree~~ moisture limitation of ~~DSM~~ DSD under apple tree in Changwu and Luochuan~~, the extracted data~~ were divided into tree age range for analysis~~ to avoid random errors~~. Simultaneously, we also collected basic data from each publication, including data source, geographic coordinates (longitude, latitude), mean annual precipitation (MAP), tree species, and soil texture. ~~Since there was relatively little~~Given the limited published information on DSM in black locust forests, we also ~~performed~~ conducted supplementary experiments to obtain relevant data, as described in Section 2.2.
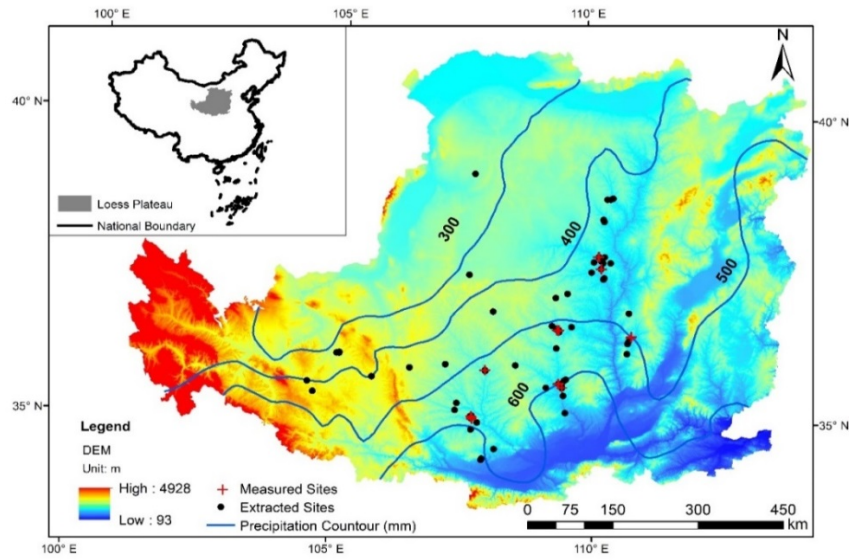
Figure 1: Distribution map of sampling sites on the Loess Plateau. The black dots represent the sampling sites extracted from the article, and the red small crosses represent the sampling sites supplemented in the field.

Table 1. Sample information used in this study.

Sites	Species	NEP (pair)	NSP (pair)	MAP (mm)	2021-P (mm)	Climate type zone
Luochuan	Apple	24	10	608	957	Semi-humid
Fufeng	Apple	1	-	606	-	Semi-humid
	Black locust	4	-		-	
Yongshou	Black locust	4	-	600	-	Semi-humid
Changwu	Apple	44	8	578	910	Semi-humid
	Black locust	6	10			
Baishui	Apple	2	-	577	-	Semi-humid
Jingchuan	Apple	1	-	571	-	Semi-humid
Qingcheng	Apple	6	-	561	-	Semi-humid
Yan'an	Apple	7	-	530	-	Semi-humid
	Black locust	15	10		704	
Daning	Apple	2	-	528	-	Semi-humid
Zichang	Apple	1	-	480	-	Semi-arid
	Black locust	1	-		-	
Zizhou	Apple	1	-	424	-	Semi-arid
Mizhi	Apple	9	10	421	441	Semi-arid
	Black locust	1	10		458	
Total	-	129	58	-	-	-

Note: NEP and NSP indicate the number of data pairs from the literature and field sampling, respectively. A data pair refers to the moisture content of a soil profile from plantation and that of a soil profile from cropland/grassland. MAP is the mean annual precipitation; 250 mm<MAP<500 mm and 500 mm<MAP<800 mm are classified as the semi-arid and semi-humid climate zone, respectively (Wang et al., 2011). The blue text indicates the supplementary sampling in this study with reference to the existing data, and these are representative plots for the different climatic regions upon which we focused.

2.2 Data measurement

2.2.1 Study area and sampling sites

The LOP covers a total area of 640,000 km², with an elevation range of 200-3000 m. It belongs to the continental monsoon

region where annual precipitation ranges from 150 mm in the northwest to 800 mm in the southeast, 55-78% of which falls from June to September (Wang et al., 2011). The location of sites from which we collected field data across the entire LOP (34°43′-41°16′ N, 100°54′-114°33′ E) are indicated by the red small crosses in Fig. 1 and the blue text in Table 1. Geographic coordinates (altitude, longitude, and latitude) for each site were obtained using a Global Positioning SystemGPS (Zhuolin A8, with an accuracy of 1 m).

2.2.2 Soil moisture content

The sampling events for soil moisture was done from April 9 to May 6 2022 (the early growing season of trees on the LOP) under the plantations of apple tree and black locust at the ages of 20-30 years old as well as under the cropland/grassland as the control due to the intact DSM below 200 cm. At first, the sampling depth was set as 0-10 m under different tree plantations; however, it was extended down to 25 m when the DSM reached the degree moisture limitation under one given aged plantation as well as under the paired control plots (sampling process is shown in the Fig. S1). The information of the tree plantations reaching the degree moisture limitation was indicated in Table 2. The maximum sampling depth was set as 25 m because previous studies reported the maximum rooting depth less than 25 m on the LOP (Wang et al., 2009; Li et al., 2019). In order to minimize the spatial variability in soil moisture caused by soil properties, the straight-line distance (SD) between the planted trees and their controls was controlled at less than 500 m, and the average straight-line distanceSD of the three replicates was shown in Table 2. All soil samples were collected by a hand auger (Φ=6 cm) at depth interval of 20 cm and 1.5 m horizontal to the trunk of trees; and three trees with similar growth status were selected for each age as repeats. Collecting soil samples in the due north direction of the first tree, a clockwise rotation of 120° around the second tree from the due north direction was used as the second sampling point, and a clockwise rotation of 240° around the third tree from the due north direction was used as the third sampling point. Soil samples without roots was were put into an aluminum specimen box and used to measure the gravimetric moisture content (g g^{-1}), which was determined by drying method at 105°C for constant weight. A total of 4200 soil moisture data were collected at 72 soil profiles. Three repeats of soil moisture data under one given tree plantation were averaged when analyzing the degree moisture and depth limitations of DSM DSD under plantations to eliminate the effect of different sampling directions. Moreover, the soil sampling under all tree plantations was done once because the temporal variation of DSM below 200 cm under tree plantations was negligible in one growing season (Figure Fig. S2; Gao et al., 2018; Li et al., 2019).

Table 2. Basic information of for the sampling trees that reaching the moisture limitation (causes the lowest deep soil moisture deficit (DSMD) of each site sampled in the field.

Sites	Plant species	Longitude	Latitude	Elevation (m)	SD (m)	Stand age (yr)	PH (m)	BD (cm)	DBH (cm)	CD (m)
Mizhi	Apple	110°10′22″	37°52′13″	1135.1	430	27	3.5±0.25	5.8±0.53	4.9±0.21	5.73±0.35
	Cropland	110°11′09″	37°52′21″	1139.6		-	-	-	-	-

	Type	Longitude	Latitude	Elevation	SD	Age	CD	PH	BD	DBH
	Black locust	110°13′58″	37°40′08″	1086.2	433	24	9.3±0.40	8.9±0.43	7.3±0.17	5.65±0.75
	Grassland	110°13′46″	37°40′16″	1076.4		-	-	-	-	-
Luochuan	Apple	109°21′59″	35°46′44″	1086.9	182	28	2.85±0.35	8.8±0.82	8.1±0.52	4.51±16.7
	Cropland	109°21′58″	35°46′38″	1083.9		-	-	-	-	-
Yan'an	Black locust	109°23′22″	36°40′02″	1325.1	412	25	14.35±0.25	9.3±0.19	7.9±0.86	5.81±0.77
	Grassland	109°22′29″	36°40′31″	1333.2		-	-	-	-	-
	Apple	107°41′01″	35°14′12″	1231.7	390	24	4.42±0.25	6.1±0.29	5.4±0.73	4.77±0.13
Changwu	Cropland	107°40′43″	35°14′20″	1232.6		-	-	-	-	-
	Black locust	107°41′45″	35°12′50″	1215.2	212	28	13.35±0.25	9.4±0.66	8.1±0.51	5.96±0.01
	Grassland	107°42′12″	35°12′36″	1219.4		-	-	-	-	-

Note: A±B, A represents the average of the three replicates of each parameter, and B represents the standard deviation. CD-Average crown diameter; PH-Average plant height; BD-Average basal diameter; DBH-Average diameter at breast height; SD-Average of straight-line distance between three trees and their controls (cropland or grassland).

2.2.3 Percentage loss of hydraulic conductivity

While collecting soil moisture, six current-year branches with 18-20 cm in length and 2-5 mm in diameter were cut off in the morning from apple and black locust trees, age of which reached the ~~degree~~ moisture limitation of ~~DSM~~DSD; and three trees with similar growth status were selected as repeats for each site. Sampled branches were sprayed with water and enclosed in humidified black plastic bags before excising to minimize water loss. After brought these branches to laboratory, we quickly cut 3-5 cm from the middle of the branch in water and immediately measured xylem hydraulic conductivity of it by using the xylem embolism measurement system (Xylem embolism meter, Bronkhorst, Mon-tigny-les-Cormeilles, France). To prevent water spilt from the branch, the initial xylem hydraulic conductivity (K_{ini}, kg s^{-1} MPa^{-1}) was measured with 1 mmol·L^{-1} CaCl$_2$ solution (pH = 6) through a filter with a filter aperture of 0.22 μm at a low pressure of 0.5-1.0 kPa. And at a high pressure of 0.2 MPa, the branch was flushed with 1 mmol·L^{-1} CaCl$_2$ solution until there was no air bubble, then the xylem hydraulic conductivity was determined again at a low pressure of 0.5-1.0 kPa and the flushing was repeated until attaining a maximum conductivity (K_{max}, kg s^{-1} MPa^{-1}). The percentage loss of hydraulic conductivity (PLC, %) was calculated by,

$$PLC = \left(1 - \frac{K_{ini}}{K_{max}}\right) \times 100 \tag{1}$$

2.2.4 Basic parameters of plantation

In order to accurately target the sample plantation, tree age was determined by using the plant growth cones (Haglof, CO300-52, Sweden) before sampling, and the crown diameter, basal diameter and diameter at breast height were measured with a tape (Table 2). The collection of plantation root samples was carried out simultaneously with the collection of soil moisture samples, and soil samples with root was stored in a sealed sample bag to minimize the loss of fine roots (≤ 2 mm), and then gently rinsed in a 100 meshes sieve, removing residual roots from the sieve with tweezers. Each fine root sample was dried at 65℃

to constant weight and weighed using an electronic balance with a precision of 0.0001 g to determine root dry weight. Finally, the fine root dry weight density (FRDWD) was calculated using the formula given by Zhao et al. (2022).

2.2.5 Soil texture and permanent wilting point

The sampling of soil properties was done simultaneously as soil moisture was sampled, and the data was showed in Table 3. Soil samples without root were air-dried, ground, and then passed through a 16 meshes sieve for measuring soil particle composition (i.e., clay, silt and sand contents) and soil pH, and through a 100 meshes sieve for determining soil organic carbon (SOC), respectively. Soil particle composition was determined by laser diffraction using a Mastersizer-2000 Laser Granularity Analyzer (Malvern Instruments, Malvern, England) (Wang et al., 2008). Soil pH was determined by the DELTA 320 pH meter. SOC was measured by using the potassium dichromate volumetric method (Fu et al., 2010), and soil organic matter (SOM) was converted from SOC (Eq. 4). Due to the challenges of collecting undisturbed soil cores within the 10 m profile, bulk density (BD) and the PWP of each region were estimated using the pedo-transfer functions (PTFs) developed by Wang et al. (2012) and Balland et al. (2008) based on the above indicators, as follows,

$$PWP_i = FC_i \left(1 - \exp \left(\frac{-0.511 \times clay_i - 0.865 \times SOM_i}{FC_i} \right) \right) \tag{2}$$

$$
\begin{aligned}
FC_i =\ & 46.481 - 4.757 \times SOC_i - 14.028 \times \log_{10}(clay_i) - 13.991 \times \log_{10}(sand_i) \\
& + 42.261 \times \log_{10}(SOC_i) - 11.763 \times sand_i^{-1} + 19.198 \times SOC_i^{-1} \\
& - 5.448 \times BD_i + 0.044 \times SOC_i^2 + 1.975 \times BD_i \times SOC_i
\end{aligned} \tag{3}
$$

$$SOM_i = SOC_i \times 1.724 \tag{4}$$

$$
\begin{aligned}
BD_i =\ & 1.8284 + 0.0429 \times \log_{10}(clay_i) + 0.0205 \times clay_i^{0.5} - 0.0125 \\
& \times \cos(clay_i) - 0.0061 \times silt_i + 0.0001 \times silt_i \times SG - 0.0098 \times SG \\
& - 0.0071 \times SOC_i - 0.0505 \times SOC_i^{0.5} + 0.0002 \times SOC_i^2
\end{aligned} \tag{5}
$$

where FC is field capacity, %; SOC and SOM are soil carbon content and soil organic matter, g kg^{-1}; BD is the soil bulk density, g cm^{-3}; clay, silt and sand are clay, silt and sand content, %, respectively; SG is slope gradient at each sample location, °; and i represents the i_{th} soil depth.

Table 3. Basic soil properties of field sampling sites.

Sites	Plant species	Soil type	Clay	Silt	Sand	Soil organic metter (g kg^{-1})	Bulk density (g cm^{-3})	pH
Mizhi	Apple	Cultivated loessial soils	15.5	24.3	60.2	2.94	1.28	7.64
	Cropland	Cultivated loessial soils	14.9	25.1	60.0	2.33	1.29	8.44
	Black locust	Cultivated loessial soils	13.6	25.0	61.4	3.09	1.28	8.03
	Grassland	Cultivated loessial soils	13.8	25.4	60.8	2.35	1.29	8.36
Luochuan	Apple	Dark loessial soils	21.5	37.1	41.4	4.62	1.31	7.54
	Cropland	Dark loessial soils	22.2	38.5	39.3	4.38	1.33	8.17
Yan'an	Black locust	Cultivated loessial soils	18.1	33.1	48.8	4.87	1.29	8.07
	Grassland	Cultivated loessial soils	19.6	31.5	48.9	4.43	1.30	8.53

	Apple	Dark loessial soils	24.6	38.7	36.7	4.76	1.31	7.35
Changwu	Cropland	Dark loessial soils	25.8	38.7	35.5	4.35	1.32	8.21
	Black locust	Dark loessial soils	22.9	38.2	38.9	5.01	1.29	7.96
	Grassland	Dark loessial soils	22.7	38.4	38.9	4.26	1.31	8.23

Note: Sampling depth of basic soil properties, including soil particles (which was divided into clay (<0.002 mm, %), silt (0.002~0.02 mm, %) and sand (0.02~2 mm, %) according to the international soil particle classification standard), soil organic carbon, and pH was 10 m for different plant species, and the average values of these parameters on different soil layers are presented here. The soil bulk density presents the average value of 1 m soil profile.

2.2.6 Meteorological parameters

The precipitation, air temperature, and relative humidity of different regions were from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land reanalysis (hereafter ERA5-Land) data, and the accuracy of which has been verified by Araújo et al. (2022). Based on the above meteorological data, vapor pressure deficit (*VPD*, kPa) was calculated by using Eq.6.

$$VPD = 0.61078 \times e^{\frac{17.27 \times T_a}{T_a + 237.3}} \times \left(1 - RH\right) \tag{6}$$

Wwhere T_a is air temperature, °C; and *RH* is relative humidity, %.

2.3 Data analysis

2.3.1 Meta-analysis

In a traditional meta-analysis, the mean values of the treatment and control with their standard deviations or standard errors are 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, the following unweighted meta-analysis approach was adopted (Li et al., 2021b).

$$RR = Ln(X_e / X_C) \tag{7}$$

where response ratio (*RR*)RR is a unit-free index with positive and negative values indicating either increasing or decreasing soil moisture in response to changes in planted tree ageplanted trees' growth,. and X_e and X_c are values of soil moisture under trees and controls for each study, respectively. The soil depth interval analyzed was 200 cm as mentioned in Section 2.1.2. We use a 95% confidence interval (CI) Toto test thesignificance of differences between soil moisture and *RR* statistical difference between the *RR* of soil moisture and zero, a 95% confidence interval (CI) was used. A previously described method (Deng et al., 2016), was used to calculate the 95% CI, the calculation methodas of 95% CI shownshowed as in Eqs. 8 and 9,

$$SE_{total} = \sqrt{\frac{V_s}{N}} \tag{8}$$

$$95\% CI = 1.96 \times SE_{total} \tag{9}$$

Wwhere SE_{total} is the standard error of RR, and V_s and N are the variances of RR and the number of observations, respectively.

In this study, the statistical difference between the RR of soil moisture and zero was considered significant if the 95% CI did not include zero, and the differences were not considered significant if the 95% CI include zero.

2.3.2 Quantitative index for moisture limitationdegree limitation of soil desiccation

The effect of different deep-rooted planted trees RWU on soil moisture was expressed as soil moisture deficit (SMD), which is the relative difference in soil moisture for given trees and adjacent cropland/grassland. Due to root distribution of the latter is too shallow (<2 m) to influence the change of DSM (Gao et al., 2014; Zhu et al., 2016; Gao et al., 2022), thus, the soil moisture of grassland/farmland measured simultaneously with that of plantation can be used as background value to eliminate the influence of climate difference, the and the $SMD_{j,k}$ calculation method as shown in Eq. 10), which could remove the interference of precipitation differences in different sampling years. Among them, the SMD of the soil layer below 2 m is the deep soil moisture deficit (DSMD). In order to compare the difference between the degreeDSMDlimitation of plantationssoil desiccation and their PWP, the SMD corresponding to PWP (SMD_PWP$_{j,k}$) along the soil profile was calculated by Eq. 11. When the $SMD_{j,k}$ corresponding to DSM is very close to SMD_PWP$_{j,k}$ suggests that the consumption of DSM by trees has reached moisture limitation.

$$SMD_{j,k} = \frac{SMC_{j,k} - SMC_{0,k}}{SMC_{0,k}} \tag{10}$$

$$SMD_{pwp,k} = \frac{PWP_k - SMC_{0,k}}{SMC_{0,k}} \tag{11}$$

$$SMD\_PWP_{j,k} = \frac{PWP_{j,k} - SMC_{0,k}}{SMC_{0,k}} \tag{11}$$

where $SMC_{j,k}$ and $SMC_{0,k}$ $PWP_{j,k}$ represent soil moisture content and permanent wilting point in the kth layer of the jth plantations and in the kth layer of the control (cropland or grassland), %, respectively; $SMC_{0,k}$; indicates soil moisture content in the kth layer of the control (cropland or grassland)and PWP_k represents the PWP in the kth layer, %.

2.3.3 Quantitative index for depth limitation of soil desiccation

The paired sample t-test in SPSS was used to analyze the significance significant difference of soil moisture between plantations and their controls. Three duplicate values were taken for each plantation and its control per site, and the straight-line distance between them was less than 500 m. If the difference of soil moisture content in the plantation and its' control becomes not statistically significant ($p>0.05$) with the soil layer deepening, the consumption of DSM by plantations will be considered to have reached the depth limitation. Conversely, it indicates that the maximum root water uptake depth has not been reached when the difference is always significant ($p<0.05$). When the significant difference becomes insignificant ($p>0.05$)

2.3.4 Statistical analysis

Redundancy analysis (RDA) was performed to evaluate the contributions of environmental factors to SMD and soil moisture

using Canoco 5 (Microcomputer Power Ithaca, New York, USA). Least significant difference (LSD) *post-hoc* tests in SPSS

22.0 software package (SPSS 22.0, SPSS Institute Ltd., USA) was used to analyze the significant differences in *PLC* of current-

year branches in planted trees, $\alpha = 0.05$ was considered statistically significant. Origin 2021 software (OriginLab Corporation,

USA) was used to draw the figures.

3 Results

3.1 Soil moisture under planted trees of the different ages

The soil moisture under apple orchards (APO) and black locust forest (BLF) varied greatly with tree age across the entire soil

layer (Fig. 2). With an increase in tree age, the negative effect of APO (0-21 m soil layer) and BLF (0-10 m soil layer) growth

on deep soil moisture (DSM) increased first and then tended to become stable. Specifically, the negative effect value of DSM

(4-10 m) under BLF older 30 years decreased by 17.4% compared with 20-30 years. Thus, the tree age at which the two

plantations had a~~n extreme~~ biggest effect on DSM appears to be between 20 and 30 years. And then, plantations between this

age range were regarded as the main subjects when analyzed the moisture and depth limitations of DSD for planted trees in

Sections 3.2 and 3.3.
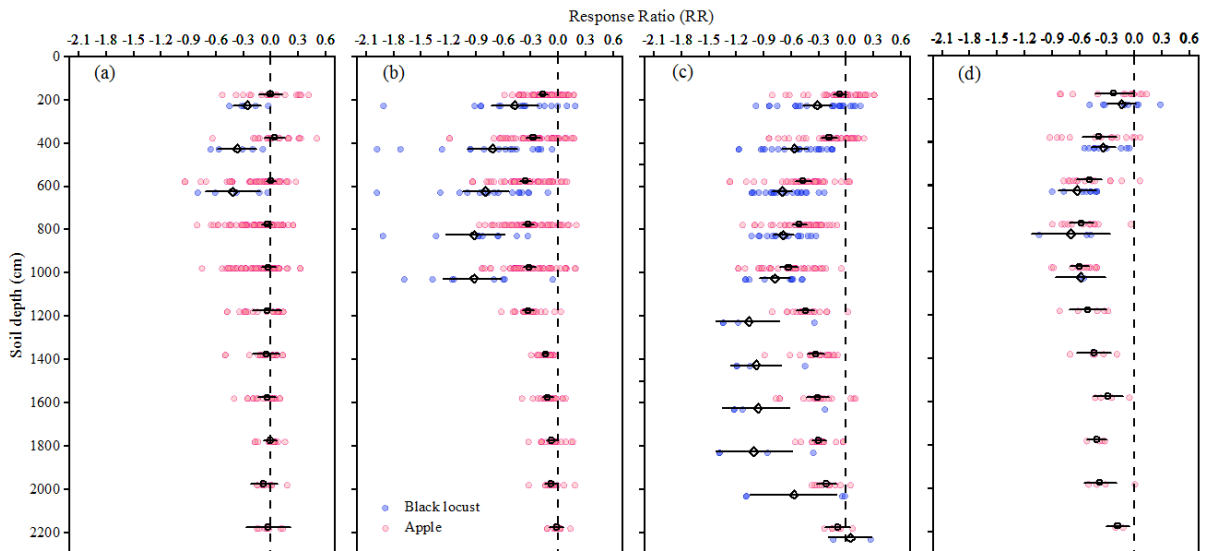
Figure 2: Mean effect sizes indicating the mean value of response ratio (*RR*, a unit-free index with positive or negative value means soil moisture increases or decreases with the older of plantations) of soil moisture response to planted trees' growth ~~with different age classes~~ on the Loess Plateau are divided into: (a) tree age <10 year, (b) 10 year ≤ tree age<20 year, (c) 20 year ≤ tree age<30 year, and (d) tree age ≥ 30 year. The vertical black dotted lines indicate *RR*=0. Blue and red dots, which involves 11980 literature extraction data and 4200 field sampling data, represent black locust forests and apple orchard *RR*s, respectively~~,~~; diamonds and circles represent the mean *RR* of black

locust and apple orchard, respectively~~.~~; and the error bars represent 95% CI.

3.2 Limitation~~s~~ of ~~DSM~~ DSD for planted trees

The DSM under a given tree species can vary largely among different years, even ~~if~~ at the same age, due to varying annual precipitation. ~~Taken the 15-year-old APO in Changwu for~~ For example, the DSM of 15-year-old APO in Changwu varied greatly ~~in~~across different sampling years (Fig. 3a). To account for climate differences between sampling years, we use ~~S~~soil moisture deficit (SMD), which is defined as the relative difference ~~of~~in soil moisture ~~under~~between the given trees and nearby controls~~, was used to eliminate the effect of climate differences in various sampling years~~. ~~Here,~~ We use the DSM of control adjacent to the plantation~~served~~ as the background soil moisture, ~~which~~as it is not influenced by root water extraction ~~due from annual crops to~~with the shallow (<100 cm) roots.~~of annual crops; hence t~~The DSM in adjacent control can be thus used to reflect local annual precipitation. We found that variation coefficient (CV) of deep soil moisture deficit (DSMD) (Fig. 3b) was lower than that of DSM, thus, DSMD was used for the following in-depth analyses.
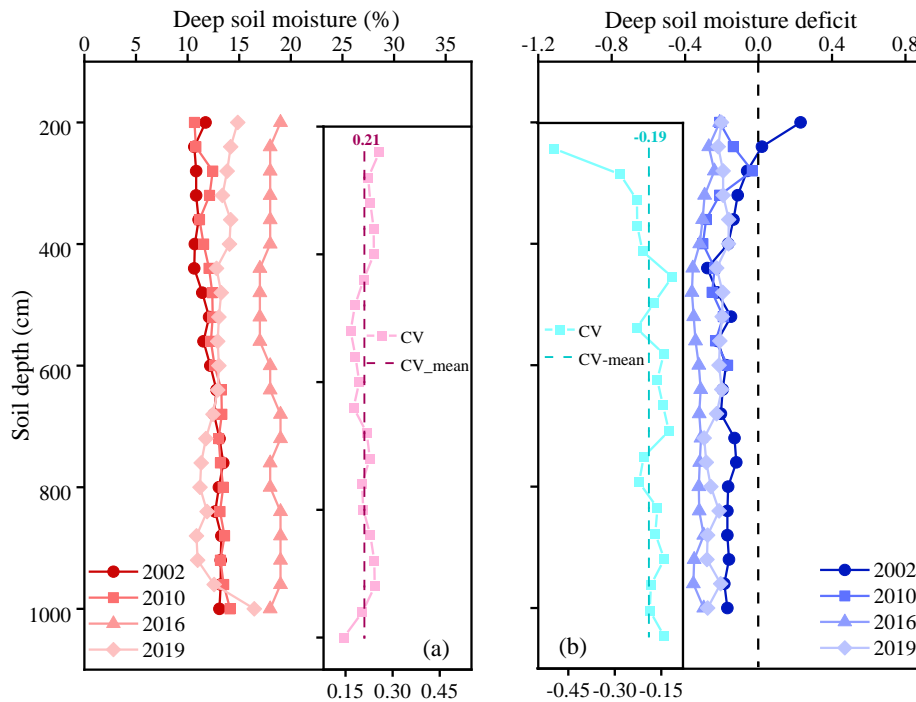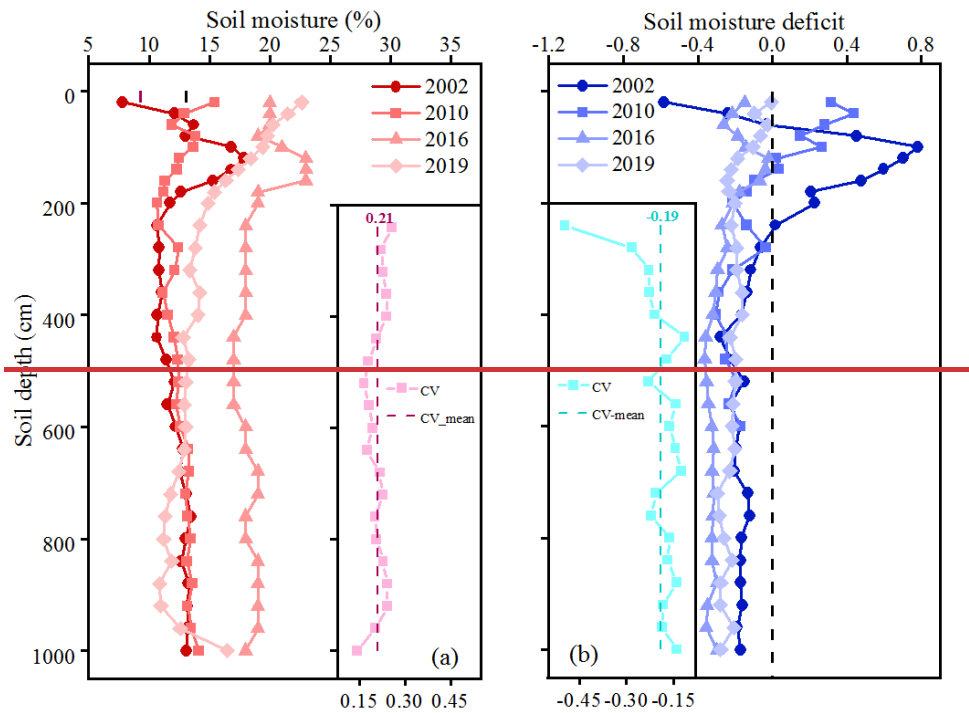
Figure 3: Distribution of deep soil moisture (a) and deep soil moisture deficit (b) ~~in~~ of 15-year-old apple orchards in Changwu in 2002, 2010, 2016 and 2019, which is all based on literature extraction data. The variation coefficient (CV) of soil moisture and soil moisture deficit below 2 m are shown in the small figures, the dashed lines of which represent the mean the mean values of the CV for deep soil moisture and deep soil moisture deficit, respectively.

3.2.1 ~~Degree~~ Moisture limitation of ~~DSM~~DSD

Combined with literature extraction (Fig. 4a and b) and measured (Fig. 4c-f) data to reveal the moisture limitation of the DSD. The DSMD fluctuation in APO over 19 years was relatively stable in Changwu, Luochuan and Mizhi (Fig. 4a, b, c). Interestingly, with the increase in tree age, there was the lowest DSMD of APO in different climate zones, and tree age between 24 and 28 years was associated with the lowest DSMD in different regions. After reaching the lowest value, apple trees can no longer extract water from the deep soil. Notably, although there were differences in soil moisture among different regions and tree species (Fig. S3), the lowest value of DSMD in three regions fluctuated around -0.6, which was very close to the DSMD value corresponding to the local PWP. In addition, DSMD of the BLF in the Changwu, Yan'an and Mizhi regions was similar to that in APO (Fig. 4d, e, f). Namely, the lowest values of DSM consumption were same as that of APO ~~The consumption of DSM reached the same lowest value~~ in different regions. This suggests that PWP is a good indicator of the ~~degree~~ moisture limitation of ~~DSM~~DSD, irrespective of tree species and site. It is worth noting that, compared with APO, the variation scope of DSMD in Changwu and Yan'an decreased significantly with the age of the BLF, which may be due to the extreme rainfall in 2021, which recharges DSM in the BLF (Table 1).
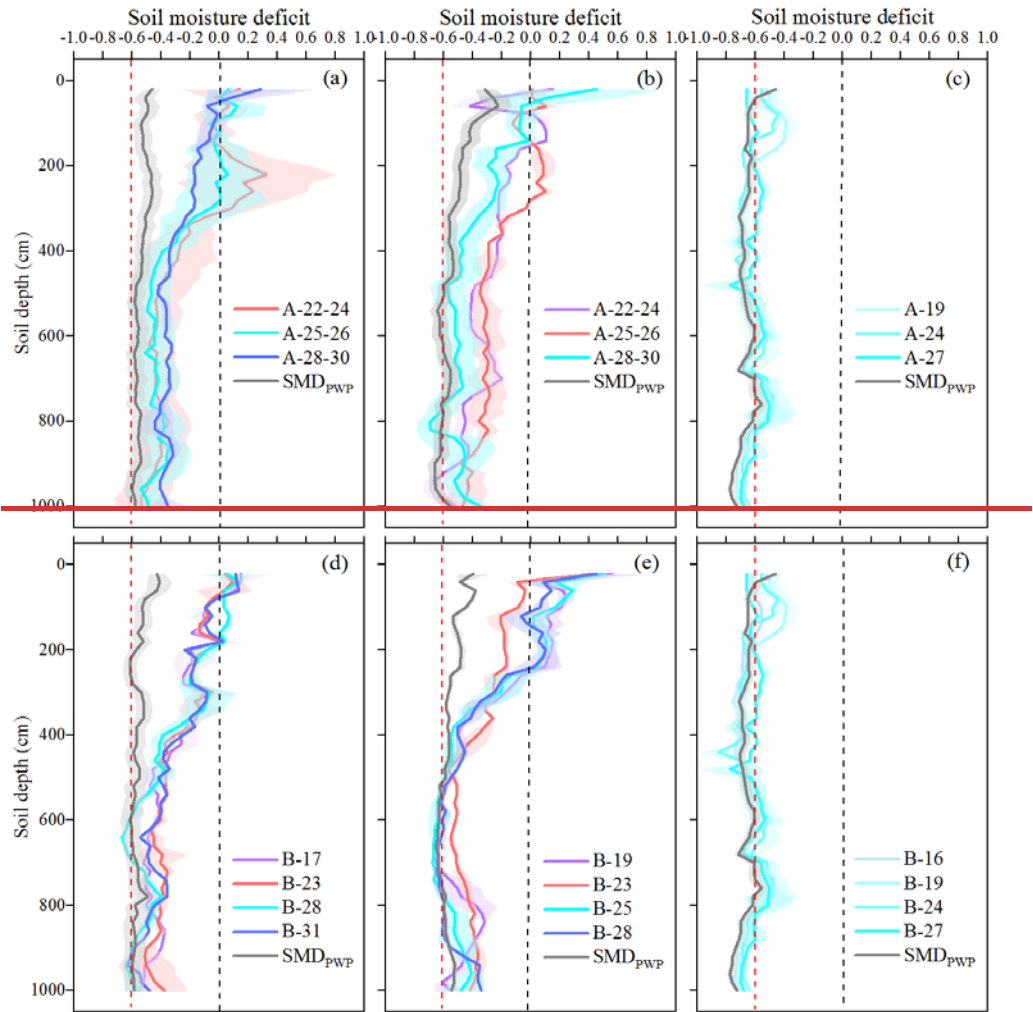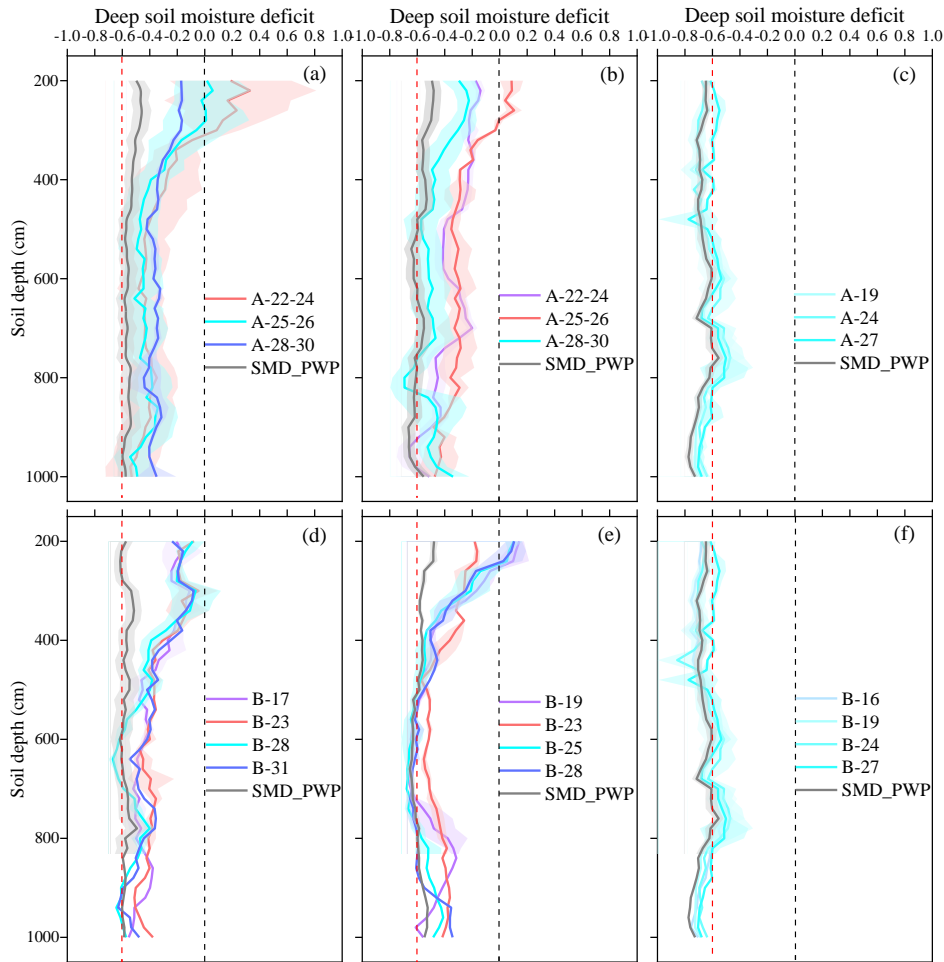
Figure 4: ~~Deep~~ Ssoil moisture deficit (~~D~~SMD) distribution under apple orchards of different ages in Changwu (a), Luochuan (b) and Mizhi (c); and SMD under black locust forests of different ages in Changwu (d), Yan'an (e) and Mizhi (f). The capital letters A and B in the legend represent apple and black locust, respectively, and the numbers after the letters represent tree age, for example, A-22 represents 22-year-old apple. (a) and (b) come from data extracted from literature, while (c)-(f) are both field measured data. In order to reduce the randomness caused by different sampling years and locations between ~~of~~ the extracted data, the data for apple trees with similar ages in Changwu (a) and Luochuan (b) were combined. The gray line indicates SMD at permanent wilting point (SMD_PWP) in each sampling site, and the red dashed line indicates the SMD equal to -0.6. The shaded portion corresponding to each line represents the positive and negative values of the standard deviation.

3.2.2 Depth limitation of ~~DSMD~~DSD

Based on the measured and literature data, we analyzed the water consumption depth limit of plantations in different regions after the ~~soil desiccation degree~~ moisture limitation of DSD was reached (Fig. 5). With an increase in depth, the soil moisture of plantations was close to or even higher than that of the control, except for the BLF in Mizhi. Thus, we calculated the difference significance of soil moisture ~~SM~~ between the plantations and control using the paired sample t-test, treating the points with no significant ($p>0.05$) soil moisture difference as the maximum water uptake depth. And it reached 18.0-22.0 m for APO at different sites; and 18.4-18.8 m for BLF in Changwu and Yan'an while in Mizhi it was deeper than 25 m.
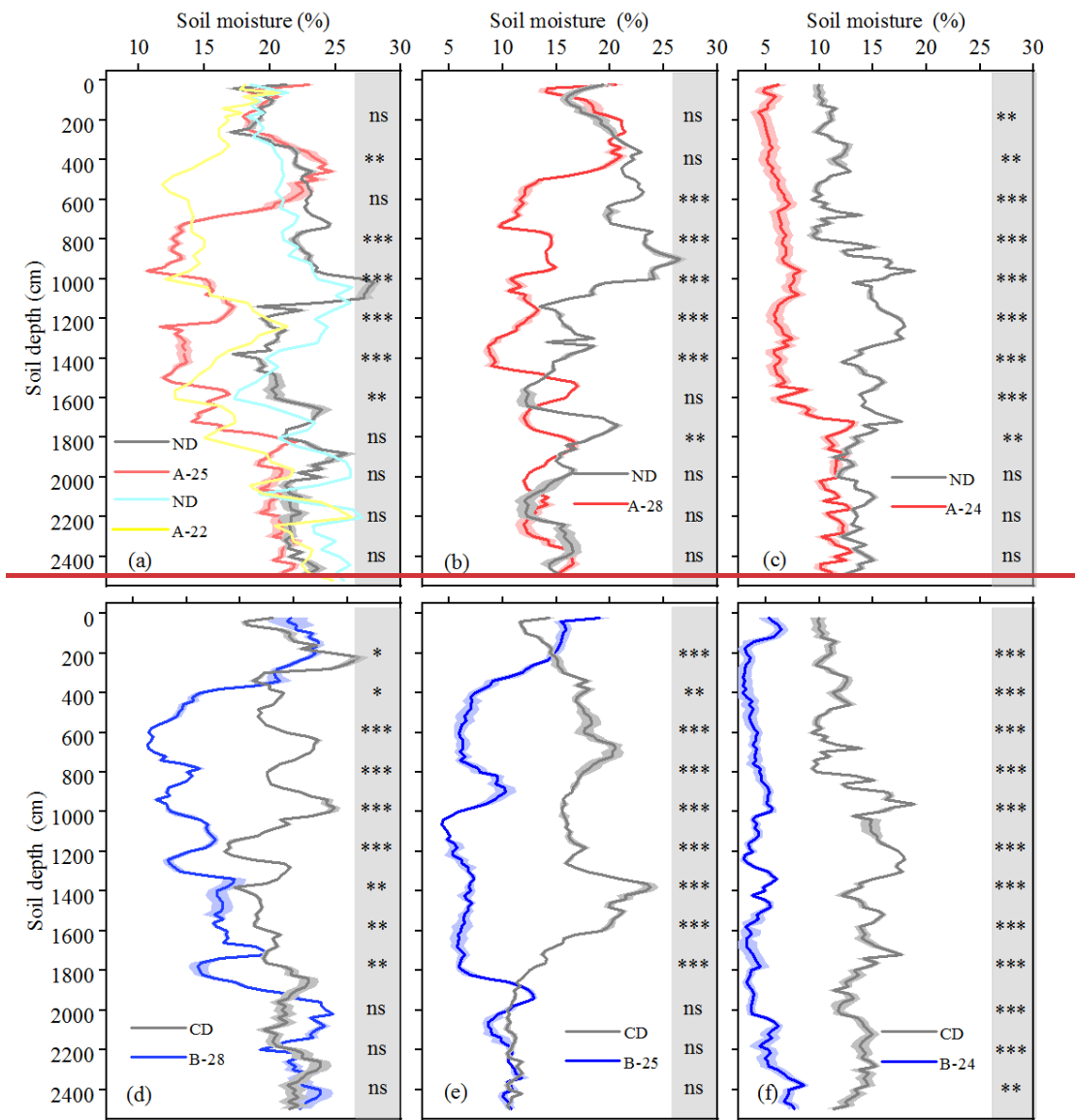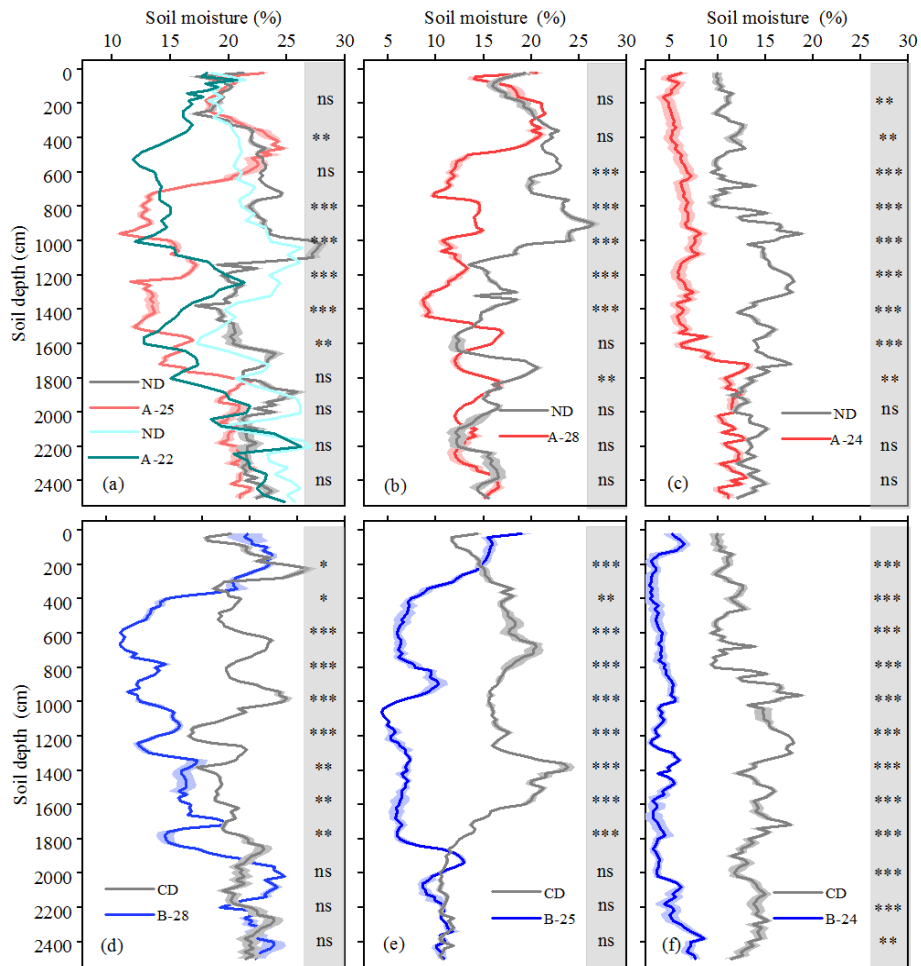
Figure 5: Dynamic distribution of maximum water absorption depth after reaching the ~~degree~~ moisture limitation of deep soil desiccation. The data of 22-year-old apple and cropland (dark green) in (a) belong to literature extraction data, and other data are field measured data.~~(a) 22- (literature data) and 25-year-old (measured data) apple in Changwu; (b) and (c) indicate 28- and 24-year-old apple in Luochuan and Mizhi, respectively; (d), (e) and (f) indicate 28-, 25- and 24-year old black locust in Changwu, Yan'an and Mizhi, respectively~~ The capital letters A and B in the legend represent apple and black locust, respectively, and the numbers after the letters represent tree age, for example, A-22 represents 22-year-old apple. (a) and (d) indicate Changwu; (b) and (e) indicate Luochuan and Yan'an, respectively; (c) and (f) indicate Mizhi. Gray line represents soil moisture of grassland (CD) or farmland (ND). ***, **, * and ns in the gray bands indicate the significance level of measured data obtained by the paired sample *t*-test for *p*< 0.001, *p*< 0.01, *p*< 0.05 and no significant differences, respectively. The shaded portion corresponding to each line represents the positive and negative values of the standard deviation.

3.3 Effect of factors on the limitations

Based on all extracted and measured data, including SMD, soil moisture ~~(SM)~~, soil texture (clay, silt), and root biomass (FRDWD) along with ERA5-Land meteorological data (MAP, mean annual temperature (MAT), relative humidity (RH), vapor pressure deficit (VPD)), redundancy analysis (RDA) was used to analyze the key factors that determine the ~~degree~~ moisture and depth limitation~~s~~ of ~~DSM~~ DSD (Fig. 6). The RDA showed that the explanatory variables (soil properties, meteorological variables and plant characteristic) account for 67.7% of the total variation of ~~SM~~ soil moisture and SMD. SMD was significantly (*p*<0.01) positively correlated with VPD, and negatively correlated with clay, silt, RH, MAT, and MAP (Fig. 6a). The clay, VPD, silt, RH, and FRDWD provided statistically significant (*p*<0.01) explanations for the distribution of SMD and

345 ~~SM~~ soil moisture (Fig. 6b), the clay content determines the lower limit of water that plants can uptake through its adsorption of water molecules. Thus, soil texture and climatic conditions were the main factors leading to the limitations of DSD in different regions~~and clay was the most important. Thus, soil texture and climatic conditions were the main factors leading to the degree and depth limitation of deep soil desiccation in different regions~~. However, the relationship between MAP and SMD was not significant, which may be due to the MAP of each region weakened the differences of precipitation in each sampling

350 year.
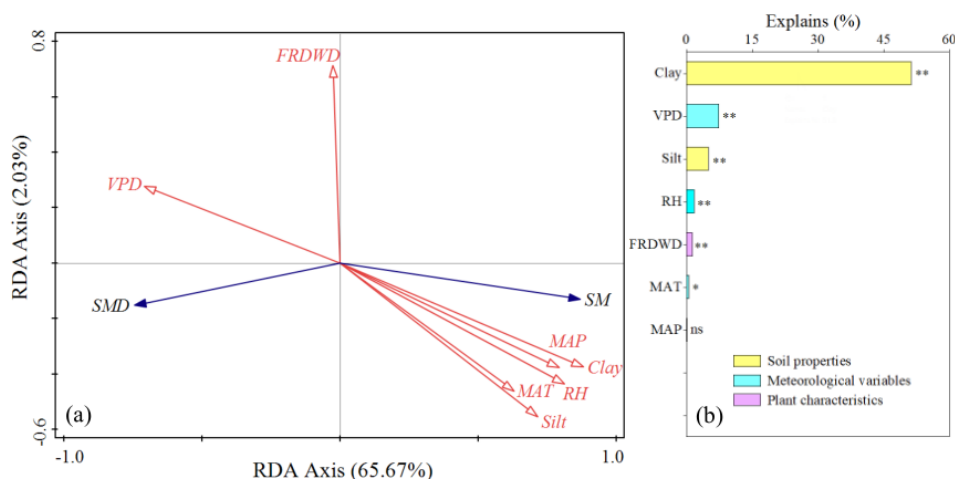
Figure 6: (a) the redundancy analysis (RDA) of "response variable (soil moisture deficit (SMD), soil moisture (SM)) and environmental factors" is based on literature and field measured data. Descriptors (red arrows) are soil properties (clay and silt), meteorological variables (vapor pressure deficit (VPD), mean annual precipitation (MAP), relative humidity (RH), and mean annual temperature (MAT)), and plant

355 characteristic (fine root dry weight density (FRDWD)). Axis 1 (65.67%, $p<0.01$) and Axis 2 (2.03%, $p<0.01$) are shown. (b) explanation provided by of each environmental variable for the response variables. **, *, and ns following the bar chart indicate that $p<0.01$, $p<0.05$, and no significant, respectively.

3.4 Effect of the DSD limitations on hydraulic conductivity

~~In order t~~To further explore how the moisture and depth limitation~~s~~ ~~caused by~~of ~~deep soil desiccation~~DSD affects the hydraulic

360 conductivity ~~of~~in plants, we compared hydraulic conductance of branches ~~of~~from plantation trees at different sites in relation to the ~~degree~~moisture and depth limitation~~s~~ of ~~deep soil desiccation~~DSD ~~at different sites ~~(Fig. 7). The *PLC* was higher than 50% for all tree species and regions. ~~Furthermore~~Additionally, the *PLC* of black locust in Mizhi was significantly higher than that in other places ($p<0.05$), ~~which indicates ~~indicating that the risk of mortality ~~of~~for black locust in Mizhi is greatest when ~~deep soil desiccation~~DSD reaches ~~degree ~~the moisture and depth limitation thresholds.
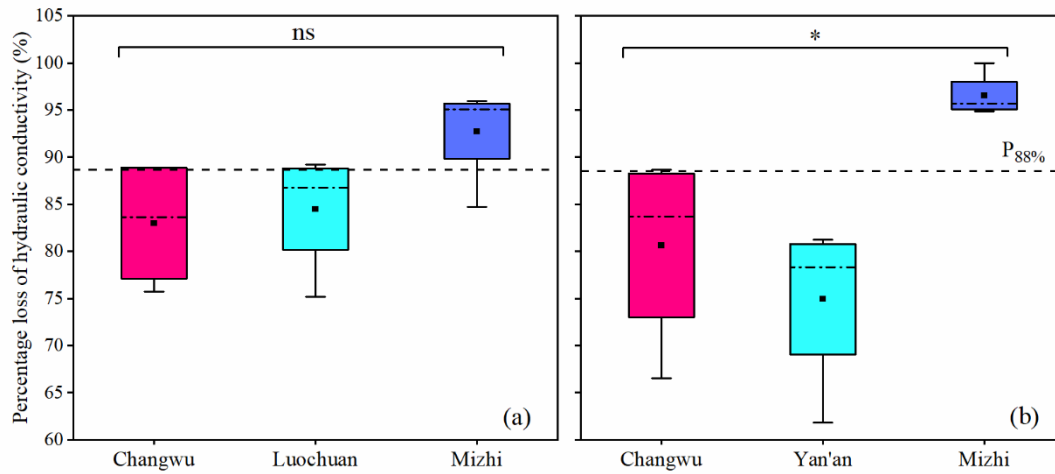
Figure 7: Differences in percentage loss of hydraulic conductivity of annual branches of apple (a) and black locust (b) measured in different regions (Changwu, Luochuan, Yan'an, and Mizhi). * and ns indicate that the significance level is *p*<0.05 and there is no statistically significant difference, respectively.

4 Discussion

4.1 The mechanism underlying for the ~~degree~~ moisture and depth limitations

Although DSM (>200 cm) decreased with an increase of planted trees age, and even reached the lowest limitation, shallow soil moisture (<200 cm) did not change significantly (Fig. 2 and 4). This is ascribed to surface or shallow layer soil moisture, which is usually greatly influenced by rainfall infiltration and evapotranspiration~~,~~. ~~while~~ However, DSM is often in a negative balance, being consumed by deep-rooted trees and unable to be replenished for a long time (Fang et al., 2016; Gao et al., 2020). As the critical water resource for plants to cope with extreme droughts, DSM has reached its lowest limitation, seriously threatening the sustainability of tree growth under future climate conditions.

In our study, the lowest DSMD fluctuated around -0.6 irrespective of tree species and site (Fig. 4). This contradicts the assumption that ~~degree~~ moisture limitation of ~~deep layer soil desiccation~~DSD ~~limitation~~ is dependent on tree species, which is mainly because the climate conditions and soil texture differ between regions (Fig. 6). The precipitation in the LOP showed a decreasing trend from southeast to northwest, the clay content also follows this trend (Wang et al., 2011). When the soil texture is coarser, it has a larger matric potential or smaller suction under the same soil moisture conditions (Dexter, 2004), resulting in a larger matric potential gradient around fine roots in areas with less rainfall (LRAs), thus effectively enhance soil water availability. Based on the results of this study and opinions from literature, Fig. 8 shows the mechanism by which plants regulate the moisture and depth limitations of DSD. Soil water potential, when the soil hydraulic conductivity (K_s) drops to lower values than the root hydraulic conductivity (K_r), can be regarded as the critical soil matric potential, at which the soil begins to limit the water flux in the soil-plant continuum (Fig. 8; Cai et al., 2022). Thus, the soil with coarser texture has higher K_s when soil starts limiting trees' RWU, causing the corresponding K_r in LRAs to be higher than that in areas with more rainfall

(MRAs) by allocating more biomass to fine root (Fig. 8). In addition, VPD in the LRAs is relatively high, and the transpiration traction force increases (Will et al., 2013; Hayat et al., 2019), causing a larger water potential gradient between roots and leaves under the same soil moisture, and thus driving roots to absorb more moisture. Thus, although the physiological and growth characteristics of apple and black locust in different regions were obviously different (Table 2; Fig. 7), the lowest DSMD of all tree species at each site both fluctuated around-0.6. This indicates that the lowest amount of soil moisture absorbed by plants is determined by VPD and soil water availability, which is mainly affected by the precipitation and soil texture (Wu et al., 2015). Notably, the lowest DSMD was very close to the DSMD value corresponding to the local PWP (Fig. 4). The reason may be that different plant species wilted at similar moisture content in soils with low clay content, although the physiological wilting of plants is both plant species and soil dependent (Torres et al., 2021). In addition, the texture down the loess profile in the same area is relatively uniform, especially in the deep (>2 m) soil profile, which is less affected by surface biochemical processes. Therefore, the temporal and spatial variability of PWP of deep soil is small, which is one of the reasons why the lowest DSMD was close to DSMD at the local PWP. In conclusion, our study confirms that PWP is a good indicator of the ~~degree~~ moisture limitation of ~~DSM~~ DSD for the tree species examined. These findings provide important ~~reference~~ information for the sustainable development of plantations on the LOP.

After soil ~~moisture~~ water use in the profile reaches the ~~degree~~ moisture limitation, plants extend their roots into the deep soil to expand their ~~water~~ water-hunting range during the dry season (Fig. 8; Ivanov et al., 2012). Our result~~s~~ ~~shows~~ show that the maximum RWU depth reached 18.0-22.0 m for APO at different sites, and 18.4-18.8 m for BLF in Changwu and Yan'an, while in Mizhi it was more than 25 m (Fig. 5). The above- and under-ground biomass allocation mechanism of plantation~~s~~ determines ~~its'~~ their root~~-~~to-~~-~~shoot ratios (Mokany et al., 2005)~~., thus~~Thus, the FRDWD of the plantation indicates that their water absorption range can only reach 18.0-22.0 m. Furthermore, roots can no longer extract moisture after reaching a certain depth, probably because the hydraulic path of water transport in the soil-plant-atmosphere continuum ~~SPAC~~ is too long and the water potential gradient is insufficient to drive water transport upwards (Ahmed et al., 2014). However, the water consumption depth of BLF in Mizhi was more than 25 m. Wang et al. (2009) also found that the maximum water consumption depth of the artificial *Caragana microphylla* forest in the semi-arid region was 22.5 m, ~~which indicates~~ indicating that chronic water shortages encourage~~s~~ planted trees to absorb water by growing roots downwards in the semi-arid region. Thus, the RWU depth of plantations in other regions has reached its maximum depth, even though BLF in LRAs can obtain water through root extension.
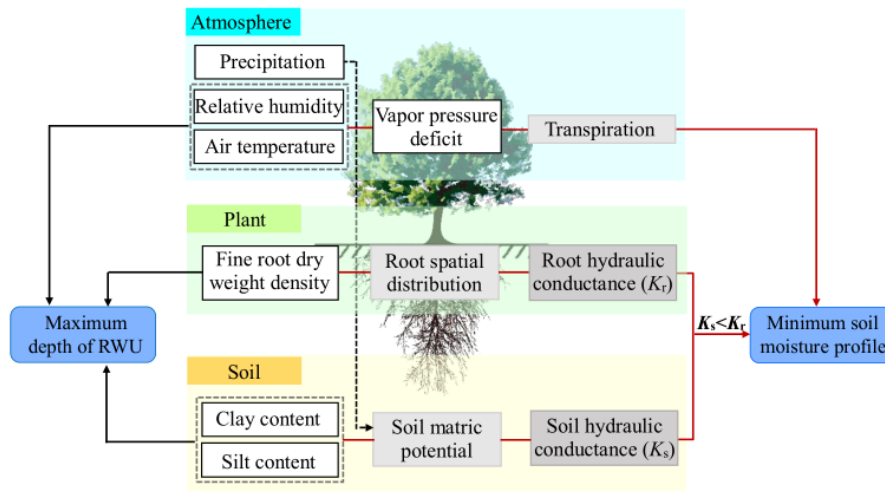
Figure 8: Regulatory mechanism of the extreme influence of root water uptake (RWU) on deep soil moisture based on literature and field measured data. The parameters of soil-plant-atmosphere continuum (SPAC) in the white rectangle are quantized, the gray rectangle represents the intermediate variables that the parameters of SPAC cause the result of minimum soil moisture profile (~~degree~~ moisture limitation), the blue rounded rectangle represents the limitation of ~~degree~~ moisture and maximum depth of RWU (depth limitation). The red arrow, the black solid arrow and the black dotted arrow indicate that the parameters of SPAC have a significant ($p<0.05$) effect on the ~~degree~~ moisture limitation, have an influence on the depth limitation, and have an indirect effect on two results, respectively.

4.2 Effects of the limitations on the hydraulic conductivity of plantations

The result showed that branches xylem of similar aged trees suffered embolism to different degrees when the moisture and depth limitations of DSD reached (Fig. 7). This is consistent with the hypothesis that the hydraulic conductivity of planted trees can be greatly reduced by severe DSD. The reason for this result is that dried soil seriously restricts the process of root water uptake, and water absorption of trees is difficult to meet the needs of aboveground metabolism, resulting in the interruption of the water column in the xylem vessels during prolonged dry periods, and thus *PLC* increases (McDowell et al., 2018; Yang et al., 2022). Subsequently, the leaf stomata close to prevent hydraulic failure as DSM approaches PWP. How long can the planted trees survive after this depends solely on the water pools of themselves and their tissues' tolerance for drought stress (McDowell et al., 2022). Nevertheless, even though DSM of all regions both have been close to the local PWP, *PLC* varied greatly between different climate zones (Fig. 7), mainly caused by the difference of precipitation about time and amount for restoring shallow soil moisture. This suggests that the decrease in xylem hydraulic conductivity caused by the limitations of DSD may be repaired after entering the rainy season for the studied species plantations in Changwu and Yan'an. The *PLC* of black locust plantation in Mizhi, however, was significantly ($p<0.05$) higher than that of other regions, and restoration of embolism was more difficult due to limited rainfall supply. Thus, the embolism in the conduit accumulated continuously as the water pool became exhaustible causing the top tip of the distal water supply began to die due to hydraulic failure of tissues (Fig. S4; Arend et al., 2021). This indicates that mature (>24 year) plantations on the LOP are already facing a great risk of dieback and even death in semi-arid regions similar to Mizhi. ~~During prolonged dry periods, deep-rooted trees often rely on DSM to avoid drought stress (Ding et al., 2021; Wang et al., 2021). However, deep soil desiccation reduces the moisture supply capacity of the soil, which can lead to xylem embolism, and even tissue dehydration and, consequently, hydraulic failure (Yang~~

et al., 2022). At the same time, water stress leads to stomatal closure, and thus photosynthesis and other physiological processes are inhibited (McDowell et al., 2018). When the xylem hydraulic conductance drops below a certain threshold, plant may occurs dieback or even die completely due to the combined occurrence of hydraulic failure and carbon starvation (Arend et al., 2021). Our results show that branches of similar aged trees that causes the DSM to reach the degree and depth limitation suffered embolism to different degrees (Fig. 7), which is consistent with the hypothesis about the hydraulic conductivity of planted trees. Furthermore, the embolism of trees is more severe LRAs because higher VPD and lower water availability increase the risk of embolism (Breshears et al., 2013). This indicates that mature (>24 year) plantations on the LOP are already facing a great risk of dieback and even death due to embolism, especially in semi-arid areas.

4.3 Limitations and practical implications

Sampling the same tree species in different regions cannot guarantee the same tree age due to Affected by objective factors such as differences in the time of planting and vegetation succession in different regions, sampling of the same tree species in different regions cannot guarantee the same tree age. In aAdditionally, the collection ofcollecting large amounts of DSM data requires a great deal of resources, and the number of samples available in this study is limited. Thus, the results of this study need to be verified in-depth verified in across different tree ages and in different regions to guide vegetation management under local conditions.

Large numbers of tree deaths caused by prolonged drought are of great concern because trees fulfil play a critical ecological role and have the largest biomass and storage of carbon storage (Feng et al., 2016; Bai et al., 2021). Thus, it is essential to understand the degree moisture and depth limitations of deep-layer soil desiccationDSD for to maintaining the sustainability of vegetation restoration under future climatic drying. Our study shows that 24-28-year-old plantations, both APO and BLF, have reached the degree moisture limitation of deep-soil desiccationDSD; and the maximum DSMD is about -0.6, which corresponds to the DSMD at local PWP, irrespective of tree species and site. On the one hand, tThis confirms that PWP is a good indicator of the degreemoisture limitation of deep-layer soil desiccationDSD for the tree species examined; on the other hand,. when When the precise wilting point of deep soil in different regions is difficult to determine, the lowest DSMD (0.6) can be used as an index for to judging judge whether DSM can sustain the survival of the typical plantations on the LOP during prolonged drought. Furthermore, except for the BLF in Mizhi, all plantations have reached the depth limitation of deep-layer soil desiccationDSD,. and aAfter reaching the degree moisture and depth limitation thresholds, plantations of different sites suffer different varying degrees of embolism. Therefore, plantations of 24 years and above face the greatest risk of dieback and death in drought years or prolonged dry periods, especially in semi-arid regions like Mizhi. This study provides practical insights into the sustainable development of vegetation restoration on the LOP in under future extreme climate conditions.

5 Conclusions

Deep soil moisture (DSM) plays an important role in maintaining the survival of deep-rooted plantations during prolonged dry periods on the water-limited Loess Plateau. Our results show that the lowest deep soil moisture deficit (DSMD) was close to the ~~D~~SMD at the permanent wilting point (SMD_PWP), irrespective of tree species and site. This confirms that PWP is a good indicator of the ~~degree~~ moisture limitation of deep soil desiccation~~DSM~~ for apple and black locust trees. The corresponding maximum water consumption depth reached 18.0-22.0 m for apple trees at different sites, and 18.4-18.8 m for black locust in Changwu and Yan'an, while it was more than 25 m in the drier site of Mizhi, thus relying on the availability of DSM and the ability of deep roots to transport water. Furthermore, when the ~~degree~~ moisture and depth limitation thresholds were reached, the percentage loss of hydraulic conductivity of planted trees' branches was between 74.9% and 96.5%, indicating that dieback and tree death may occur. Our study provides insights into the management and sustainable development of revegetated sites on the water-limited regions including the Loess Plateau.

Data availability

The basic data, including extracted and measured set of soil moisture, environmental factors, and percentage loss of hydraulic conductivity of trees' branches, are available for download at https://doi.org/10.5281/zenodo.7412472.

Author contributions

XG and XZ conceived the study; NH, DG, YW and DG performed field experiments and collected the data; NH performed the analysis and prepared the first draft of the manuscript with the help of LT and LZ; XG edited and commented on the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgments

The authors thank Shaofei Wang and Min Yang for their help. This work was jointly supported by the National Natural Science Foundation of China (42125705), Natural Science Basic Research Program of Shaanxi Province (2021JC-19), the Cyrus Tang Foundation, the Shaanxi Key Research and Development Program (2020ZDLNY07-04), Shaanxi Province Key R&D Plan (2022NY-064) and Chinese Universities Scientific Fund (2452020242).

References

Ahmed, M. A., Kroener, E., Holz, M., Zarebanadkouki, M., and Carminati, A.: Mucilage exudation facilitates root water uptake in dry soils, Func. plant boil., 41(11), 1129-1137, 10.1071/FP13330, 2014.

Araújo, C. S. P. de, Silva, I. A. C., Ippolito, M., and Almeida, C. D. G. C. de: Evaluation of air temperature estimated by ERA5-Land reanalysis using surface data in Pernambuco, Brazil. Environ. Monit. Assess, 194, 381-394, 10.1007/s10661-022-10047-2, 2022.

Arend, M., Link, R. M., Patthey, R., Hoch, G., Schuldt, B., and Kahmen, A.: Rapid hydraulic collapse as cause of drought-induced mortality in conifers, PNAS, 118(16), 10.1073/pnas.2025251118, 2021.

Cao, S., Xia, C., Suo, X., Wei Z.: A framework for calculating the net benefits of ecological restoration programs in China, Ecosyst. Serv., 50(2021), 101325, 10.1016/j.ecoser.2021.101325, 2021.

Choat B., Brodribb T. J., Brodersen C. R., Duursma R. A., López R., and Medlyn B. E.: Triggers of tree mortality under drought, Nature, 558, 531–539, 10.1038/s41586-018-0240-x, 2018.

Bai, X., Jia, X., Zhao, C., and Shao, M.: Artificial forest conversion into grassland alleviates deep-soil desiccation in typical grass zone on China's Loess Plateau: Regional modeling, Agric. Ecosyst. Environ., 320 (5), 107608, 10.1016/j.agee.2021.107608, 2021.

Balland, V., Pollacco, J., and Arp, P.: Modeling soil hydraulic properties for a wide range of soil conditions. Ecol. Model., 219 (3-4), 300-316, 10.1016/j.ecolmodel.2008.07.009, 2008.

Breshears, D. D., Adams, H. D., Eamus, D., McDowell, N. G., Law, D. J., Will, R. E., Williams, A. P., and Zou, C. B.: The critical amplifying role of increasing atmospheric moisture demand on tree mortality and associated regional die-off, Front. plant sci., 4, 266-269, 10.3389/fpls.2013.00266, 2013.

Cai, G., Ahmed, M. A., Abdalla, M., and Carminati, A.: Root hydraulic phenotypes impacting water uptake in drying soils, Plant cell environ., 45 (3), 650-663, 10.1111/pce.14259, 2022.

Dexter, A. R.: Soil physical quality, Geoderma, 120 (3-4), 201-214, 10.1016/j.geoderma.2003.09.004, 2004.

Deng L., Yan W., Zhang Y., and Shangguan Z.: Severe depletion of soil moisture following land-use changes for ecological restoration: Evidence from northern China, For. Ecol. Manage., 366, 1-10, 10.1016/j.foreco.2016.01.026, 2016.

Ding, Y., Nie, Y., Chen, H., Wang, K., and Querejeta, J. I.: Water uptake depth is coordinated with leaf water potential, water use efficiency and drought vulnerability in karst vegetation, New Phytol., 229 (3), 1339-1353, 10.1111/nph.16971, 2021.

Fang, X., Zhao, W., Wang, L., Feng, Q., Ding, J., Liu, Y., and Zhang, X.: Variations of deep soil moisture under different vegetation types and influencing factors in a watershed of the Loess Plateau, China, Hydrol. Earth Syst. Sci., 20 (8), 3309-3323, 10.5194/hess-20-3309-2016, 2016.

Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü Y., Zeng Y., Li Y., Jiang X., and Wu B.: Revegetation in China's Loess Plateau is approaching sustainable water resource limits, Nat. Clim. Change, 6 (11), 1019-1022,

10.1038/nclimate3092, 2016.

Fu, B., Wang, S., Liu, Y., Liang, W., and Miao, C.Y.: Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the Loess Plateau of China, Annu. Rev. Earth Planet Sci., 45, 223-243, 10.1146/annurev-earth-063016-020552, 2016.

530

Fuchs, S., Leuschner, C., Link M. R., and Schuldt, B.: Hydraulic variability of three temperate broadleaf tree species along a water availability gradient in central Europe, New Phytol., 231 (4), 1387-1400, 10.1111/nph.17448, 2021.

Fu, X., Shao, M., Wei, X., and Horton, R.: Soil organic carbon and total nitrogen as affected by vegetation types in Northern Loess Plateau of China. Geoderma, 155 (1-2), 31-35, 10.1016/j.geoderma.2009.11.020, 2010.

535 Gao, X., Wu, P., Zhao, X., Wang, J., Shi, Y.: Effects of land use on soil moisture variations in a semi-arid catchment: Implications for land and agricultural water management, Land Degrad. Develop., 25, 163-172, 10.1002/ldr.1156, 2014.

Gao, X., Li, H., Zhao, X., Ma, W., and Wu, P.: Identifying a suitable revegetation technique for soil restoration on water-limited and degraded land: Considering both deep soil moisture deficit and soil organic carbon sequestration, Geoderma, 319 (5), 61-69, 10.1016/j.geoderma.2018.01.003, 2018.

540 Gao, X., Zhao, X., Wu, P., Yang, M., Ye, M., Tian, L., Zou Y., Wu Y., Zhang F., and Siddique K. H. M.: The economic-environmental trade-off of growing apple trees in the drylands of China: A conceptual framework for sustainable intensification, J. Clean. Prod., 296 (3), 126497, 10.1016/j.jclepro.2021.126497, 2021.

Gao, X., Li, H., and Zhao, X.: Impact of land management practices on water use strategy for a dryland tree plantation and subsequent responses to drought, Land Degrad Dev, 32, 439-452, 10.1002/ldr.3687, 2020.

545 Gao, X., He, N., Jia, R., Hu, P., Zhao, X.: Redesign of dryland apple orchards by intercropping the bioenergy crop canola (Brassica napus L.): Achieving sustainable intensification, Glob. Change Biol. Bioenergy, 14, 378-392, https://doi.org/10.1111/gcbb.12916, 2022.

Gessler, A., Bottero, A., Marshall, J., Arend M.: The way back: recovery of trees from drought and its implication for acclimation, New Phytol., 228(6), 1704-1709, 10.1111/nph.16703, 2020.

550 Griscom, B., Jackson, R. B., Konijnendijk, C., Luyssaert, S., Friess, D., Rudee, A., and Seddon, N.: Trees as Nature-Based Solutions, One earth, 2, 387-389, 2020.

Hayat, F., Ahmed, M. A., Zarebanadkouki, M., Cai, G., and Carminati, A.: Measurements and simulation of leaf xylem water potential and root water uptake in heterogeneous soil water contents, Adv. Water Resour., 124, 96–105, 10.1016/j.advwatres.2018.12.009, 2019.

555 Hou, Q., Huang X., Han, S., Zhang, X.: The status of soil moistures and nutrients in small-old-tree stands and impact on tree growth (In Chinese), 5(2), 75-83, Journal of Soil Water Conservation, 10.13870/j.cnki.stbcxb.1991.02.012, 1991.

Ivanov, V. Y., Hutyra, L. R., Wofsy, S. C., Munger, J. W., Saleska, S. R., Oliveira, R. C. de, and Camargo, P. B.: Root niche

separation can explain avoidance of seasonal drought stress and vulnerability of overstory trees to extended drought in a mature Amazonian forest, Water Resour. Res., 48 (12), 12507, 10.1029/2012WR011972, 2012.

560   Jia, X., Shao, M., Zhu, Y., and Luo, Y.: Soil moisture decline due to afforestation across the Loess Plateau, China, J. Hydrol., 546, 113-122, 10.1016/j.jhydrol.2017.01.011, 2017.

Jia, X., Shao, M., Wei, X., Zhu, Y., Wang, Y., and Hu, W.: Policy development for sustainable soil water use on China's Loess Plateau, Sci. Bull., 65, 2053-2056, 10.1016/j.scib.2020.09.006, 2020.

Li, B., Li, P., Zhang, W., Ji, J., Liu, G., and Xu, M.: Deep soil moisture limits the sustainable vegetation restoration in arid and

565   semi-arid Loess Plateau, Geoderma, 399 (12), 115122, 10.1016/j.geoderma.2021.115122, 2021a.

Li, B., Zhang W., Li S., Wang J., Liu G., and Xu M.: Severe depletion of available deep soil water induced by revegetation on the arid and semiarid Loess Plateau, For. Ecol. Manage., 491, 119156, 10.1016/j.foreco.2021.119156, 2021b.

Li, H., Ma, X., Lu, Y., Ren, R., Cui, B., and Si, B.: Growing deep roots has opposing impacts on the transpiration of apple trees planted in subhumid loess region, Agric. Water Manage., 258, 107207, 10.1016/j.agwat.2021.107207, 2021.

570   Li, H., Si, B., Wu, P., and McDonnell, J.: Water mining from the deep critical zone by apple trees growing on loess, Hydrol. Process, 33, 320-327, 10.1002/hyp.13346, 2019.

Liu, Y., Kumar, M., Katul, G. G., Feng, X., and Konings, A. G.: Plant hydraulics accentuates the effect of atmospheric moisture stress on transpiration, Nat. Clim. Change, 10 (7), 691-695, 10.1038/s41558-020-0781-5, 2020.

Lobet, G., Couvreur, V., Meunier, F., Javaux, M., and Draye, X.: Plant water uptake in drying soils, Plant physiol., 164 (4),

575   1619-1627, 10.1104/pp.113.233486, 2014.

Lucia H. W., Neyde F. B. G., Renato P. de L., Cassio A. T., Lorena C. T., and Ariane L. de P.: Comparing the classical permanent wilting point concept of soil ($-15,000$ hPa) to biological wilting of wheat and barley plants under contrasting soil textures, Agric. Water Manage., 230, 105965, 10.1016/j.agwat.2019.105965, 2020.

McDowell, N., Allen, C. D., Anderson-Teixeira, K., Brando, P., Brienen, R., Chambers, J., Christoffersen, B., Davies, S.,

580   Doughty, C., Duque, A., Espirito-Santo, F., Fisher, R., Fontes, C. G., Galbraith, D., and Goodsman, D.: Drivers and mechanisms of tree mortality in moist tropical forests, New Phytol., 219 (3), 851-869, 10.1111/nph.15027, 2018.

McDowell, N.G., Sapes, G., Pivovaroff, A., Adams, H.D., Allen, C.D., Anderegg, W.R.L., Arend, M., Breshears, D.D., Brodribb, T., Choat, B., Cochard, H., et al.: Mechanisms of woody-plant mortality under rising drought, CO_2 and vapour pressure deficit, Nat. Rev. Earth Env., 3(5), 294-308, 10.1038/s43017-022-00272-1, 2022.

585   Mokany, K., Raison, R. J., and Prokushkin, A. S.: Critical analysis of root: shoot ratios in terrestrial biomes, Global Change Biol., 12, 84-96, 10.1111/j.1365-2486.2005.001043.x, 2005.

Shao, M., Wang, Y., Xia, Y., and Jia, X.: Soil Drought and Water Carrying Capacity for Vegetation in the Critical Zone of the Loess Plateau: A Review, Vadose Zone J., 17, 170077, 10. 2136/vzj2017.04.007, 2018.

Shi, P., Huang, Y., Ji, W., Xiang, W., Evaristo, J., and Li, Z.: Impacts of deep-rooted fruit trees on recharge of deep soil water using stable and radioactive isotopes, Agr. Forest Meteorol., 300 (23), 108325, 10.1016/j.agrformet.2021.108325, 2021.

Stovall, A. E. L., Shugart, H., and Yang, X.: Tree height explains mortality risk during an intense drought, Nat. Commun., 10 (1), 4385, 10.1038/s41467-019-12380-6, 2019.

Su, B. and Shangguan, Z.: Decline in soil moisture due to vegetation restoration on the Loess Plateau of China, Land Degrad. Dev., 30 (3), 290-299, 10.1002/ldr.3223, 2019.

Tao, Z., Li, H., and Si, B.: Stand age and precipitation affect deep soil water depletion of economical forest in the loess area, Agr. Forest Meteorol., 310, 108636, 10.1016/j.agrformet.2021.108636, 2021.

Tormena, C., Karlen, D. L., Logsdon, S., and Cherubin, M. R.: Corn stover harvest and tillage impacts on near-surface soil physical quality, Soil Till. Res., 166, 122-130, 10.1016/j.still.2016.09.015, 2017.

Torres, L. C., Keller T., Lima R. P. de, Tormena, C. A., Lima H. V. de, and Giarola N. F. B.: Impacts of soil type and crop species on permanent wilting of plants, Geoderma, 384, 114798, 10.1016/j.geoderma.2020.114798, 2021.

Wang, L., Wang, Q., Wei, S., Shao, M., and Li, Y.: Soil desiccation for Loess soils on natural and regrown areas, For. Ecol. Manage., 255 (7), 2467-2477, 10.1016/j.foreco.2008.01.006, 2008.

~~Wang, S., Yang, M., Gao, X., Zhang, Z., Wang, X., Zhao, X., and Wu, P.: Comparison of the root soil water relationship of two typical revegetation species along a precipitation gradient on the Loess Plateau, Environ. Res. Lett., 16 (6), 064054, 10.1088/1748-9326/ac00e4, 2021.~~

Wang, Y., Shao, M., and Liu, Z.: Large-scale spatial variability of dried soil layers and related factors across the entire Loess Plateau of China, Geoderma, 159, 99-108, 10.1016/j.geoderma.2010.07.001, 2010.

Wang, Y., Shao, M., and Liu, Z.: Pedotransfer functions for predicting soil hydraulic properties of the Chinese Loess Plateau. Soil Sci., 177 (7), 424-432, 10.1097/SS.0b013e318255a449, 2012.

Wang, Y., Shao, M., Zhu, Y., and Liu, Z.: Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China, Agr. Forest Meteorol., 151 (4), 437-448, 10.1016/j.agrformet.2010.11.016, 2011.

Wang, Z., Liu, B., Liu, G., and Zhang, Y.: Soil water depletion depth by planted vegetation on the Loess Plateau, Sci. China Ser D-Earth Sci, 52(6), 835-842, 10.1007/s11430-009-0087-y, 2009.

Will, R. E., Wilson, S. M. Zou, C. B., and Hennessey, T. C.: Increased vapor pressure deficit due to higher temperature leads to greater transpiration and faster mortality during drought for tree seedlings common to the forest-grassland ecotone, New Phytol., 200 (2), 366-374, 10.1111/nph.12321, 2013.

Wu, W., Li, H., Feng, H., Si, B., Chen, G., Meng, T., Li, Y., and Siddique, K. H. M.: Precipitation dominates the transpiration of both the economic forest (Malus pumila) and ecological forest (Robinia pseudoacacia) on the Loess Plateau after about 15 years of water depletion in deep soil, Agr. Forest Meteorol., 297 (1–4), 108244, 10.1016/j.agrformet.2020.108244,

620   2021.

Wu, Y., Huang, M., Warrington, D.: Black Locust Transpiration Responses to Soil Water Availability as Affected by Meteorological Factors and Soil Texture, Pedosphere, 25(1), 57-71, 10.1016/S1002-0160(14)60076-X, 2015.

Yang, M., Gao, X., Wang, S., and Zhao, X.: Quantifying the importance of deep root water uptake for apple trees' hydrological and physiological performance in drylands, J. Hydrol., 606 (11), 127471, 10.1016/j.jhydrol.2022.127471, 2022.

625   Zhao, L., He, N., Wang, J., Siddique, K. H. M., Gao, X., and Zhao, X.: Plasticity of root traits in a seedling apple intercropping system driven by drought stress on the Loess Plateau of China, Plant Soil, 24 (1), 273, 10.1007/s11104-022-05603-1, 2022.

Zhu, G., Deng, L., Zhang, X., Shangguan, Z.: Effects of grazing exclusion on plant community and soil physicochemical properties in a desert steppe on the Loess Plateau, China, Ecol. Eng., 90, 372-381, 10.1016/j.ecoleng.2016.02.001, 2016.

630   Zhu, X.: Rebuild soil reservoir is a rational approach for soil and water conservation on the Loess Plateau (In Chinese), Bulletin of Chinese Academy of Sciences, 21(4), 320-324, 10.16418/j.issn.1000-3045.2006.04.014, 2006.

Zhu, X.: Rescue the "soil reservoir" to control the ecological environment of the Loess Plateau (In Chinese), Bulletin of Chinese Academy of Sciences, 2000(04), 293-295, 10.16418/j.issn.1000-3045.2000.04.019, 2000.