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

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Abstract. In water-limited areas, planted trees can abstract substantial amounts of soil water from deep layers (>200 cm) to meet their 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 in relation to both degree and depth of deep-layer soil moisture (DSM) 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 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 limitation of DSM 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 and depth limitations were reached, the percent loss of xylem hydraulic conductivity of planted tree's 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

35   thickness of 50-200 m loess (Shao et al., 2018), has been one of the most active regions for tree planting during the last four 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 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

40   data from the National Forestry and Grassland Administration, http://www.forestry.gov.cn). As a result, a number of ecosystem 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 can incur other ecological issues, such as soil desiccation due to excessive water

45   consumption in drylands (Wang et al., 2010; Jia et al., 2017; Wu et al., 2021), preventing the sustainable development 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;

50   Tao et al., 2021), because DSM below 200 cm is hardly recharged by precipitation under tree plantations. In fact, deep-layer soil 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 amount of soil moisture that limits growth (hereafter "degree limitation") and/or the maximum depth from which trees are able to extract water (hereafter "depth limitation") for different

55   species and in different climate zones, which is critical to estimate the amount of available soil water 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

60   uses soil moisture at -15 bar as the surrogate without considering differences between plant species (Torres et al., 2021). However, a recent synthesis indicated that the lowest soil moisture (degree 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 limitation of DSM 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 (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 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 the effect of deep-layer soil desiccation on xylem hydraulic conductivity of planted trees when degree limitation and depth limitation of DSM are reached.

To address the gaps, we built a dataset, including 11980 observations of 380 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 and depth limitation of DSM for different tree species and the influencing factors, and (ii) to disentangle their impact on xylem hydraulic conductivity of planted trees in different climatic zones on the LOP. Our hypotheses were that the degree and depth limitation of deep-layer soil desiccation depends on tree species because of their different drought-resistance capacity; and that the xylem hydraulic conductivity of planted trees is greatly reduced when degree and depth limitation 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, 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 this 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.

95 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 farmland or

100 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, a total of 11980 observations from 380 soil profile, which covered 83 sites in 4 provinces or municipalities (Fig. 1) and extracted from 34 peer-reviewed publications were retrieved, and the specific information is

105 shown in Table 1. The original data were either clearly obtained from tables in the selected papers or intuitively extracted from figures in those papers using GetData Graph Digitizer (version 2.24, http://getdata-graph-digitizer.com). 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 independently when analyzing

110 the influence of forest age on soil moisture. When analyzing the degree limitation of DSM 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 published information on DSM in black locust forests, we also performed supplementary experiments to obtain relevant data, as described in Section 2.2.
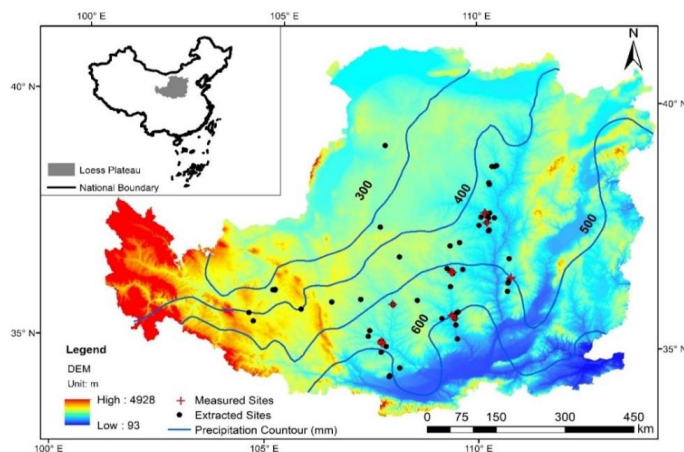
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Figure 1: Distribution map of sampling sites on the Loess Plateau. The black dots represent the sampling sites extracted from the article,

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 km^2, 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 GPS (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 crop/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 limitation under one given aged plantation as well as under the paired control plots. The information of the tree plantations reaching the degree 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 control was controlled at less than 500 m, and the average SD 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. Soil samples without roots was 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℃ 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 and depth limitation of DSM under plantations. 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 S2; Gao et al., 2018; Li et al., 2019).

Table 2. Basic information of the sampling trees that causes the lowest deep soil moisture deficit (DSMD).

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		-	-	-	-	-
	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		-	-	-	-	-
Changwu	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
	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 control (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 limitation of DSM; 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

160 spilt from the branch, the initial xylem hydraulic conductivity (K_{ini}, kg s^{-1} MPa^{-1}) was measured with 1 mmol Ł$^{-1}$ 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 Ł$^{-1}$ 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,

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

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2.2.4 Basic parameters of plantation

In order to accurately target the sample plantation, tree age was determined on the basis of 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

170 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 mesh (0.15 mm) 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

175 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 mesh sieve for measuring soil particle

composition (i.e., clay, silt and sand contents) and soil pH, and through a 100 mesh 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

180 320 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,

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

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

185

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

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

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

190   location, °; and i represents the i_{th} soil depth.

Table 3. Basic soil properties of 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
Changwu	Apple	Dark loessial soils	24.6	38.7	36.7	4.76	1.31	7.35
	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

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

195   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.

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

Where T_a is air temperature, ℃; and RH is relative humidity, %.

2.3 Data analysis

200   **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

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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).

205
$$RR = Ln(X_e / X_C) \tag{7}$$

where 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 age, and X_e and X_c are values of soil moisture under trees and controls for each study, respectively. To test the significance of differences between soil moisture and RR, a 95% confidence interval (CI) was used. A previously described method (Deng et al., 2016) was used to calculate the 95% CI, as shown in Eqs. (8) and (9),

210
$$SE_{total} = \sqrt{\frac{V_s}{N}} \tag{8}$$

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

Where 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 differences between soil moisture and RR was considered significant if the 95% CI did not include zero, and the differences were not considered significant if the 95% CI did not include zero.

215 **2.3.2 Quantitative index for degree limitation of soil desiccation**

The effect of different deep-rooted planted trees RWU on soil moisture was expressed as soil moisture deficit (SMD, the calculation method as shown in Eq. (10)), which could remove the interference of precipitation differences in different sampling years. In order to compare the difference between the degree limitation of soil desiccation and the PWP, the SMD corresponding to PWP along the soil profile was calculated by Eq. (11).

220
$$SMD_{j,k} = \frac{SMC_{j,k} - SMC_{0,k}}{SMC_{0,k}} \tag{10}$$

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

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

2.3.3 Quantitative index for depth limitation of soil desiccation

225 The paired sample t-test in SPSS was used to analyze the significance of soil moisture between plantations and their controls. When the significant difference becomes insignificant ($p>0.05$) as the soil layer deepens, which is considered that the DSM consumption of the plantation has reached the depth limitation. However, the difference is always significant ($p<0.05$)

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indicates that the maximum water uptake depth has not been reached.

2.3.4 Statistical analysis

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

using Canoco 5. 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

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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

240   plantation had an extreme effect on DSM appears to be between 20 and 30 years.
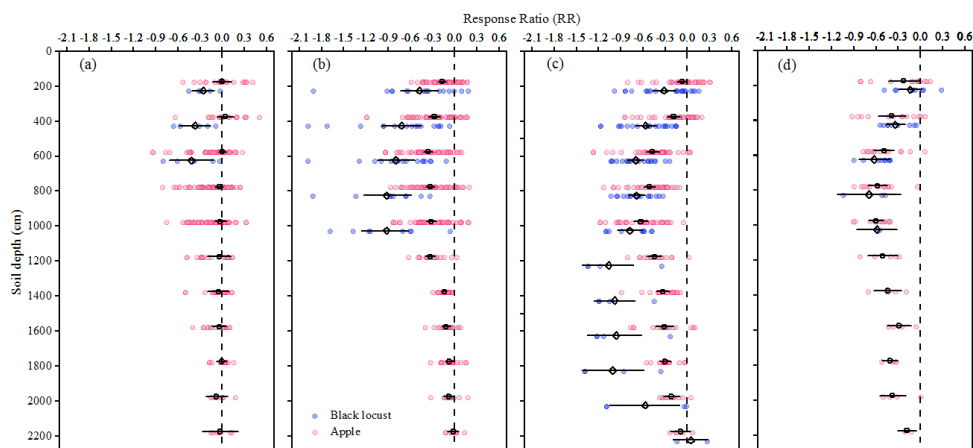

Figure 2: Mean effect sizes of soil moisture response to planted trees' growth with different age classes on the Loess Plateau: (a) tree age
<10 year, (b) 10 year ≤ tree age<20 year, (c) 20 year ≤ tree age<30 year, and (d) tree age ≥ 30 year. The vertical black dotted lines indicate
RR=0. Blue and red dots represent black locust forests and apple orchard *RR*s, respectively, diamonds and circles represent the mean *RR* of
245   black locust and apple orchard, respectively, and the error bars represent 95% CI.

3.2 Limitation of DSM 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 example, the DSM varied greatly in different sampling years (Fig.

3a). Soil moisture deficit (SMD), defined as the relative difference of soil moisture under given trees and nearby controls,

250   was used to eliminate the effect of climate differences in various sampling years. Here, the DSM of control adjacent to the

plantation served as the background soil moisture, which is not influenced by root water extraction due to the shallow (<100

cm) roots of annual crops; hence the DSM in adjacent control can be 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.
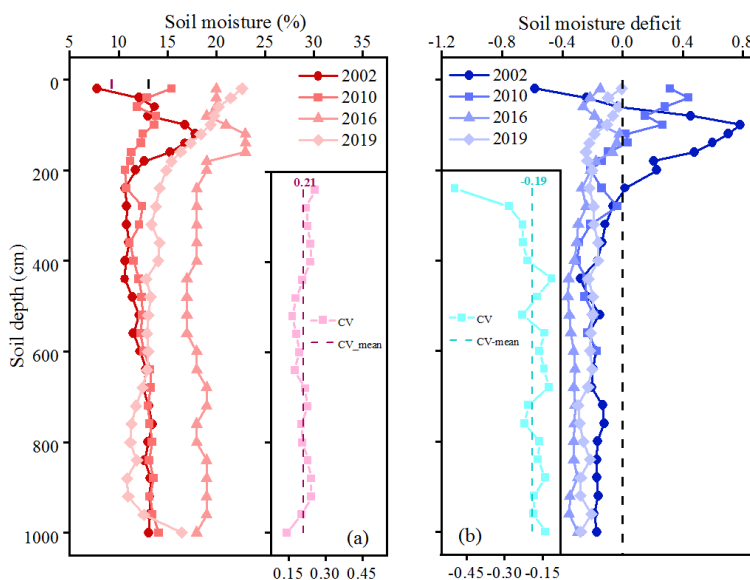
Figure 3: Distribution of soil moisture (a) and soil moisture deficit (b) in 15-year-old apple orchards in Changwu in 2002, 2010, 2016 and 2019. The variation coefficient (CV) of soil moisture and soil moisture deficit below 2 m are shown in the small picture, and the dashed lines in the figure represent the mean values of the CV of deep soil moisture and deep soil moisture deficit, respectively.

3.2.1 Degree limitation of DSM

260   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, 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

265   Changwu, Yan'an and Mizhi regions was similar to that in APO (Fig. 4d, e, f). The consumption of DSM reached the same

lowest value in different regions. This suggests that PWP is a good indicator of the degree limitation of DSM, 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).
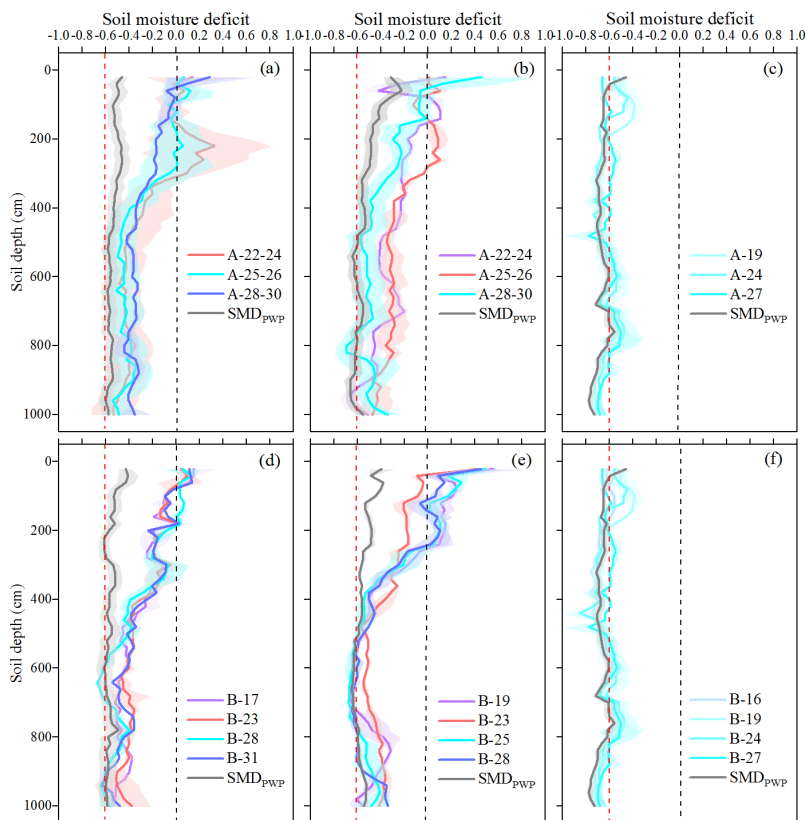
Figure 4: Soil moisture deficit (SMD) distribution under apple orchards of different ages in Changwu (a), Luochuan (b) and Mizhi (c); and SMD under black locust forests of different ages in Changwu (d), Yan'an (e) and Mizhi (f). The capital letters A and B in the legend represent apple and black locust, respectively, and the numbers after the letters represent tree age, for example, A-22 represents 22-year-old apple. In order to reduce the randomness of the extracted data, the data for apple trees with similar ages in Changwu and Luochuan 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.

3.2.2 Depth limitation of DSM

Based on the measured and literature data, we analyzed the water consumption depth limit of plantations in different regions after the soil desiccation degree limitation 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 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.

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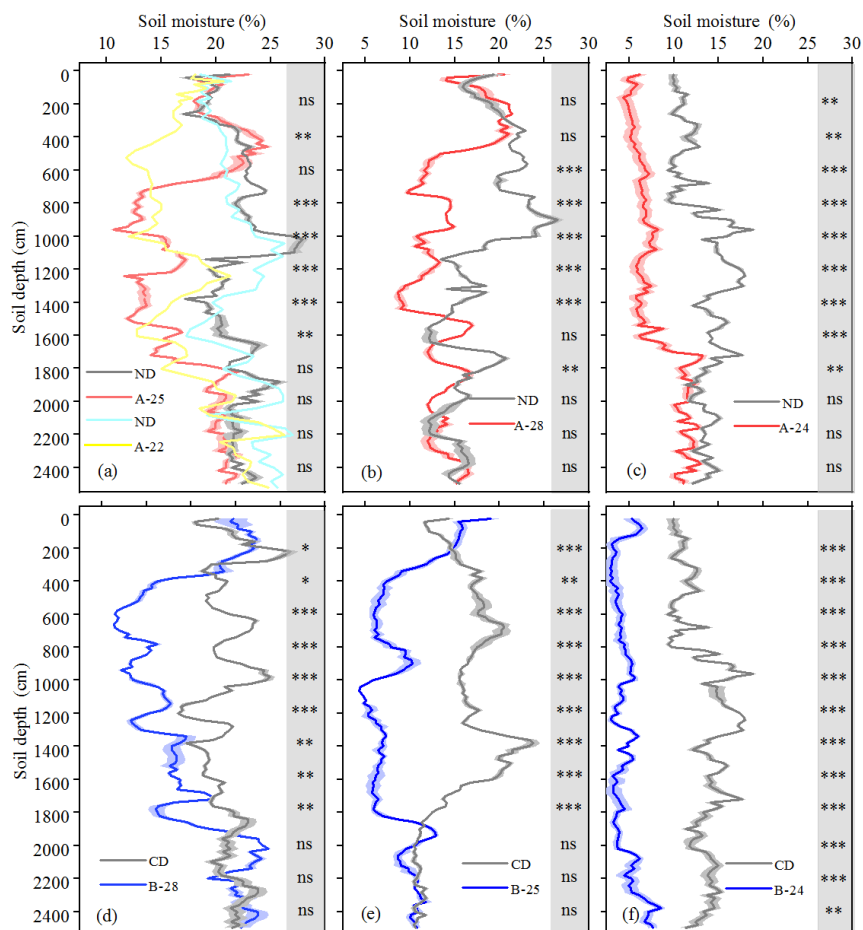
Figure 5: Dynamic distribution of maximum water absorption depth after reaching the degree limitation of deep soil desiccation. (a) 22-(literature data) and 24-year-old (measured data) apple in Changwu; (b) and (c) indicate 28- and 24-year-old apple in Luochuan and Mizhi, respectively; (d), (e) and (f) indicate 28-, 25- and 24-year-old black locust in Changwu, Yan'an and Mizhi, respectively. Gray line represents soil moisture of grassland or farmland. ***, **, * 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.

3.3 Effect of factors on the limitation

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 and depth limitation of DSM (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 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 SM (Fig. 6b), 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,

300   which may be due to the MAP of each region weakened the differences of precipitation in each sampling year.
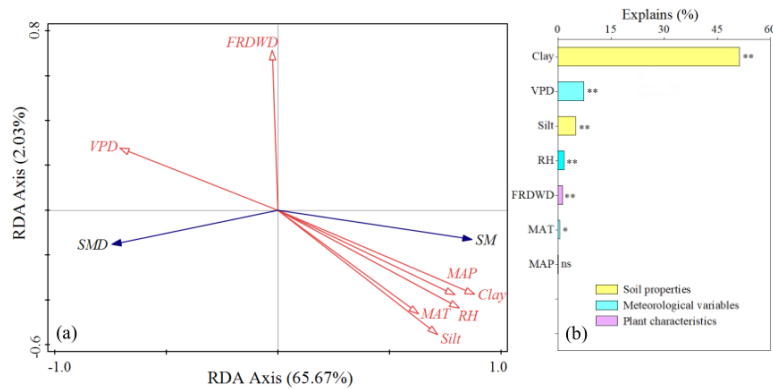

Figure 6: (a) redundancy analysis (RDA) of "response variable (soil moisture deficit (SMD), soil moisture (SM)) and environmental factors". Descriptors (red arrows) are soil properties (clay and silt), meteorological variables (vapor pressure deficit (VPD), mean annual precipitation (MAP), relative humidity (RH), and mean annual temperature (MAT)), and plant characteristic (fine root dry weight density

305   (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 limitations on hydraulic conductivity

In order to further explore how the limitation caused by deep soil desiccation affects the hydraulic conductivity of plants, we

compared hydraulic conductance of branches of plantation trees in relation to the degree and depth limitation of deep soil

310   desiccation at different sites (Fig. 7). *PLC* was higher than 50% for all tree species and regions. Furthermore, the *PLC* of

black locust in Mizhi was significantly higher than that in other places ($p<0.05$), which indicates that the risk of mortality of

black locust in Mizhi is greatest when deep soil desiccation reaches degree and depth limitation thresholds.
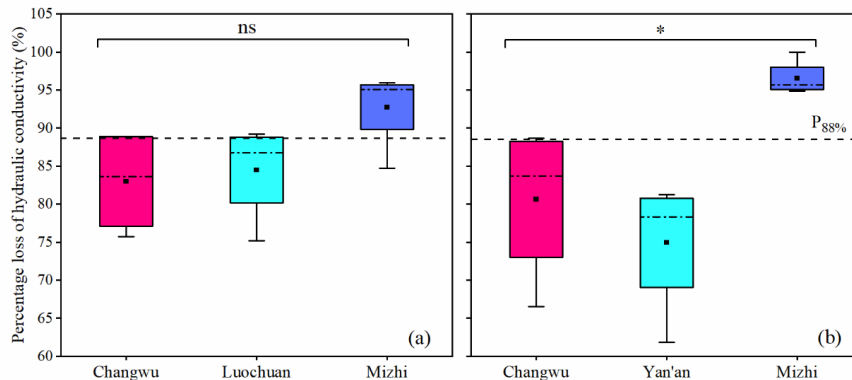

Figure 7: Differences in percentage loss of hydraulic conductivity of annual branches of apple (a) and black locust (b) in different regions

315   (Changwu, Luochuan, Yan'an, and Mizhi). * or ns indicate that the significance level is $p<0.05$ or there is no significant difference,

respectively.

14

4   Discussion

4.1 The mechanism underlying for the degree and depth limitation

Although DSM (>200 cm) decreased with an increase of planted trees age, and even reached the lowest limitation, shallow

320   soil moisture (<200 cm) did not change significantly (Fig. 2 and 4). This is ascribed to surface or shallow layer soil moisture is usually greatly influenced by rainfall infiltration and evapotranspiration, while 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.

325   In our study, the lowest DSMD fluctuated around -0.6 irrespective of tree species and site (Fig. 4). This contradicts the assumption that degree of deep-layer soil desiccation 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

330   matric potential gradient around fine roots in areas with less rainfall (LRAs), thus effectively enhance soil water availability. 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

335   (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

340   soil water availability, which is mainly affected by the precipitation and soil texture. 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

345   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 limitation of DSM for the tree species examined. These findings provide important reference information for the sustainable development of plantations on

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the LOP.

After soil moisture use in the profile reaches the degree limitation, plants extend their roots into the deep soil to expand their

350 water hunting range during the dry season (Fig. 8; Ivanov et al., 2012). Our result shows 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 determines its' root: shoot

ratios (Mokany et al., 2005), thus, the FRDWD of the plantation indicates that their water absorption range can only reach

18-22 m. Furthermore, roots can no longer extract moisture after reaching a certain depth, probably because the hydraulic

355 path of water transport in the 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 that chronic water shortages encourages 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,

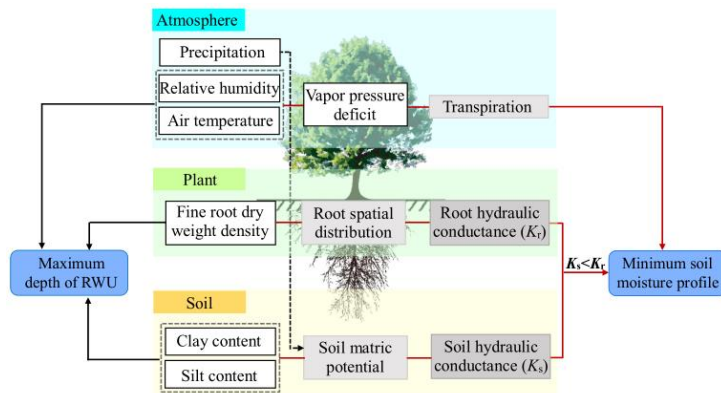360 even though BLF in LRAs can obtain water through root extension.

Figure 8: Regulatory mechanism of the extreme influence of root water uptake (RWU) on deep soil moisture. 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 limitation), the blue rounded rectangle represents the

365 limitation of degree 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 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

During prolonged dry periods, deep-rooted trees often rely on DSM to avoid drought stress (Ding et al., 2021; Wang et al.,

370 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

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combined occurrence of hydraulic failure and carbon starvation (Arend et al., 2021). Our results show that branches of

375   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.

380   **4.3 Limitations and practical implications**

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 addition, the collection of large amounts of DSM data requires a great deal of resources, the number of samples available in this study is limited. Thus, the results of this study need to be in-depth verified in different tree ages and in different regions to guide vegetation

385   management under local conditions.

Large numbers of tree deaths caused by prolonged drought are of great concern because trees fulfil a critical ecological role and have the largest biomass and storage of carbon (Feng et al., 2016; Bai et al., 2021). Thus, it is essential to understand the degree and depth limitation of deep-layer soil desiccation for 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

390   limitation of deep soil desiccation; 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, this confirms that PWP is a good indicator of the degree limitation of deep-layer soil desiccation for the tree species examined; on the other hand, 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 judging whether DSM can sustain the survival of the typical plantations on the LOP during prolonged drought. Furthermore, except for the BLF in

395   Mizhi, all plantations have reached the depth limitation of deep-layer soil desiccation, and after reaching the degree and depth limitation thresholds, plantations of different sites suffer different 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 future extreme climate.

400   **5   Conclusions**

Deep soil moisture 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 DSMD at the permanent wilting point (PWP), irrespective of tree species and site. This confirms that PWP is a good

indicator of the degree limitation of DSM for apple and black locust trees. The corresponding maximum water consumption

405 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 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

410 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

415 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

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