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Deep Soil Water Availability Regulates the Transpiration of Afforested Apple Trees (*Malus pumila* Mill.) in a Sub-Humid Loess Region

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Abstract: Many studies have investigated how soil water availability in shallow soil affects forest transpiration, but how deep soil water status (below 1 m depth) alters tree water use remains poorly understood. To improve our understanding of how deep soil water changes tree transpiration dynamics, we measured soil water content (SWC) in more than 20 m depths, the radial sap flow profile and the leaf area index (LAI) in the 2017 growing season in 9-, 12-, 16-, 19- and 23-year-old afforested apple (*Rosaceae*) trees on the Chinese Loess Plateau. SWC was also measured in long-term cultivated farmland to derive SWC before afforestation. The results showed that there was no statistical difference in SWC in shallow soil among orchards ($p > 0.05$), while SWC in deep soil reduced rapidly with increasing tree age. The average SWC at 1–20 m decreased from 0.27 ± 0.02 cm^3 cm^{-3} in farmland to 0.21 ± 0.03 cm^3 cm^{-3} in the 23-year-old orchard. Moreover, water storage in deep soil decreased by 139 mm yr^{-1} between the 9- and 12-year-old stands, 105 mm yr^{-1} between the 12- and 16-year-old stands, 44 mm yr^{-1} between the 16- and 19-year-old stands, and 9 mm yr^{-1} from the 19- to 23-year-old stands, indicating that gradually decreased SWC in deep soil has restricted tree water use. Due to the changes in SWC, growing-season transpiration and the LAI peaked in the 16-year-old orchard and then decreased with increasing stand age. Growing-season transpiration in the 23-year-old orchard was only 77% of that in the 16-year stands, despite the older trees having larger diameters at the breast height. Our results suggest that soil water availability in deep soil plays an important role in regulating trees' transpiration.

Keywords: sap flow; transpiration; deep soil; soil water content

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Citation: Li, P.; Zuo, Y.; Zhang, X.; Wang, Y.; Wu, Z.; Liu, X.; Wu, N.; Lu, Y.; Li, H.; Si, B. Deep Soil Water Availability Regulates the Transpiration of Afforested Apple Trees (*Malus pumila* Mill.) in a Sub-Humid Loess Region. *Agronomy* **2024**, *14*, 841. https://doi.org/10.3390/agronomy14040841

Academic Editor: Paula Paredes

Received: 9 March 2024
Revised: 13 April 2024
Accepted: 14 April 2024
Published: 17 April 2024

1. Introduction

Forestation has been encouraged globally for its great potential in carbon sequestration [1,2], soil erosion control [3,4] and water cycle regulation [4,5]. This is particularly the case on the Chinese Loess Plateau (CLP), which once had the severest soil erosion in the world, with soil erosion rates ranging from 2000 to 20,000 t km^{-2} yr^{-1} [6]. In this context, the Chinese government conducted the Grain to Green Program (GTGP) to convert previously cultivated farmland to perennial woody species [7,8]. So far, the GTGP has converted 9610 km^2 of native farmland to secondary forest [9] and has greatly improved vegetation cover in the area [10,11].

The mean annual precipitation on the Chines Loess Plateau ranges from 200 to 750 mm from southeast to northwest [12]. However, potential evapotranspiration may exceed

3000 mm in some areas [13]. In this context, the water demand of revegetated forests is of particular concern in water-limited environments due to the high evapotranspiration of forest ecosystems [7,14]. Many studies have found that newly planted trees in this area not only deplete the rainfall from the current year but also absorb a significant amount of water stored in the soil from previous seasons/years [15,16]. Therefore, the sustainability of revegetated plants depends, to a large extent, on plant resilience to drought stress. Previous researchers have investigated plants' response to drought stress from the stand scale [17–19] to the leaf scale [20,21] and with regard to molecular features [22,23]. Most of these studies focused on soil water availability in shallow soil, and little attention has been paid to the effect of deep soil water, defined as water stored in soil below 1 m depths [24,25], on tree water use.

Recent evidence has indicated that plant roots go far deeper than 1 m [26]. Revegetated trees on the Loess Plateau were found to develop deep root systems to extract water from deep soil [27–31]. The water in deep soil was from previous precipitation that infiltrated to this depth many decades ago [32]. To alleviate dry-season drought stress, even tropical forests absorb soil water at a depth greater than 10 m below the soil surface [33]. Although deep soil water was found to impact forests' transpiration, the interaction between soil water availability in deep soil and trees' water use remains poorly understood.

Sap flow measurements permit the continuous observation of tree water use with low costs, as compared to weighing lysimeters [34,35], soil water balance [36,37], chemical tracing [38,39] and the eddy covariance method [40,41]. Moreover, sap flow is not sensitive to spatial heterogeneity and topography variance [17,42,43]. However, as sapwood degrades as the wood ages, the water conductivity also degrades. Thus, sap flow rates are rarely even across sapwood [18,44]. Moreover, the radial pattern of sap flow varies with stand age, with older trees experiencing a steeper decrease in sap flow rate [45,46]. For these reasons, the radial patterns of sap flow are critical for evaluating plant responses to environmental drivers and performing the up-scaling of point scale sap flow measurements [47–49].

In this study, radial sap flow profiles, deep soil water, leaf area indexes (LAIs) and diameters at breast height (DBHs) were measured in widely afforested apple trees across stand ages in a sub-humid region on the Chinese Loess Plateau. Our objective was twofold: firstly, to quantify the transpiration rates of apple trees across varying stand ages, and secondly, to assess the influence of deep soil water availability on the observed transpiration rates across these stand ages. The results are expected to extend our understanding of the effect of deep soil water status on trees' transpiration, which is meaningful for forest ecohydrology and for evaluating the sustainability of afforestation.

2. Materials and Methods

2.1. Description of the Experimental Site

The study was conducted in Changwu county, in the southern area of the CLP (Figure 1), as the CLP is the largest apple tree cultivation area in the world [50]. This region experiences a sub-humid climate with average annual precipitation of 560 mm (from 1960 to 2023), about 70% of which falls between June and September. The number of frost-free days is 170 and the average annual temperature is 9.2 °C. The soil is aeolian loess with a silty loam texture and is uniformly distributed across sites. The groundwater level is approximately 80 m below the surface. Apple trees have been widely planted in this region since the 1990s, and now, they have become the primary land use type in this region. All farmlands and orchards in this region are rainfed due to the lack of accessible surface and ground water.

2.2. Experimental Design

In the growing season of 2017 (from April 25 to September 30), five orchards with stand ages of 9, 12, 16, 19 and 23 years were selected. The five chosen orchards displayed consistent spatial tree density, with a distance of 3 m between plants within rows and 3.5 m between rows. The area of each orchard is greater than 40 m × 40 m. Long-term cultivated farmland was selected to benchmark soil water status before the afforestation of apple trees. All study sites were located within a 4 km^2 area. Furthermore, all sampling sites were located on flat highlands.

2.3. Measurements

2.3.1. Meteorological Measurements

During the 2017 growing season, continuous meteorological data were measured in a weather station within the study region, including daily precipitation, air temperature, solar radiation, humidity, and wind speed. The daily meteorological data were used to calculate potential crop evapotranspiration (ET_p): the crop coefficient for apple trees was derived from the recommended values provided by FAO, with values of 0.50 during the initial growing season, 1.20 in the middle of the growing season and 0.95 towards the end of the growing season [51]. ET_p was divided into potential evaporation (E_p) and potential transpiration (T_p) according to measured *LAIs* based on Beer's law [52]. The meteorological data were from a weather station located within the study region (Figure 1a).

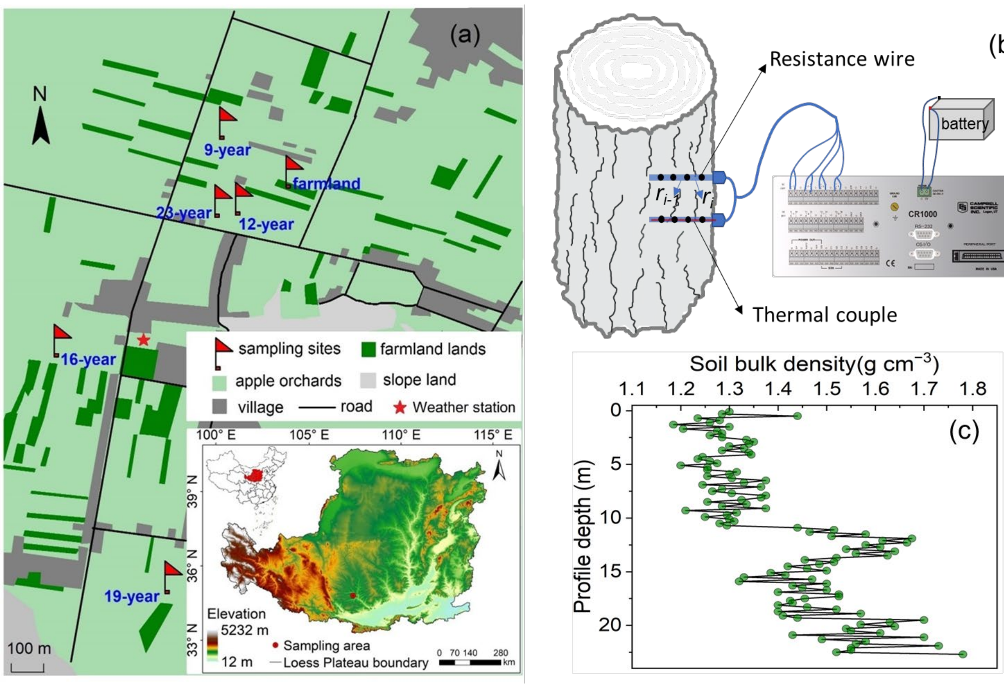

Figure 1. The location of the sampling site (**a**), the design diagram for a thermal dissipation probe (**b**), and the soil bulk density information in the study region (**c**) [53].

2.3.2. Soil Water Content

In April 2017, soil samples were collected with a soil auger at 20 cm intervals in depth in 9-, 12-, 16-, 19- and 23-year-old orchards and long-term cultivated farmland. The minimum sampling depth in each orchard was 10 m (the sampling depth of the 9-year-old orchard was 10 m, the sampling depths of the 12- and 16-year-old orchards were 20 m, and the sampling depths of the 19- and 23-year-old orchards were 21 m and 23 m, respectively). Therefore, 520 soil samples were taken in all orchards. All sampling sites were in the center of each orchard. The volume of each soil sample (0.2 m depth) amounted to 251.2 cm^3. Due to space constraints, it was not feasible to accommodate the entire sample in an aluminum box, necessitating the mixing of soil samples. Therefore, each soil sample was well mixed, and then, a subsample (about 40 g) was collected in an aluminum box and oven dried at 105 °C to a constant weight to determine gravimetric soil water content. The gravimetric soil water content was converted to volumetric soil water content by multiplying the ratio of soil bulk density to water density [53]. Then, the measured volumetric soil water contents in the 9-, 12-, 16-, 19- and 23-year-old orchards were used to calibrate the neutron probe in each orchard (R^2 = 0.80). Our previous research revealed a low level of soil water spatial variability in this region [53], and therefore, only one neutron probe was installed in the center of each orchard. However, considering the heterogeneity of root spatial distribution, installing multiple observation points at varying distances from the tree trunk may have enhanced the persuasiveness of the observational outcomes. In the 2017 growing season, soil water contents in each orchard were measured every 15 to 30 days using a neutron probe (L520-D, Nanjing, China). The water extraction rates in deep soil (WERD, mm yr^{-1}) were determined by calculating the difference in soil water storage in deep soil between two different stand ages and dividing it by the difference in the ages of the stands, as follows:

$$WERD = \frac{SWS_i - SWS_j}{j - i} \quad (1)$$

where SWS_i and SWS_j represent the water storage in deep soil in stand ages i and j, respectively.

2.3.3. Vegetation Survey

In each orchard, four representative apple trees were selected. The crown area and diameter at breast height (DBH) of all selected individuals were measured (Table 1). The LAI was measured with an LAI-2200C plant canopy analyzer (LI-COR, Inc. Lincoln, NE, USA) during the growing season at a frequency of once every 15 to 30 days.

Table 1. Diameter at breast height (DBH), thermal dissipation probe (TDP) measurement depth, crown area, cumulative actual transpiration (Ta) derived from sap flow and deep soil water deficit in orchards with different stand ages.

Stand Age Years	DBH cm	TDP Measure Depth cm	Crown Area m^2	Cumulative Ta mm
9	11.92 ± 0.87	1, 3	13.57 ± 0.52	NA
12	15.36 ± 1.19	1, 3, 5	9.97 ± 0.11	267
15	18.18 ± 1.39	1, 3, 5, 7	12.07 ± 0.05	289
19	19.98 ± 1.54	1, 3, 5, 7	12.61 ± 0.80	274
23	19.26 ± 1.67	1, 3, 5, 7	8.57 ± 0.12	222

Note: In the 9-year-old orchard, the probes were broken from 6 June to 24 August, so the sap flow data were missing in this period. NA: the data were not available.

2.3.4. Probe Design and Sap Flow Measurements

We constructed Granier-type thermal dissipation probes (TDPs) that can measure sap flow at different depths. The TDP length and total measurement depths were based on the measured DBH in each orchard (Table 1). Each TDP consisted of one upper probe (2 mm outside diameter) containing the heater source and one lower reference sensor probe (Figure 1b). The heater probe was constructed by inserting a loop of Nichrome 80 alloy resistance wire (diameter 0.13 mm, resistance 87 Ω m^{-1}, Pelican Wire Co., Naples, FL, USA) into the probe along its entire length. T-type thermocouples (TT-T-36-SLE, Omega Engineering, Stamford, CT, USA) were embedded in both the upper and the lower probes every 2 cm, starting at 1 cm to measure the temperature difference at different depths between the two probes (Figure 1b).

In each orchard, a TDP was installed about 0.8 m above soil surface in the south side of the selected four representative trees. The distance between the heater and reference probe was 4 cm. All probes were wrapped in reflective insulation to shield the probes from precipitation and solar radiation. Thermocouples in each TDP were connected to a CR1000 data logger (Campbell Scientific, Logan, UT, USA). The temperature in each thermocouple was measured at 1 min intervals, and the means of 10 scans were recorded during the growing season from 25 April to 30 September. The temperature difference (ΔT) between two probes was used to calculate the sap flow velocity (J_s, cm h^{-1}) based on the following equation by Granier [54]:

$$J_s = 0.0119 \times \left(\frac{\Delta T_m - \Delta T}{\Delta T}\right)^{1.231} \times 3600 \quad (2)$$

where ΔT is the dynamic temperature difference between the heated probe and the reference probe, and ΔT_m is the maximum temperature difference between the two probes. ΔT_m could be obtained between 02:00 and 05:00, because in this period, J_s was close or equal to zero [54]. It is worth noting that using the thermal dissipation method with Granier's equation method to accurately measure tree transpiration requires the calibration of parameters, which is particularly important for comparing the water consumption characteristics of different tree species [55]. This study only investigated how the changes in moisture conditions in deep soil affect the transpiration evolution of a single species, the apple tree. Therefore, no parameter calibration was performed.

We converted the 10 min mean J_s measured at different depths to tree stem flow (F, cm^3 h^{-1}) using the following equation [47,56]:

$$F = \sum_{i=1}^{n} \pi \times \left(r_i^2 - r_{i-1}^2\right) \times J_{si} \quad (3)$$

Here, the thermocouples were located at the center of the sapwood area bounded by the inner radius (r_{i-1}) and outer radius (r_i) (Figure 1c). We assumed that the measurement zone of each thermocouple junction was 2 cm wide and did not overlap with the adjacent zones [47,56]. The TDP in the 9-year-old orchard was broken from 6 June to 24 August, and therefore, no data were collected in this period. Subsequently, F was converted to daily transpiration (T_a, mm day^{-1}) based on the crown area as follows:

$$T_a = \frac{F}{C_a} \times 240 \quad (4)$$

where C_a is the crown area (cm^2) and F is the daily average tree stem flow (cm^3 h^{-1}). Then, the average daily transpiration of the four selected trees was utilized to represent the actual transpiration of an apple orchard.

2.3.5. Statistical Analysis

The differences among treatments were analyzed using a one-way analysis of variance (ANOVA). Post hoc tests were performed with the Tukey-LSD method at the $p = 0.05$ significance level. The statistical tests were performed with IBM SPSS Statistics for Windows, Version 26.

3. Results

3.1. Meteorology and Leaf Area Index

During the growing season, the recorded daily mean air temperature fluctuated from 9 °C to 25 °C, with an average of 17 °C. The daily average vapor pressure deficit, which ranged from 0.02 to 1.78 kPa, showed a generally decreasing trend (Figure 2). The growing-season precipitation was 392 mm, with 45% (175 mm) received after 10 August. Compared with other periods, the timeframe from June 6 to August 10 exhibited a notably higher daily potential transpiration (T_p) rate. Throughout this span, the cumulative daily average potential evapotranspiration (ET_p) reached 375 mm, while the total precipitation recorded during this time was only 92 mm. Hence, in this study, this particular period was classified as the dry season.

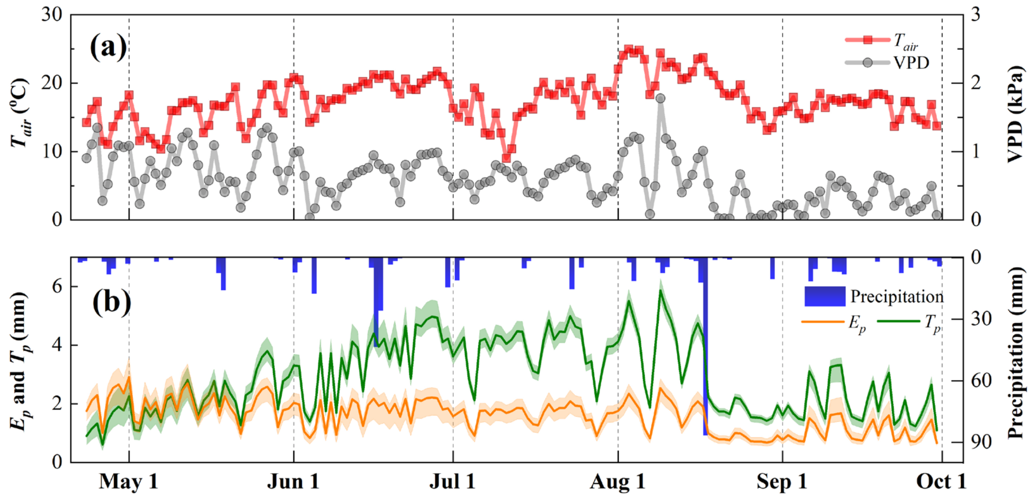

Figure 2. Time series of daily average air temperature (T_{air}), vapor pressure deficit (VPD) (**a**), precipitation, potential evaporation (E_p) and potential transpiration (T_p) (**b**) during the growing season. The shadow in (**b**) is the range between the maximum and minimum value in the five orchards with sap flow measurement.

The leaf area index increased rapidly from April to June (Figure 3) and reached its saturation from July to September. The LAI increased rapidly with the increase in stand age from 9- to 16-year-old orchards but decreased with the increase in stand age when an apple tree was older than 16 years. The LAI in the 23-year-old orchard was significantly smaller than the LAIs in the 12-, 16-, and 19-year-old orchards ($p < 0.05$).

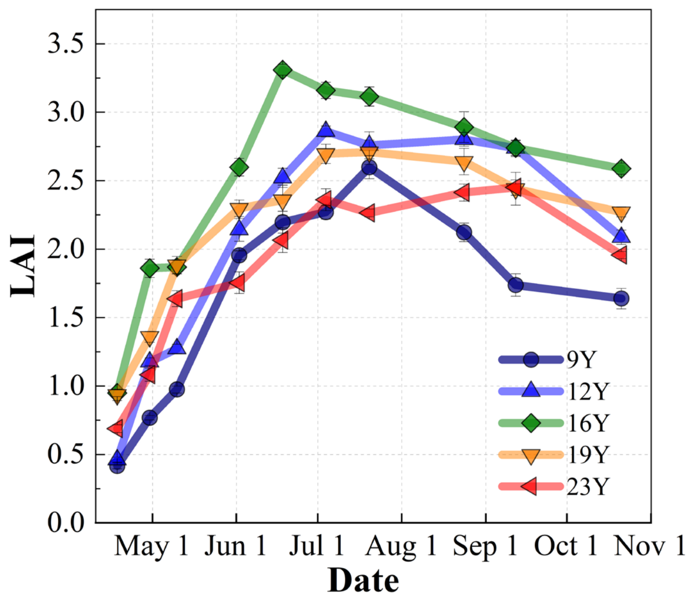

Figure 3. Leaf area index (LAI) across stand ages.

3.2. Soil Water Content (SWC)

The SWC in orchards was significantly less than that in farmland ($p < 0.05$) (Figure 4). Moreover, SWC along the measured profile in the orchards decreased with the increase in stand age, and the SWC differences were mainly in deep soil (>1 m in depth), not so much in shallow soil (Figures 4 and 5). SWC in deep soil (1–20 m) decreased from 0.27 ± 0.02 cm^3 cm^{-3} in farmland to 0.21 ± 0.03 cm^3 cm^{-3} in the 23-year-old orchard (Figure 5). Further, water depletion depth—defined as the depth above which an apple orchard has lower soil water contents, but below which the apple orchard has the same soil water contents with nearby farmland—increased with stand age and was greater than 20 m in the 23-year-old orchard (Figure 4).

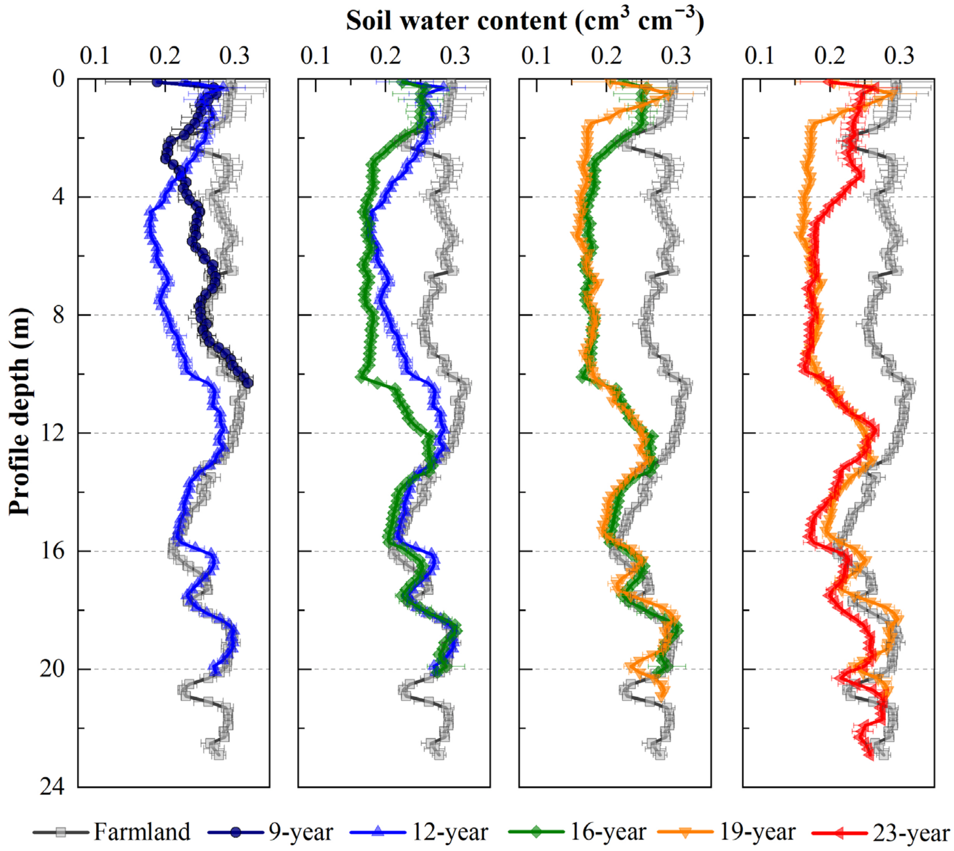

Figure 4. Soil water contents in farmland and apple orchards with different stand ages (n = 6).

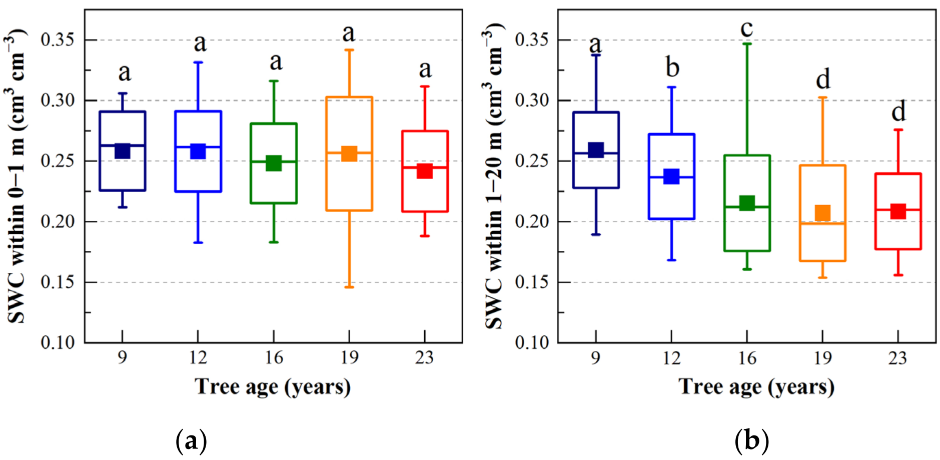

Figure 5. Comparison of measured soil water contents within 0−1 m (**a**) and 1−20 m (**b**) in orchards observed during the growing seasons. Box size represents the interquartile range, the horizontal line within the boxes represents the median and the solid square point is the mean. Whiskers extend from the box to the minimum and maximum value on the lower and the upper side of the box, respectively. a, b, c, and d represent the significance of the difference.

Water extraction rates from deep soil were obtained from the difference in soil water storage in deep soil between two stand ages divided by stand age difference. The water extraction rate in deep soil increased from 15 mm year^{-1} for trees ≤9 years old to 139 mm year^{-1} for the stands between 9- and 12-years old (Figure 6). Thereafter, the water extraction rate in deep soil decreased rapidly with the increase in tree age. For the orchards between 19- and 23 years old, trees only extracted 9 mm water per year from deep soil. This gradually decreased water extraction rate in deep soil indicated that deep soil water absorption could not be sustained, and SWC in the 23-year-old orchard was close to or reached its lower limit for apple trees to access.

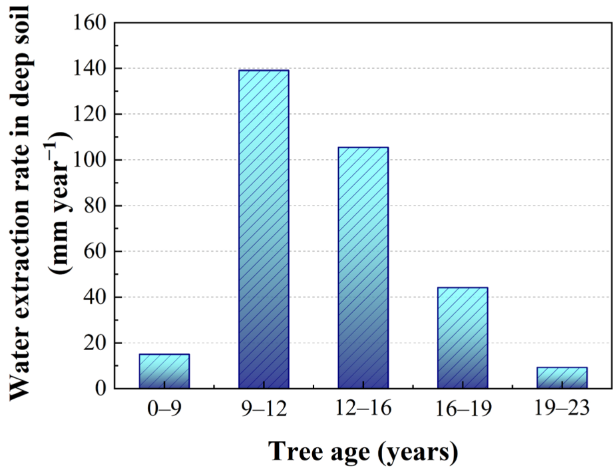

Figure 6. Water extraction rate in deep soil for apple trees of different ages.

3.3. Sap Flow Velocity

Sap flow increased, as expected, in the morning and reached the peak rates around 14:00, and then decreased gradually (Figure 7). Sap flow decreased with the increase in sapwood depth in the five orchards. For the 9-year-old orchard, the sap flow at the 3 cm depth accounted for 70% of that at the 1 cm depth. However, in other orchards, the sap flow decreased rapidly with the increase in sapwood depth, and the sap flow at the 3 cm depth only accounted for about 30% of that at the 1 cm depth. For the 16-, 19- and 23-year-old orchards, the sap flows at the 5 cm and 7 cm depths were quite low, and the maximum sap flow rates at these two depths were less than 3 cm h^{-1}. Additionally, the 1 cm depth sap flow in the 23-year-old orchard was significantly less than that in other treatments ($p < 0.01$).

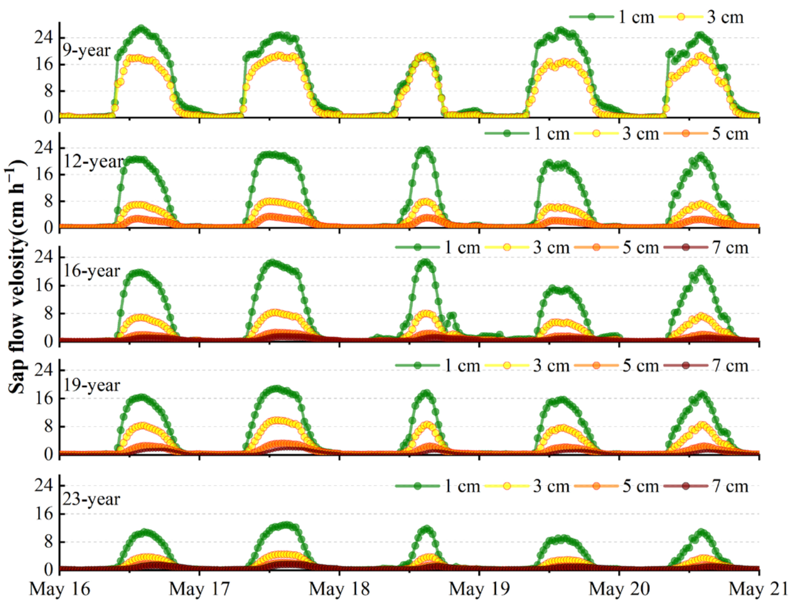

Figure 7. Sap flow velocity in different measurement depths for trees with different stand ages.

3.4. Transpiration of Apple Trees

Under the same meteorological conditions, all orchards experienced similar growing-season transpiration dynamics (Figure 8): daily transpiration increased gradually from April and reached its peak around July, and then decreased gradually thereafter. However, the daily transpiration amount was different among them. Daily transpiration during the growing season increased from the 12- to 16-year-old orchards and then decreased with the increase in stand age (Figure 9). Daily transpiration in the 23-year-old orchard was significantly less than that in the 12-, 16- and 19-year-old orchards ($p < 0.05$) (Figure 9).

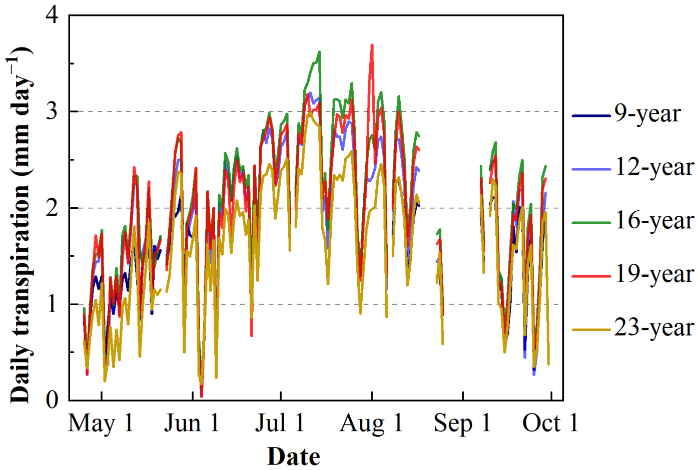

Figure 8. Transpiration dynamics for apple orchards with different stand ages.

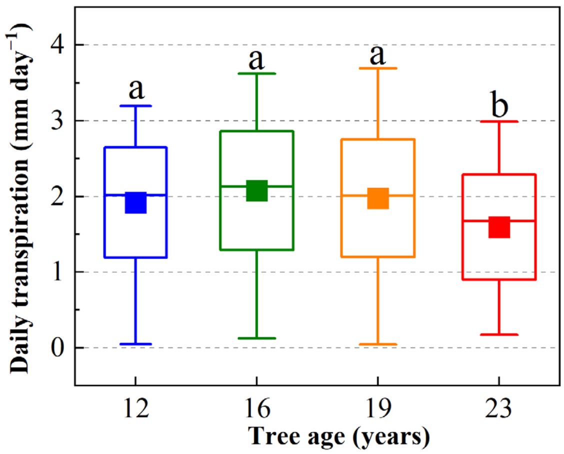

Figure 9. Daily transpiration for apple orchards with different stand ages. Box size represents the interquartile range, the horizontal line within the boxes represents the median and the solid square point is the mean. Whiskers extend from the box to the minimum and maximum value on the lower and the upper side of the box, respectively. a and b represent the significance of the difference.

The cumulative T_a values in the growing season were 267 mm, 289 mm, 274 mm and 222 mm for the 12-, 16-, 19- and 23-year-old orchards, respectively (Table 1). The total transpiration in the 23-year-old orchard was only 77% of that in the 16-year-old orchard (Figure 9), albeit with a larger DBH of the 23-year-old orchard than that of the 16-year-old orchard (Table 1). This suggested that without enough available water in deep soil, like that in the 23-year-old orchard (Figure 3), apple trees would experience water shortages, which resulted in less growing-season transpiration.

3.5. Growing Season Water Stress

In this study, we used T_a/T_p to evaluate water stress. T_a/T_p was divided into three phases based on its dynamics during the growing season: before the dry season (before 4 June), during the dry season (from 5 June to 10 August) and after the dry season (after 10 August) (Figure 10). Before the dry season, the daily mean T_a/T_p values were 0.76, 0.75, 0.64, 0.66 and 0.55 for the stand age of 9, 12, 16, 19 and 23 years, respectively (Figure 10b). The 9- and 12-year-old orchards had higher T_a/T_p and thus experienced lower water stress compared with other treatments ($p < 0.05$) (Figure 10b). T_a/T_p did not differ significantly between the 16- and 19-year-old orchard, and the 23-year-old orchard had the lowest T_a/T_p among all treatments (Figure 10b).

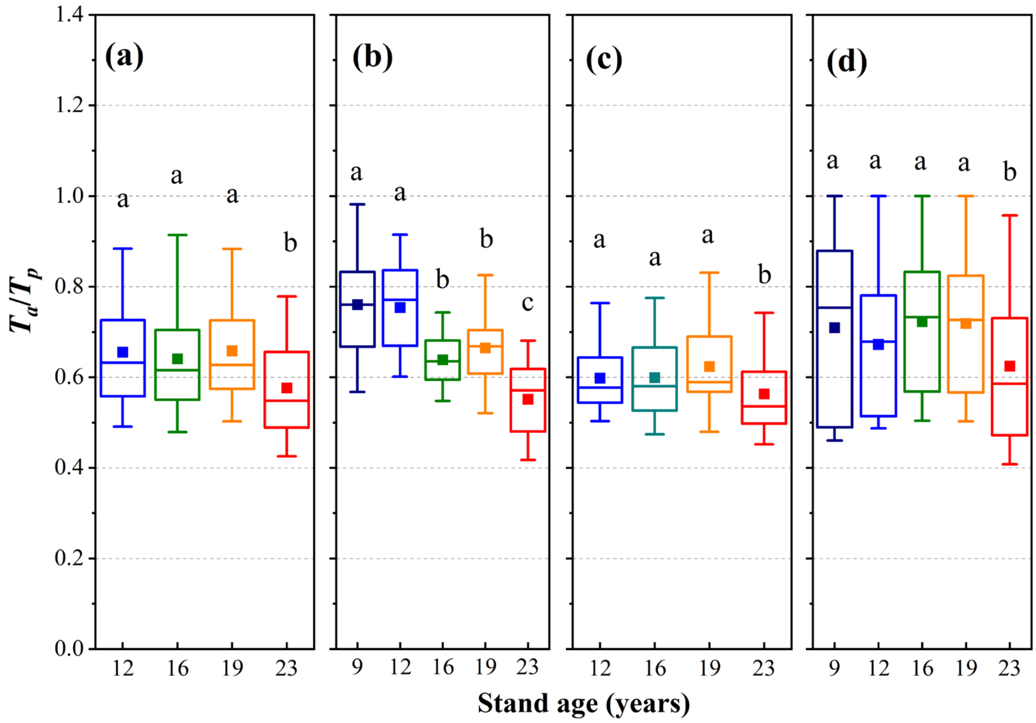

Figure 10. T_a/T_p for (**a**) the whole growing season, (**b**) before dry season (before 7 June), (**c**) during dry season (from 7 June to 10 August) and (**d**) after dry season (after 10 August). Box size represents the interquartile range, the horizontal line within the boxes represents the median and the solid square point is the mean. Whiskers extend from the box to the minimum and maximum value on the lower and the upper side of the box, respectively. a, b and c represent the significance of the difference.

During the dry season, all orchards had lower T_a/T_p as compared with the previous period (Figure 10c). Moreover, the 12-year-old orchard experienced a more rapid decrease in T_a/T_p (from 0.75 to 0.59) than older orchards, while the T_a/T_p changes in the 16-, 19- and 23-year-old orchards were less than 0.05. After the dry season, all orchards experienced a rapid increase in T_a/T_p (Figure 10d). During the whole growing season, the mean T_a/T_p values were 0.66, 0.64, 0.66 and 0.58 for the 12-, 16-, 19- and 23-year-old orchard, respectively (Figure 10a). T_a/T_p in the 23-year-old orchard was significantly less than in other orchards ($p < 0.05$), and the T_a/T_p values for other orchards did not differ statistically.

4. Discussion

4.1. Deep Soil Cannot Provide Long-Term Stable Water for Apple Trees in the Loess Plateau

Trees normally have deep roots and, therefore, can extract water from deep soil. A meta-analysis indicated that the maximum rooting depth for trees was 7.2 m at the global scale [57]. Water extraction in deep soil has been demonstrated as an effective way to combat surface drought stress and has been reported in both tropical [26,58–60] and semiarid regions [25,31,61]. In our study region, apple trees rooted progressively deeper for water with increasing stand age and reached 23.2 ± 0.8 m for the 22-year-old trees [29] (Figure 11). Moreover, the maximum rooting depth was found to correlate well with the water loss in depth soil for apple trees [29] and other tree species [15] on the Loess Plateau of China. Water isotope tracing indicated that deep soil layers below 2 m can contribute 36% of the transpiration of apple trees in this region [62].

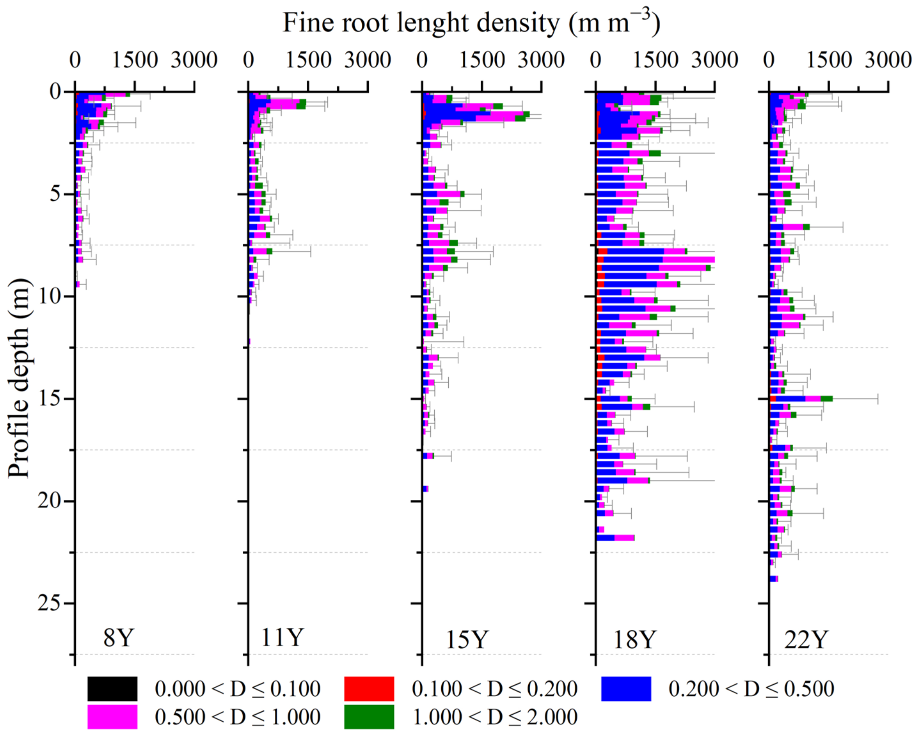

Figure 11. Fine root distribution of apple trees across various ages. The data were gathered from our observations in 2016 [29], and the orchards surveyed are the same as those utilized in this study.

Our observation revealed that all apple orchards had similar water conditions in shallow soil, while the soil water content in deep soil decreased gradually with increasing tree age (Figures 4 and 5). The decreased soil water content forced trees to absorb water at deeper soil layers, resulting in great water depletion depths (>20 m) in old orchards. Moreover, the water extraction rate in deep soil decreased from 139 mm year^{-1} for trees between 9 and 12 years old to 9 mm year^{-1} from 19- to 23-year-old stands. The decreased water extraction rate from deep soil demonstrated that deep soil water is not a stable safety net for apple trees growing on the Loess Plateau. In line with our results, continuous soil water loss in deep soil was observed for other tree plantations, for instance, apricot and Chinese pine on the Loess plateau [63,64]. All these findings suggest that depleted deep soil water by trees revegetated in semi-humid/arid environments cannot be replenished, and thus, the deep soil water supply cannot be sustained, which is different from trees growing in humid climates.

4.2. Soil Water Availability in Deep Soil Regulates Transpiration of Afforested Apple Trees

For the revegetated apple trees, transpiration change across stand ages reflects, to a large extent, how water stress varies following afforestation, which is of great significance for the evaluation of afforestation sustainability. In this study, apple trees' transpiration increased with tree age first, reached its maximum around at 16 years, but then decreased with the increase in tree age (Table 1 and Figure 9). Growing-season transpiration in the 23-year-old orchard only accounted for 77% of that in the 16-year-old orchard, albeit with older trees having larger DBHs (Table 1). This is different from the reports on tropical [65,66] and subtropical forests [67,68], where both tree water use and the LAI increase with increasing DBH. The difference may be explained by annual precipitation between our study and that in tropical and subtropical regions. In humid climates, trees' water demand can be satisfied by timely precipitation or the water stored in the vadose zone, and depleted deep soil water can be effectively replenished by wet-season precipitation [69]. In our study, however, the revegetated apple trees not only consumed annual precipitation, but also took up, and consequently reduced, water stored in deep soil. When the available deep soil water was exhausted, older trees experienced higher water stress and less transpiration, especially when the growing-season precipitation was below normal. Thus, the relationships among DBH, LAI and transpiration were affected by soil water conditions, and the relationships built in wet environments should be used with caution in water-limited environments.

Soil water availability and meteorology condition play important roles in regulating trees transpiration [17,43,70]. In this study, all orchards experienced the same meteorological conditions and similar shallow soil water contents in the 2017 growing season (Figure 5). However, the water stress in five orchards, as indicated by T_a/T_p, varied across stand ages, with the highest level of water stress appearing in the 23-year-old orchard (Figure 10). This may have been caused by the continuous water depletion in deep soil that decreased SWC to a low level (Figure 4). Water in soil under lower soil water contents has lower soil matric potential, which would restrict root water uptake [71]. Therefore, in the higher-stand-age orchards, trees experienced more water stress due to the low soil water contents in deep soil (Figure 5). In line with our results, a scenario analysis revealed that trees living in tropical regions would face continuous water loss in deep soil and higher water stress when precipitation is reduced to a certain extent [72,73]. In addition, soil water at great depth has lower gravitational potential, which would also prevent water extraction in deep soil. This is particularly the case in this study: for apple trees ≥16 years old, water extraction in deep soil mainly appeared at depths below 12 m. Moreover, water transport resistance from deep to shallow roots that was caused by xylem cavitation and suberized barriers also stressed root water uptake, and the intensity of the barriers was positively correlated with water deficit [74,75]. Therefore, the gradually decreased SWC in deep soil restricted water extraction in deep soil, resulting in less transpiration in old orchards (Figure 12).

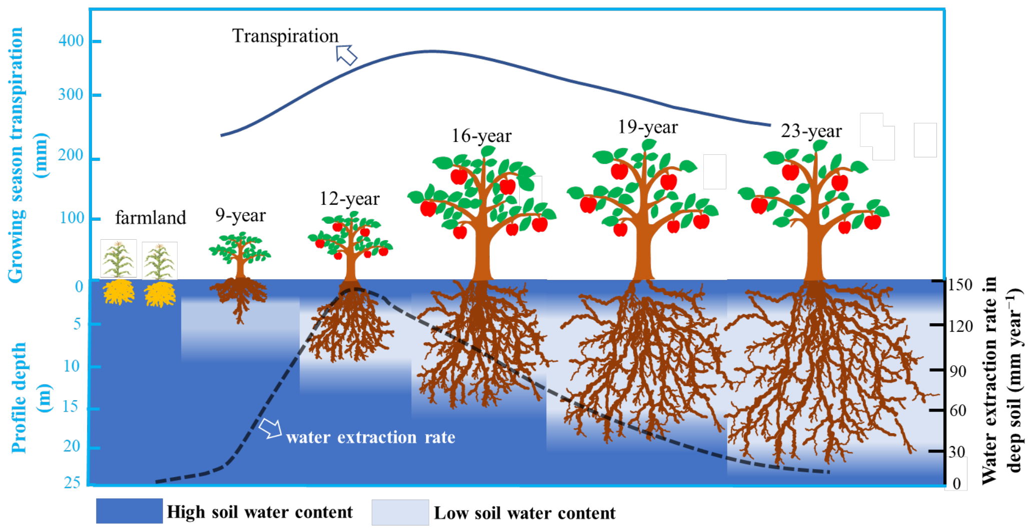

Figure 12. A diagram of the changes in soil water content, water extraction rate in deep soil and growing-season transpiration following afforestation of apple trees on CLP.

Strengths and Weaknesses of This Study

Using the space for time substitution method, this study offers a thorough analysis of how deep soil water availability influences apple trees' transpiration, bridging a notable gap in our current understanding. However, this study still exhibits several weaknesses:

(i) This study focuses solely on the dynamics of SWC within a single crop season. A more comprehensive analysis covering multiple seasons could provide a more robust understanding of how SWC in deep soil may affect trees transpiration. (ii) This study fails to utilize updated crop coefficient (Kc) values adjusted for factors such as plant density, ground cover fraction and climate conditions. (iii) Without the calibration of the coefficient of Granier's method, there is a risk of inaccuracies in estimating transpiration.

5. Conclusions

The interaction between apples trees' transpiration and deep soil water availability was investigated using the space for time substitution method. All orchards had similar water conditions in shallow soil. However, deep soil water was tapped for transpiration without replenishment, which caused the continuous decrease in soil water content in deep soil, forcing trees to extract water at deeper layers with increasing tree age. After 23 years of afforestation, the water depletion depth was greater than 20 m below the soil surface. Continuous water loss in deep soil led to the water extraction rate in deep soil decreasing rapidly with increasing tree age. Due to the decreases in extractable water in deep soil, apple trees' transpiration and the LAI, after peaking in the 16-year-old orchard, decreased gradually with the increase in stand age. Growing-season transpiration in the 23-year-old orchard only accounted for 77% of that in the 16-year-old stand, and the water stress of the 23-year-old stand, as indicated by T_a/T_p, was significantly higher than that in younger orchards. This study revealed that deep soil water plays an important role in supporting trees' transpiration. Therefore, in environments with limited water resources, the productivity and sustainability of deep-rooted forestlands heavily rely on the maintenance of suitable moisture conditions in deep soil.

Author Contributions: Conceptualization, P.L., Y.Z., X.Z. and H.L.; methodology, Y.Z., X.Z., Z.W. and H.L.; formal analysis, H.L. and B.S.; investigation, P.L., X.L. and Y.W.; resources, Y.Z. and X.Z.; data curation, P.L., H.L., Y.Z. and X.Z.; writing—original draft preparation, P.L., Y.Z. and X.Z.; writing—review and editing, H.L., B.S., Y.L. and N.W.; visualization, Z.W., X.L. and Y.W.; supervision, B.S., Y.L. and N.W.; funding acquisition, H.L. and B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the National Key R&D Program of China (2022YFE0100300), the National Natural Science Foundation of China (42101018), the Yantai City Science and Technology Innovation Development Plan (2023JCYJ092), Shandong Province Higher Education Institutions' Youth Entrepreneurship Team Program (2022KJ289) and the Shandong (China)-Israel Cooperation Program (2023KJHZ007). Special thanks to the staff of the Changwu CERN station.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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