Received: 31 May 2018 | Accepted: 16 November 2018
DOI: 10.1002/hyp.13346

SCIENTIFIC BRIEFING

WILEY HP TODAY

Water mining from the deep critical zone by apple trees growing on loess

Huijie Li[1] | Bingcheng Si[1,2] | Pute Wu[1] | Jeffrey J. McDonnell[3,4]

[1] Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A&F University, Yangling, China

[2] Department of Soil Science, University of Saskatchewan, Saskatoon, Canada

[3] Global Institute for Water Security; School of Environment and Sustainability, University of Saskatchewan, Saskatoon, Canada

[4] School of Geography, Earth & Environmental Sciences, University of Birmingham, Birmingham, UK

Correspondence
Bingcheng Si, Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A&F University, Yangling 712100, China.
Email: bing.si@usask.ca

Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 41630860, 41371233 and 41601222; 111 Project, Grant/Award Number: B12007; Fundamental Research Funds for the Central Universities, Grant/Award Number: 2452017317

Abstract

There have been significant recent advances in understanding the ecohydrology of deep soil. However, the links between root development and water usage in the deep critical zone remains poorly understood. To clarify the interaction between water use and root development in deep soil, we investigated soil water and root profiles beyond maximum rooting depth in five apple orchards planted on farmland with stand ages of 8, 11, 15, 18, and 22 years in a subhumid region on the Chinese Loess Plateau. Apple trees rooted progressively deeper for water with increasing stand age and reached 23.2 ± 0.8 m for the 22-year-old trees. Soil water deficit in deep soil increased with tree age and was 1,530 ± 43 mm for a stand age of 22 years. Measured root deepening rate was far great than the reported pore water velocity, which demonstrated that trees are mining resident old water. The deficits are not replenished during the life-span of the orchard, showing a one-way mining of the critical zone water. The one-way root water mining may have changed the fine root profile from an exponential pattern in the 8-year-old orchard to a relative uniform distribution in older orchards. Our findings enhance our understanding of water-root interaction in deep soil and reveal the unintended consequences of critical zone dewatering during the lifespan of apple trees.

KEYWORDS

critical zone, deep soil, root distribution, soil water content, stand age, water mining

1 | INTRODUCTION

Measuring, modelling, and understanding the deep critical zone is a research frontier that cuts across soil science, plant physiology, geomorphology, and hydrology (Grant & Dietrich, 2017). This is especially true in afforestation efforts where understanding how trees exploit the root zone is key to predicting water resource outcomes at the catchment scale (McDonnell et al., 2018). Recent work has suggested that the climate and ecosystem determine this storage capacity (Gao et al., 2014). Other studies have explored the importance of storage variation with time and how this determines the impact of storage on runoff (Nijzink et al., 2016). Although significant new findings have come from coupled exploration of plant water use and groundwater recharge tradeoffs (Brooks, Barnard, Coulombe, & McDonnell, 2009), much of the work to date has been exclusive to shallow soil profiles. We know that trees plumb and exploit the critical zone (Brantley et al., 2017) but our inability to measure these processes limits our understanding of the connections, couplings, and controls of deep roots and soil water dynamics. Recent work that has gone deeper into the critical zone has revealed new behaviours as linked to tree water sourcing of rock moisture (Rempe & Dietrich, 2018) and down-valley subsidy of groundwater to their parent watersheds (Ameli, Gabrielli, Mortgenster, & Mcdonnell, 2018). However, one issue that continues to vex critical zone scientists is the linkage between root development and water usage in deep soil that is, beyond 1-m depth as defined by (Pierret et al., 2016).

Deep roots are a common trait among a wide range of plant species at the global scale (Canadell et al., 1996; Fan, Miguezmacho, Jobbágy, Jackson, & Oterocasal, 2017), and have significant influence on the water cycle (Ivanov et al., 2012; Oliveira et al., 2005) and carbon sequestration (Maeght, Rewald, & Pierret, 2013; Ward et al., 2016; Wiesmeier et al., 2012). However, compared with shallow roots in the upper 1-m soil layer, deep root systems are poorly understood and characterized (Pierret et al., 2016). We lack understanding of how their depth and distribution relates to the infiltration depth of storm rainfall (Fan et al., 2017) and how they control the source apportionment of forest transpiration (Evaristo, Jasechko, & McDonnell, 2015; Evaristo & McDonnell, 2017). Recent work by Zhang, Evaristo, Li, Si, and McDonnell (2017) has related deep rooting profiles to the age of extracted soil water by tree xylem water. That work leveraged deep loess sequences where apple trees were observed to root down to 12 m and extract, on average, 29-year-old soil water from the soil profile (Zhang, Evaristo, et al., 2017). But beyond the qualitative evidence of roots being encountered in soil cores at a maximum depth of 12 m, no information was available on the vertical interactions among deep soil water, rooting depth, and root distributions to support their estimates of water sources distribution through the profile.

Here, we present new experimental findings of rooting depth of apple trees across five age classes, from 8 to 22 years old. Beyond the local interest in understanding these root distributions, such work is vitally needed to test assumptions made regarding deep root distributions in the absence of measured data (Fan et al., 2017) and additional factors regulating rooting depth and root profile developments. Indeed, most root distribution models assume an exponential decrease of fine root with depth. Here we explore the following questions: What is the root distribution? How do root distributions change with stand age? What are the water-root interactions in deep soil across stand age?

We leverage the extreme depth of the unsaturated zone at our field site on the Loess Plateau and the minimal annual rainfall that would otherwise complicate water-root relations. We present measured soil water and root profiles from 0 to 25 m depth over five stand ages of afforested apple orchards. The results of this study could be valuable for understanding ecohydrological processes in deep loess that covers about 10% of the Earth's surface (Liu, 1985), and other regions where soil is thick and plants are under long term or periodic water stress.

2 | MATERIALS AND METHODS

2.1 | Study area

Our field work was conducted in Changwu county, in the southeastern Chinese Loess Plateau (35°14′ N, 107°41′ E; Figure 1). The site has an elevation of 1,200 m above sea level and experiences a continental monsoon climate. Average annual precipitation is 579 mm (averaged from 1960 to 2016), approximately 55% of which is received between July and September. The annual average temperature is 9.2°C and frost-free days average 170 per year. The area is covered by loess soil with a silt loam texture and the depth to water table is more than 80 m. Apple orchards have been replacing traditional cultivated wheat and maize since the 1990s and have become the predominant land use type in this region.

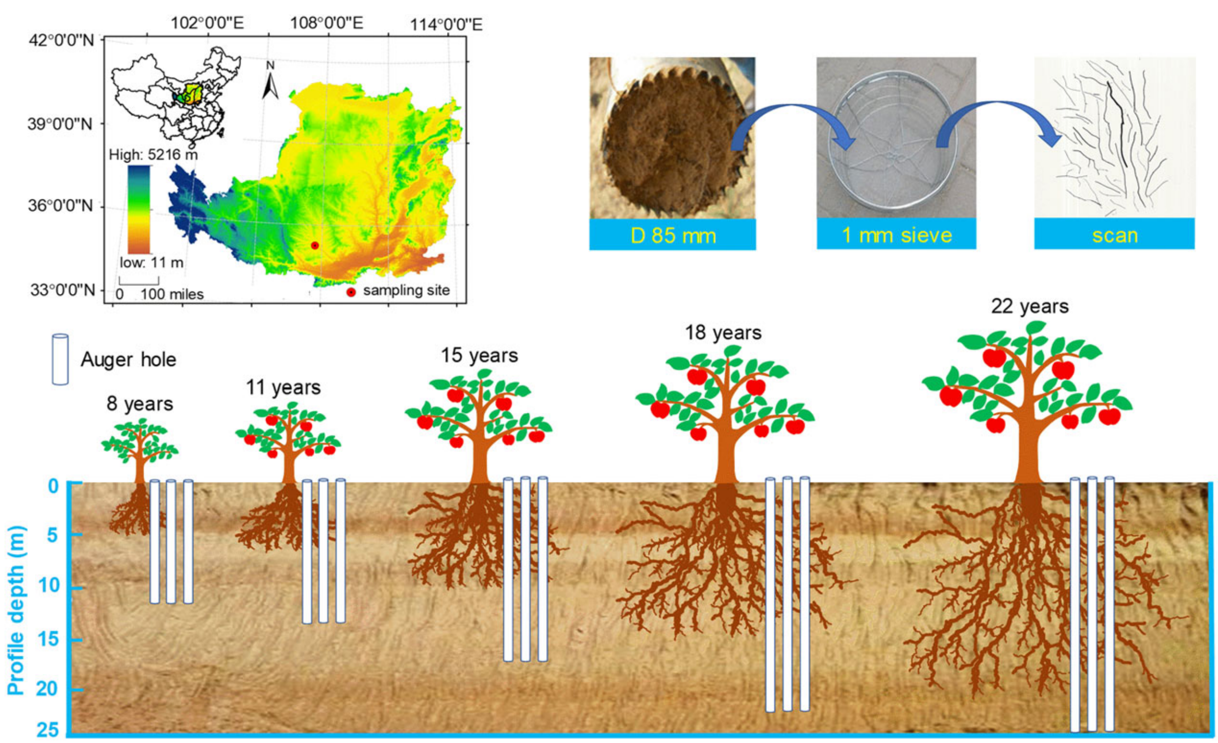

FIGURE 1 The location of the sampling site, sampling depth in each orchard. We used a root auger with 85 mm inner diameter for soil sampling. The lengths of the roots that did not pass through a 1 mm sieve were determined by processing scanned images. Soil water content was measured using well mixed soil

2.2 | Sampling and analytical methods

We sampled in July 2016, five representative apple orchards (*Malus pumila Mill*) with a stand age of 8, 11, 15, 18, and 22 years. Farmers in this region normally plant 1-year-old seedlings (with a diameter about 0.8 cm). The stand age in this study is defined as the number of years since the planting of seedlings. Apple trees start to bear fruit with a stand age of about 7 years, and normally reach their highest production at about 15 years old. Prior to the establishment of these orchards, the land use was cultivated farmland. Thus, soil water contents (SWCs) were measured in three long-term cultivated farmlands in the study region as the benchmark of the SWCs before land conversion to apple orchards. All the apple orchards and farmlands were rain-fed (i.e., there was no irrigation).

All treatments were in a flat tableland area and had the same topography. The soil is aeolian in origin and horizontally uniformly distributed among all sites, which is corroborated by the nearly identical deep SWC profiles in the three farmlands, and the similar SWCs between farmlands and orchards below the root zone (Part 3.2). Although there were anomalously wet or hot years in past 20 years, changes in average of precipitation over three or four consecutive years were small. As the stand age differences between orchards were 3 or 4 years, the effect of climate on space-for-time substitution was neglectable in this study. Previous investigation suggested that the farmers in this region employ similar fertilisation practices (Zhang, Li, Si, & Feng, 2017). Thus, the soil, topography, climate, and management practices meet the requirements of the space-for-time substitution method.

The selected orchards have relatively a uniform spatial distribution of trees: 3 m between plants in each row and a 3.5-m row space. In each orchard, based on tree spatial distribution, three deep soil cores were obtained using a root auger (an internal diameter of 8.5 cm) radially out from the tree trunk around 40, 120, and 200 cm along the diagonals of the rectangle formed by the nearest four trees. Vertical sampling intervals were 20 cm in the upper 2 m and 40 cm intervals below 2 m to a depth beyond the root zone, where SWC in orchards and farmlands converged and had no significant difference. Each soil sample was well mixed and then a subsample (about 40 g) was collected in an aluminium box and oven dried at 105°C for 12 hr to determine SWC. Precipitation during the sampling time (from 4 July to 23 July) was only 27.2 mm, and its effect on SWC change was neglected. We only measured SWCs once in each treatment during the growing season, and acknowledge SWC variation over time. However, during the growing season, SWCs vary greatly in shallow soil, which is largely affected by precipitation and evapotranspiration. For deep soil, the measured SWC change during the growing season of 2017 is quite small. For example, the in-situ neutron probe that measured SWCs in the "15-year"-old orchard in the 2017 growing season (in 2017, the trees are 16-year-old) showed an average fluctuation <0.014 cm^3 cm^{-3} (Figure 2), which is within the measurement error range of a neutron probe in the field (Klenke & Flint, 1991).

The remaining soil sample was sieved first and then washed carefully in a 1 mm sieve to obtain fresh root samples. The sieved fresh roots were then scanned on a flatbed scanner (Epson model V700) and the scanned images were analysed using WinRHIZO image analysis software (Regent Instruments Inc.) to calculate the root length of different root diameters. All roots were oven-dried at 60°C for 72 hr and weighed to determine root dry weight. Fine root (<2 mm) length density was calculated as: fine root length density = length/V_S, where V_S is the volume of soil.

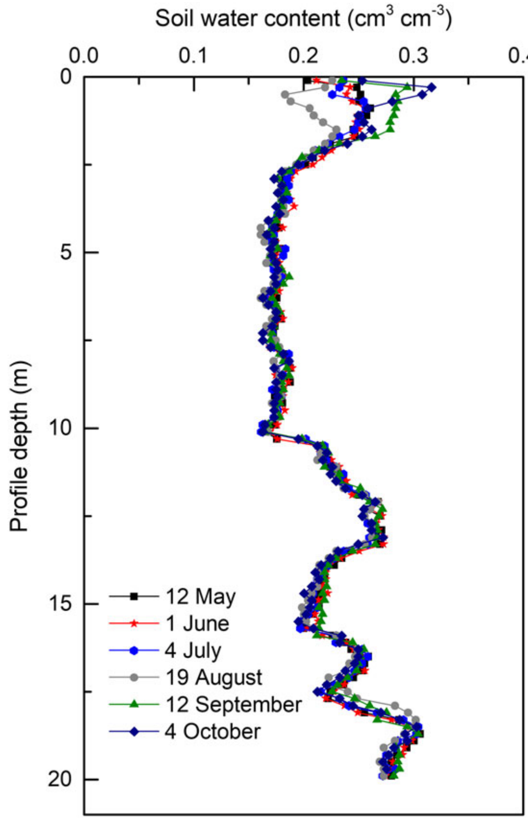

FIGURE 2 In-situ neutron probe measured soil water contents (SWCs) in the "15-year"-old orchard in the 2017 growing season (in 2017, the trees are 16 years old)

Soil samples were collected to a depth of 19.8, 25.0, and 25.2 m from three adjacent farmlands, respectively, by using a soil auger with a diameter of 4 cm to determine SWCs before land use change.

For apple orchards, cumulative soil water deficit (mm) was defined as the soil water storage difference between orchards and farmlands:

$$\text{Cumulative soil water deficit} = \sum_{i=1}^{n} (\theta_{Fi} - \theta_{Ai}) \times d_i \times 10^3, \quad (1)$$

where θ_{Fi} and θ_{Ai} are SWC (m^3 m^{-3}) in farmland and apple orchard in depth increment i, respectively; d_i is the thickness (m) of depth increment i.

3 | RESULTS

3.1 | Root distribution with increasing stand age

The maximum rooting depths increased progressively with stand age from 9.60 ± 0.40 to 23.20 ± 0.80 m for the five stand ages between 8 and 22 years (Table 1). Root deepening rate, calculated as the maximum rooting depth divided by stand age, averaged 0.96 ± 0.56 m $year^{-1}$, with a maximum deepening rate of 1.67 ± 0.15 m $year^{-1}$ from 15 to 18 years. Beyond 18 years, the

TABLE 1 Water deficit, maximum rooting depth of fine roots (diameter <2 mm), tree height and diameter at breast height in five orchards of different stand ages

Treatment	8 years	11 years	15 years	18 years	22 years
Water deficit below 1 m (mm)	109.66e (31.99)[a]	230.29d (38.74)	1,050.57c (70.36)	1,205.75b (23.37)	1,530.04a (43.42)
Maximum depth of <2-mm fine roots (m)	9.60e (0.40)	11.73d (0.61)	18.40c (1.05)	21.73b (0.92)	23.2a (0.8)
Tree height (m)	3.10ab (0.23)	3.02b (0.14)	3.13ab (0.13)	3.02b (0.03)	3.28a (0.15)
Diameter at breast height (cm)	11.92c (0.87)	15.36b (1.19)	18.18a (1.39)	19.98a (1.54)	19.26a (1.68)

[a]number in bracket is the standard deviation (n = 3). The maximum rooting depth in each orchard was calculated as the average of the three greatest depths where roots were found in the three soil profiles. The differences among treatments was analysed using one-way analysis of variance (ANOVA). Post-Hoc tests were performed with Turkey-LSD method with a significant level of 0.05.

deepening rate slowed considerably to 0.37 ± 0.42 m year^{-1} for stand ages 18 to 22 years.

The fractions of fine root length in the upper 1 m displayed a decreasing trend (except for that in 18-year orchard) and accounted for 26 ± 1% to 5 ± 1% of the total root length (Figure 3). The fine root length density in 8-years orchard showed an exponential decline with soil depth but the other four orchard ages showed a rather uniform distribution in the deep profile (Figure 3).

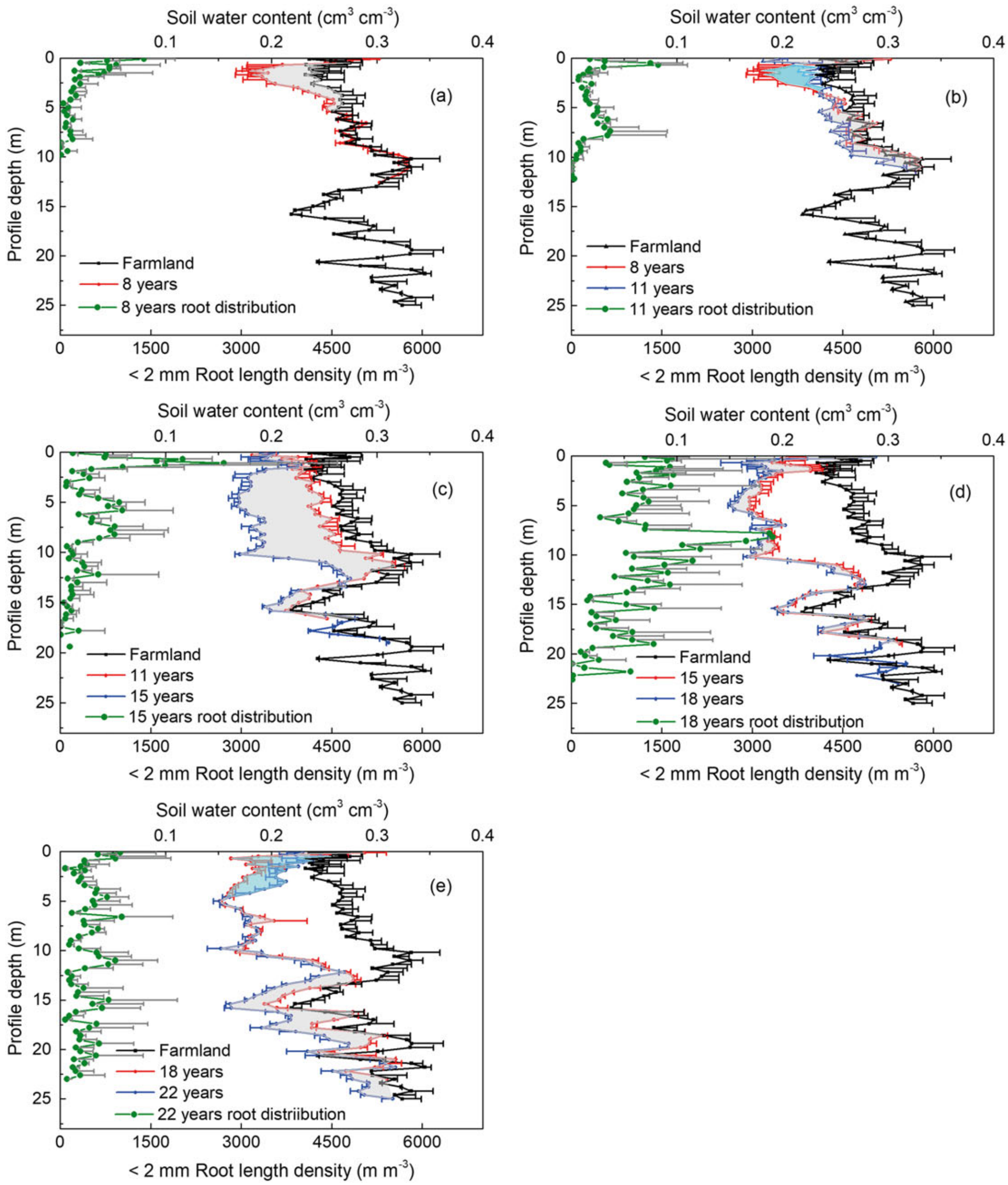

FIGURE 3 Vertical distribution of soil water contents (SWCs), and the fine root (<2 mm) distribution in (a) 8, (b) 11, (c) 15, (d) 18, and (e) 22-years apple orchard relative to the average of the three farmlands. The error bar represents the standard deviation (n = 3). SWC difference between two adjacent stand ages was coloured via grey colour and the blue area represents the SWC reduction from the older orchard to the younger one

3.2 | Deep soil water extraction as affected by stand age

In the five orchards, deep SWCs within the root zone were significantly smaller than those of the farmlands (Figure 3; $p < 0.05$), and the difference became progressively larger as the stand age increased. This suggested that enhanced evapotranspiration from apple trees not only exhausted seasonal precipitation, but also extracted additional deep soil water for transpiration. Consequently, the depth where reduction of SWC occurred became progressively greater with the increasing stand age, relative to that of farmland (the initial value before afforestation). The maximum water extraction depth (defined as the depth below which there was no discernable difference in SWC between the apple orchard and the farmland) increased with stand age from 5.6–25.2 m. The resulting depletion depth increased on average, 1.3 m year^{-1}, with the maximum of 2.0 m year^{-1} from 15 to 18 years of stand ages.

Cumulative water deficits in deep soil increased progressively with stand age from 110 to 1,530 mm (Figure 4 and Table 1). Measured SWCs within 1–12 m decreased from 0.27 ± 0.01 to 0.19 ± 0.01 cm^3 cm^{-3} in the first 15 years (Figure 3). The highest rates of water extraction occurred from stand ages 11 to 15 years during which 677 ± 60 mm additional deep soil water was removed from the 1- to 12-m. From stand ages of 15 to 18 years, the apple trees extracted additional 110 ± 42-mm water from the 1- to 12-m portion of the profile; from stand ages of 18 to 22 years, the soil water extractions occurred within depths below 12 m, and a further 415 ± 20-mm water was extracted in that 4-year period.

4 | DISCUSSION

4.1 | Why such uniform deep root profiles?

The average global maximum rooting depth are 4.6 ± 0.5 m; 7.0 ± 1.2 m for trees (Canadell et al., 1996). Our measurement showed that apple tree roots invaded the yet-unexplored deep soil at an average rate of 0.96 ± 0.56 m year^{-1} and reached

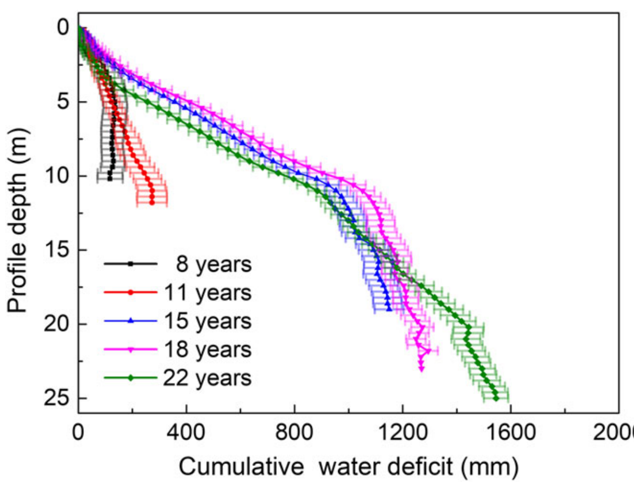

FIGURE 4 Cumulative soil water deficits for the five orchards. The error bar represents the standard deviation (n = 3)

23.2 ± 0.40 m in the 22-year old orchard. Previous work has either studied fine root distribution in shallow soil (0- to 1-m depth; Gan, Zhou, & Liu, 2010), or investigated root distribution to a depth less than maximum rooting depth. For instance, Wang, Shao, Liu, and Zhang (2012) investigated apple tree root dry weight distribution to 18-m depth, but still not reaching the maximum rooting depth as indicated by significant SWC differences between farmland and orchard. Thus, this study, for the first time, reported fine root distributions of apple trees with different ages to the maximum rooting depth on the Chinese Loess Plateau.

Previous research demonstrated that tree water use increases with the increasing diameter at breast height (Horna, Schuldt, Brix, & Leuschner, 2011; Otieno et al., 2017). In this study, the diameter at breast height generally increased with stand age (Table 1). Thus, the potential water demand should also increase with stand age. As indicated by the small water deficit and shallow rooting depth, the water demand of 8-year apple trees may mainly depend on the precipitation and soil water stored in the upper layers. Consequently, at this stand age, fine root distribution decreased exponentially with depth (Figure 3). However, as water demand increased with increasing stand age, limited precipitation and shallow soil water storage could not satisfy plant transpiration demands. This stimulated the apple trees to extract more water at greater depth by either actively developing more roots in deep soil in response to evapotranspiration demand, or activating water uptake from deep roots already developed as stand age increased, but otherwise staying dormant if deep soil water is not available for evapotranspiration. However, our key finding is that the extracted deep soil water is not replenished, which causes SWC in a given deep soil layer to decrease continuously with the increasing stand age and finally, to a lower limit for root water uptake. For example, the average SWC within 1–12 m decreased from 0.27 ± 0.01 cm^3 cm^{-3} in farmlands to 0.19 ± 0.01 cm^3 cm^{-3} in the 15-year-old orchard, and did not change thereafter. This indicated that apple trees cannot extract additional soil water from the 1- to 12-m soil layer after 15-year growth. Excessive water depletion was far greater than the marginal replenishment, which made deep soil water can be extracted only once during the life span of apple trees. This is particularly the case when the soil depth is greater than the maximum precipitation infiltration depth. Water mining caused continuous decrease of SWCs. The one-way water mining enabled apple trees to develop deeper roots to explore more available soil water at greater depths with increasing stand age, causing larger deep soil water deficits in older orchards (Figure 5). The water stressed deep roots in this study are far different in form from the reported shallow roots in humid temperate forests (Gaines et al., 2016). The water mining in deep soil changed the root profile from the exponential type in the 8-year-old orchard to the relatively uniform distribution type in old orchards.

The relatively uniform fine root distribution profiles in this study (beyond the 8-year-stand age) are quite different from the widely accepted exponential model (Schenk, 2008). Others have shown that competition with shallow rooted fibrous root systems could force woody species to develop more deep roots to extract more water from deeper layers (Cardinael et al., 2015; Kulmatiski & Beard, 2013;

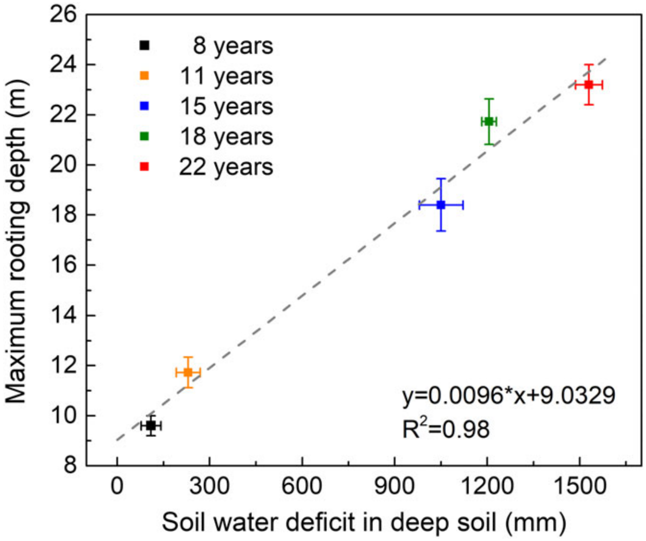

FIGURE 5 The relationship between soil water deficit in deep soil (below 1 m) and maximum rooting depth of fine roots (diameter <2 mm)

Mulia & Dupraz, 2006). Our site had little replenishment of the depleted water due to the rainfall regime and the water-demanding apple trees. We hypothesize that the relatively uniform available soil water in deep soil, resulted in the relative uniform root distribution in the soil profile.

4.2 | Mining of "old" water from the deep critical zone by apple trees

For the 1- to 12-m soil, the "control" sites in the nearby farmlands showed an average SWC of about 0.27 ± 0.01 cm^3 cm^{-3}, which can be considered as the SWC prior to the establishment of the apple orchards. By stand age 15 years, these SWC values dropped to 0.19 ± 0.01 cm^3 cm^{-3} and remained almost unchanged thereafter. This SWC value may be a lower threshold value for root water uptake. All this suggests mining of soil water on these deep loess sites. Soil water replenishment in deep rooting apple orchards in this region is very unlikely because: (a) earlier work has shown that matrix flow dominates deep soil water transport in the region with little, if any, evidence of preferential flow (Zheng, Si, Zhang, Li, & Wu, 2017); (b) annual average groundwater recharge rates in shallow root systems, such as farmlands and grasslands, were less than 60 mm $year^{-1}$ (Huang, Pang, & Edmunds, 2013; Li et al., 2016; Z. Zhang, et al., 2017); and (c) all orchards have a cumulative water deficit larger than 60 mm in the 0- to 2.8-m depth interval (Figure 4), which suggests that under matrix flow, precipitation is unable to infiltrate to a depth greater than 2.8-m depth. This deduction is demonstrated by small groundwater recharge (3 mm $year^{-1}$ in old apple orchards) reported in our study region (Zhang, Li et al., 2017). Anomalous wet years with large precipitation, may potentially result in greater infiltration depth. However, for the extreme wet year of 2003, with an annual precipitation of 954 mm, precipitation only infiltrated to 5-m depth in farmland (Liu et al., 2010). Apple trees have higher evapotranspiration rates, and thus the maximum infiltration depth should be less than 5-m depth, which is still far from the bottom of the soil water deficit layer. Furthermore, shallow roots may also "intercept" otherwise downward moving soil water before reaching deep soil, thus reducing water recharge to deep soil. This is because loess soil, being silt loam-textured, has a large capacity to store water inputs from large precipitation events, which extends water residence time and leaves enough time for plants to adsorb the water before it flows beyond the root zone. This is supported by other studies of groundwater recharge rates of 3 to 58 mm $year^{-1}$ elsewhere on the Chinese Loess Plateau (Huang et al., 2013; Li et al., 2016; Zhang, Li et al., 2017). Moreover, the reported recharge rate corresponds to a pore water velocity less than 0.17 m $year^{-1}$, whereas our measured root deepening rate was between 0.37 ± 0.42 and 1.67 ± 0.15 m $year^{-1}$, outpacing the water recharge velocity by as much as nine times. Thus, the extracted water in deep soil is "old" soil water that recharged many years, decades, or centuries earlier. Indeed, such a conceptual model is supported by our previous work where we found average tritium values in the apples that represented a mean extracted soil water age of 29 years (Zhang, Evaristo et al., 2017).

The root deepening rates showed a sharp reduction from 1.11 ± 0.60 m $year^{-1}$ for stand ages between 15 and 18 years to 0.37 ± 0.42 m $year^{-1}$ for stand ages between 18 and 22 years (Table 1), suggesting that the root deepening rates may be much smaller at ages beyond 22 years or older. These data suggest that these 22-year-old apple trees may be close to or have reached their maximum depth of water access. We predict that this enhanced evapotranspiration of the old water cannot be sustained due to the lack of replenishment of the depleted water and that it will gradually reduce to an amount that is equal to the precipitation when the "mineable" deep soil water is depleted.

4.3 | Comparison with other ecosystems and implications

In humid regions and in Mediterranean climates, deep soil water is often replenished by wet or nongrowing season precipitation (Aulenbach & Peters, 2018; Ivanov et al., 2012; Rempe & Dietrich, 2018). However, unlike the often-measured deep soil water replacement, the extracted deep soil water is not replenished at our site. Instead, we show that SWCs in deep soil are undergoing a unidirectional decrease. Ecohydrologically, this further stimulates root penetration to deeper soil to mine deep water. This negative feedback in rooting depth and the depth of soil water uptake is fundamentally different from the repetitive cycle shown in previous work (Nepstad et al., 1994; Aulenbach & Peters, 2018; Rempe & Dietrich, 2018). It implies that in addition to changes in climate (Gao et al., 2014), soil and water table depth (Fan et al., 2017), the availability of old soil water storage at depth may also be important in regulating outcomes of afforestation efforts on the loess plateau, where plantations on former farmland or grassland effectively mine the deep critical zone. Extensive deep soil water extraction shown in this study is quite different from the root water uptake in shallow soil underlain by weathered bedrock, where trees have been shown to depend more on shallow soil water (Gaines et al., 2016; Querejeta, Estrada-Medina, Allen, & Jimenez-Osornio, 2007), or thrive on water within rock cracks (Hasenmueller et al., 2017; Schwinning, 2010).

5 | CONCLUSIONS

We performed deep root and soil water mapping on the Chinese Loess Plateau and found evidence of tree root mining of the deep unsaturated critical zone. Soil water deficits increased with stand age and the water extracted from deep soils can be from as deep as 25 m. Because of no replenishment over the lifespan of individual apple trees, SWCs in deep soil showed a unidirectional decrease with depth. The feedback of growth of roots and subsequent depletion of water in the deep critical zone led to relatively uniform root distributions with depth. This is in contrary to the widely used exponential root distribution profile in most earth system models. Our work further suggests that "old" water in deep soil plays a significant role in regulating water consumption and the rooting profile.

ACKNOWLEDGMENTS

This study was funded by the National Natural Science Foundation of China (41630860, 41371233, and 41601222), the Fundamental Research Funds for the Central Universities (2452017317) and the 111 Project [No. B12007]. Special thanks to the staff of the Changwu CERN station.

ORCID

Bingcheng Si https://orcid.org/0000-0002-7497-5033

REFERENCES

Ameli, A., Gabrielli, C., Mortgenster, U., & Mcdonnell, J. J. (2018). Groundwater subsidy from headwaters to their parent watershed: A combined field-modeling approach. *Water Resources Research*, *54*. https://doi.org/10.1029/2017WR022356

Aulenbach, B. T., & Peters, N. E. (2018). Quantifying climate-related interactions in shallow and deep storage and evapotranspiration in a forested, seasonally water-limited watershed in the Southeastern United States. *Water Resources Research*, *54*, 3037–3061. https://doi.org/10.1002/2017wr020964

Brantley, S. L., Eissenstat, D. M., Marshall, J. A., Godsey, S. E., Balogh-Brunstad, Z., Karwan, D. L., … Weathers, K. C. (2017). Reviews and syntheses: On the roles trees play in building and plumbing the critical zone. *Biogeosciences Discussions*, 1–41. https://doi.org/10.5194/bg-2017-61

Brooks, J. R., Barnard, H. R., Coulombe, R., & McDonnell, J. J. (2009). Ecohydrologic separation of water between trees and streams in a Mediterranean climate. *Nature Geoscience*, *3*, 100–104. https://doi.org/10.1038/ngeo722

Canadell, J., Jackson, R. B., Ehleringer, J. B., Mooney, H. A., Sala, O. E., & Schulze, E. D. (1996). Maximum rooting depth of vegetation types at the global scale. *Oecologia*, *108*, 583–595. https://doi.org/10.1007/BF00329030

Cardinael, R., Mao, Z., Prieto, I., Stokes, A., Dupraz, C., Kim, J. H., & Jourdan, C. (2015). Competition with winter crops induces deeper rooting of walnut trees in a Mediterranean alley cropping agroforestry system. *Plant and Soil*, *391*, 219–235. https://doi.org/10.1007/s11104-015-2422-8

Evaristo, J., Jasechko, S., & McDonnell, J. J. (2015). Global separation of plant transpiration from groundwater and streamflow. *Nature*, *525*, 91–94. https://doi.org/10.1038/nature14983

Evaristo, J., & McDonnell, J. J. (2017). Prevalence and magnitude of groundwater use by vegetation: A global stable isotope meta-analysis. *Scientific Reports*, *7*, 44110. https://doi.org/10.1038/srep44110

Fan, Y., Miguezmacho, G., Jobbágy, E. G., Jackson, R. B., Oterocasal, C. 2017. Hydrologic regulation of plant rooting depth. Proceedings of the National Academy of Sciences of the United States of America: 10572–10577.

Gaines, K. P., Stanley, J. W., Meinzer, F. C., McCulloh, K. A., Woodruff, D. R., Chen, W., … Eissenstat, D. M. (2016). Reliance on shallow soil water in a mixed-hardwood forest in central Pennsylvania. *Tree Physiology*, *36*, 444–458. https://doi.org/10.1093/treephys/tpv113

Gan, Z., Zhou, Z., & Liu, W. (2010). Vertical distribution and seasonal dynamics of fine root parameters for apple trees of different ages on the Loess Plateau of China. *Agricultural Sciences in China*, *9*, 46–55. https://doi.org/10.1016/s1671-2927(09)60066-3

Gao, H., Hrachowitz, M., Schymanski, S. J., Fenicia, F., Sriwongsitanon, N., & Savenije, H. H. G. (2014). Climate controls how ecosystems size the root zone storage capacity at catchment scale. *Geophysical Research Letters*, *41*(22), 7916–7923. https://doi.org/10.1002/2014GL061668

Grant, G. E., & Dietrich, W. E. (2017). The frontier beneath our feet. *Water Resources Research*, *53*, 2605–2609. https://doi.org/10.1002/2017WR020835

Hasenmueller, E. A., Gu, X., Weitzman, J. N., Adams, T. S., Stinchcomb, G. E., Eissenstat, D. M., … Kaye, J. P. (2017). Weathering of rock to regolith: The activity of deep roots in bedrock fractures. *Geoderma*, *300*, 11–31. https://doi.org/10.1016/j.geoderma.2017.03.020

Horna, V., Schuldt, B., Brix, S., & Leuschner, C. (2011). Environment and tree size controlling stem sap flux in a perhumid tropical forest of Central Sulawesi, Indonesia. *Annals of Forest Science*, *68*, 1027–1038. https://doi.org/10.1007/s13595-011-0110-2

Huang, T., Pang, Z., & Edmunds, W. M. (2013). Soil profile evolution following land-use change: Implications for groundwater quantity and quality. *Hydrological Processes*, *27*, 1238–1252. https://doi.org/10.1002/hyp.9302

Ivanov, V. Y., Hutyra, L. R., Wofsy, S. C., Munger, J. W., Saleska, S. R., de Oliveira, R. C., & de Camargo, P. B. (2012). Root niche separation can explain avoidance of seasonal drought stress and vulnerability of overstory trees to extended drought in a mature Amazonian forest. *Water Resources Research*, *48*. https://doi.org/10.1029/2012wr011972

Klenke, J. M., & Flint, A. L. (1991). Collimated neutron probe for soil water content measurements. *Soil Science Society of America Journal*, *55*, 916–923. https://doi.org/10.2136/sssaj1991.03615995005500040003x

Kulmatiski, A., & Beard, K. H. (2013). Woody plant encroachment facilitated by increased precipitation intensity. *Nature Climate Change*, *3*, 833–837. https://doi.org/10.1038/nclimate1904

Li, H., Si, B. C., Jin, J. J., Zhang, Z. Q., Li, H. J., Wu, Q. F., & Wang, H. X. (2016). Estimation of deep drainage rates on the slope of Loess Plateau based on the use of environmental tritium. *Journal of Soil and Water Conservation*, *30*, 91–95.

Liu, D. (1985). *Loess and the environment*. Beijing: China Ocean Press.

Liu, W., Zhang, X. C., Dang, T., Ouyang, Z., Li, Z., Wang, J., … Gao, C. (2010). Soil water dynamics and deep soil recharge in a record wet year in the southern Loess Plateau of China. *Agricultural Water Management*, *97*, 1133–1138. https://doi.org/10.1016/j.agwat.2010.01.001

Maeght, J. L., Rewald, B., & Pierret, A. (2013). How to study deep roots—and why it matters. *Frontiers in Plant Science*, *4*, 299. https://doi.org/10.3389/fpls.2013.00299

McDonnell, J. J., Evaristo, J., Bladon, K. D., Buttle, J., Creed, I. F., Dymond, S. F., … Tague, C. (2018). Water sustainability and watershed storage.

Nature Sustainability, *1*, 378–379. https://doi.org/10.1038/s41893-018-0099-8

Mulia, R., & Dupraz, C. (2006). Unusual fine root distributions of two deciduous tree species in Southern France: What consequences for modelling of tree root dynamics? *Plant and Soil*, *281*, 71–85. https://doi.org/10.1007/s11104-005-3770-6

Nepstad, D. C., de Carvalho, C. R., Davidson, E. A., Jipp, P, H., Lefebvre, P. A., Negreiros, G. H., … Vieira, S. (1994). The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature*, *372*, 666–669. https://doi.org/10.1038/372666a0

Nijzink, R. C., Samaniego, L., Mai, J., Kumar, R., Thober, S., Zink, M., … Hrachowitz, M. (2016). The importance of topography-controlled sub-grid process heterogeneity and semi-quantitative prior constraints in distributed hydrological models. *Hydrology and Earth System Sciences*, *20*, 1151–1176. https://doi.org/10.5194/hess-20-1151-2016

Oliveira, R. S., Bezerra, L., Davidson, E. A., Pinto, F., Klink, C. A., Nepstad, D. C., & Moreira, A. (2005). Deep root function in soil water dynamics in cerrado savannas of central Brazil. *Functional Ecology*, *19*, 574–581. https://doi.org/10.1111/j.1365-2435.2005.01003.x

Otieno, D., Li, Y., Liu, X., Zhou, G., Cheng, J., Ou, Y., … Tenhunen, J. (2017). Spatial heterogeneity in stand characteristics alters water use patterns of mountain forests. *Agricultural and Forest Meteorology*, *236*, 78–86. https://doi.org/10.1016/j.agrformet.2017.01.007

Pierret, A., Maeght, J. L., Clement, C., Montoroi, J. P., Hartmann, C., & Gonkhamdee, S. (2016). Understanding deep roots and their functions in ecosystems: An advocacy for more unconventional research. *Annals of Botany*, *118*, 621–635. https://doi.org/10.1093/aob/mcw130

Querejeta, J. I., Estrada-Medina, H., Allen, M. F., & Jimenez-Osornio, J. J. (2007). Water source partitioning among trees growing on shallow karst soils in a seasonally dry tropical climate. *Oecologia*, *152*, 26–36. https://doi.org/10.1007/s00442-006-0629-3

Rempe, D. M., & Dietrich, W. E. (2018). Direct observations of rock moisture, a hidden component of the hydrologic cycle. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 2664–2669. https://doi.org/10.1073/pnas.1800141115

Schenk, H. J. (2008). The shallowest possible water extraction profile: A null model for global root distributions. *Vadose Zone Journal*, *7*, 1119–1124. https://doi.org/10.2136/vzj2007.0119

Schwinning, S. (2010). The ecohydrology of roots in rocks. *Ecohydrology: N/a-N/a.*. https://doi.org/10.1002/eco.134

Wang, Y. Q., Shao, M. A., Liu, Z. P., & Zhang, C. C. (2012). Changes of deep soil desiccation with plant growth age in the Chinese Loess Plateau. *Hydrology and Earth System Sciences Discussions*, *9*, 12029–12060. https://doi.org/10.5194/hessd-9-12029-2012

Ward, S. E., Smart, S. M., Quirk, H., Tallowin, J. R., Mortimer, S. R., Shiel, R. S., … Bardgett, R. D. (2016). Legacy effects of grassland management on soil carbon to depth. *Global Change Biology*, *22*, 2929–2938. https://doi.org/10.1111/gcb.13246

Wiesmeier, M., Spörlein, P., Geuß, U., Hangen, E., Haug, S., Reischl, A., … Kögel-Knabner, I. (2012). Soil organic carbon stocks in southeast Germany (Bavaria) as affected by land use, soil type and sampling depth. *Global Change Biology*, *18*, 2233–2245. https://doi.org/10.1111/j.1365-2486.2012.02699.x

Zhang, Z., Li, M., Si, B., & Feng, H. (2017). Deep rooted apple trees decrease groundwater recharge in the highland region of the Loess Plateau, China. *The Science of the Total Environment*, *622-623*, 584–593. https://doi.org/10.1016/j.scitotenv.2017.11.230

Zhang, Z. Q., Evaristo, J., Li, Z., Si, B. C., & McDonnell, J. J. (2017). Tritium analysis shows apple trees may be transpiring water several decades old. *Hydrological Processes*, *31*, 1196–1201. https://doi.org/10.1002/hyp.11108

Zheng, S. K., Si, B. C., Zhang, Z. Q., Li, M., & Wu, Q. F. (2017). Mechanism of rainfall infiltration in apple orchards on Loess Tableland, China. *Chinese Journal of Applied Ecology*, *28*, 2870–2878.

How to cite this article: Li H, Si B, Wu P, McDonnell JJ. Water mining from the deep critical zone by apple trees growing on loess. *Hydrological Processes*. 2019;33:320–327. https://doi.org/10.1002/hyp.13346