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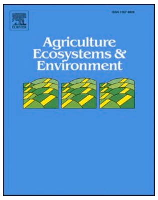

Afforestation triggers water mining and a single pulse of water for carbon trade-off in deep soil

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ABSTRACT

Clarifying the water-root-carbon nexus in the entire root zone is crucial for unlocking the potential of afforestation in mitigating climate change. But the nexus in deep soil (depth > 1 m) remains poorly understood. Here we report contrasts in deep soil water and root distributions across 72 paired sites of adjacent farmlands, representing typical pre-afforestation conditions, and tree plantations, representing modern afforestation across the Loess Plateau of China. Ranging from 6 to 25 m of depth, these profiles included plantations of 13 tree species ranging from 1 to 25 years of age. The observations revealed sustained water mining in deep soil following afforestation with mean soil water decline of 75.2 ± 9.8 mm yr^{-1} that were accompanied by root deepening rates of 1.00 ± 0.06 m yr^{-1} with an associated biomass input of 0.18 ± 0.04 Mg C ha^{-1} yr^{-1}. A water for carbon trade-off in deep soil become evident, likely involving a single pulse of C gains and water losses as no signs of soil rewetting under tree plantations where observed total soil water exhaustion that accumulated the equivalent of up to 2.8 years of mean annual precipitation inputs. The reported water-root-carbon nexus reveals overlooked hydrological costs and, more importantly, over-optimistic expectations of sustained C sequestration under afforestation that may rather represent a single-pulsed C gain supported by deep soil water exhaustion.

1. Introduction

Afforestation has been placed on the United Nations' 2030 Agenda for Sustainable Development due to its potential for carbon sequestration and ecological restoration (Desa, 2016). Global afforestation is increasing rapidly with most restoration efforts being focused on temperate water-limited regions (Liu et al., 2008; Song et al., 2018; Chen et al., 2019) where increasing water demand by planted forests can be of concern as tree establishment raises evapotranspiration rates compared to pre-afforestation farming and grazing conditions, compromising water storage and yield. Decreases in stream flow and groundwater storage have frequently been reported with afforestation (Feng et al., 2016; de Ferraz et al., 2019; Wu et al., 2019), pointing out a water for carbon trade-off with its implementation (Jackson et al., 2005; Gherardi and Sala, 2020). So far, most work on this problem has focused on regions of shallow soils where the bulk of tree rooting is concentrated above the top meter (Germon et al., 2020). However, many regions of the world show much greater soil depth (Shangguan et al., 2017). This is especially the case for loess deposits which cover about 6% of the Earth's surface (Li et al., 2020). Loess soils are dispersive and erosion reduction has been the early aim of many afforestation efforts, the largest of which is the Grain for Green Program on the China's Loess Plateau, with benefits in terms of C (carbon) sequestration being a more recent aspect of interest. In this region, where unconsolidated sediments are often deeper than 30 m, 16,000 km^2 of croplands have already been converted to planted woody vegetation over the current century (Feng et al.,

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2016). Therefore, exploring the interactions between water consumption and carbon sequestration in deep soil (here defined as >1 m in depth) holds immense importance in understanding the sustainability of the afforestation initiatives on the Loess Plateau and other water-limited regions worldwide that possess deep soil.

Plant roots adjust their growth and architecture in response to changes in soil water status (Brunner et al., 2015). Access to water during periodical or prolonged drought events stimulates roots extend to deep soil (Germon et al., 2020). At the global scale, the maximum rooting depth of trees is up to 7.0 ± 1.2 m, with certain tropical trees are capable of growing roots to a depth of 20–50 m or more (Fan et al., 2017). In addition, some trees can grow roots deep into weathered and fractured rock beyond the soil layers to access water supplies that shallow roots cannot (Rempe and Dietrich, 2018). In the Amazonian rain forest, taller trees have deeper rooting systems, which enable them to access deeper soil moisture and make them more resilient to drought (Molina et al., 2019). For the *fusiformis* in Texas, the hydraulic conductance of 20 m deep roots increased 2.6-fold during severe drought, thus avoiding total hydraulic failure (Johnson et al., 2014). For the tree-dominated *cerrado denso* ecosystem in tropical savannas, about 82% of the ET comes from deep soil (Oliveira et al., 2005). In a sub-humid region on the Loess Plateau, the water extrected by deep roots contributed about 40% of apple trees transpiration (Li et al., 2021). Therefore, to combat drought stress, growing deep roots to extract water beyond shallow soil appears to be a widespread phenomenon among tree species globally.

Beyond hydrology, the production and turnover of fine roots significantly affects global carbon cycle (McCormack et al., 2015). In a large fraction of terrestrial ecosystems, the fraction of total net productivity allocated belowground exceeds 50% and decreases from arid to humid ecosystems (Gherardi and Sala, 2020). Accompany with the benefits of deep soil water, recent research has highlighted the significance of deep roots in forest ecosystems in terms of carbon sequestration (Thorup-Kristensen et al., 2020). It has been found that the root biomass in deep soil can constitute a substantial proportion of the total forest root biomass (Wu et al., 2021; Wang et al., 2022), and in some cases, this proportion even close to 50% (Li et al., 2019a). These findings have important implications for our understanding the function of forests in mitigating climate change, as deep soil C is thought to be a more stable and long-term carbon sink compared to aboveground biomass (Gao et al., 2018). While several studies have quantified tree water use and water depletion in deep soil, their sampling depth rarely taps the deepest roots, thereby possibly underestimating forest water demand and carbon sequestration. Moreover, deep soil is normally neglected in current land surface models and large-scale field observations (Ochsner et al., 2013), meaning that the water-root-carbon nexus in deep soil are poorly represented.

The aim of this study was to explore the water-root-carbon nexus in deep soil following afforestation using the paired borehole experimental design and measured soil water contents, root profiles, and carbon inputs by root biomass on the Loess Plateau of China. This study took advantage of the combination of the ongoing most ambitious afforestation initiative in the world and the deep vadose zone of loessal soils to explore a poorly constrained aspect of water-carbon trade-offs, due to the deep boundary of ecosystems.

2. Materials and methods

2.1. Site description

Our sampling sites are located on the Loess Plateau of China, the most concentrated loess area on Earth, with an area of approximately 6.4×10^5 km^2. The thickness of the loess here is greater than 30 m in most areas; the topsoil is predominantly silty loam to sandy loam with a silt (0.002–0.05 mm) content ranging from 50% to 70%. This region has a temperate continental monsoon climate, with annual precipitation ranging from 240 mm to 700 mm; approximately 85% of which occurs during the growing season (from April to October). The dryness index, defined as the ratio of annual potential evapotranspiration to annual precipitation (ET_p/P), is 2.08 ± 0.09. This region once had the largest rates of agricultural soil erosion in the world. To alleviate agricultural soil erosion and restore the degraded ecosystem, the Grain for Green Program was initiated on the Loess Plateau since 1999. This program converted 16,000 km^2 of rain-fed farmland to planted vegetation, resulting in vegetation coverage increased from 31.6% in 1999 to 59.6% in 2013 (Chen et al., 2015). As a result, traditional cultivated crops were replaced with grasses (e.g., *Medicago sativa* Linn.), shrubs (e.g., *Caragana microphyllla* Lam. and *Hippophae rhamnoides* Linn.) and trees (e.g., *Robinia pseudoacacia* Linn., *Pinus tabulaeformis* Carr., *Ziziphus jujube* Mill. and *Malus pumila* Mill.).

2.2. Soil water and root profile observations

A paired experimental design was conducted to investigate soil water, root and carbon changes in the lands afforested for different years. Each paired site had two adjacent sampling locations: one was in shallow-rooting farmland/grassland, and the other was in a deep-rooting forest (Fig. 1a). To understand the root water uptake process following afforestation, we collected 72 paired sites on the Loess Plateau, of which 42 were collected from 12 published reports, and 11 of the 42 paired water profiles reached the maximum rooting depth of the forest (i.e., the soil water content at the bottom of forest site converged with that in adjacent farmland/grassland) (Tab. S1). The remaining 30 were measured in this study from 2016 to 2018, and all of them were sampled to depths below the maximum rooting depth. These profiles, varying in depth from 6 to 25 m, included sites occupied by 13 different tree species distributed across a broad climate gradient with annual precipitation ranging from 240 to 700 mm. The stand ages of the sampled forest—the number of years since the trees were planted—ranged from 1 to 25 years. We tested the null hypothesis that soil water storage (SWS) in deep soil is the same under non-irrigated rain-fed farmland and planted forest across a broad range of precipitation gradients and tree species.

We collected 24 forest roots profiles among the 30 sites (Tab. S2). A root auger with an internal diameter of 8.5 cm was used to collect soil samples at 20 cm sampling intervals to the depths (5–25 m) where no roots were found. To minimize the effect of spatial variability, the sampling point was selected at position that was one-fourth of the diagonal (formed by four adjacent trees) length from the tree trunk at each site (Fig. 1a), according to our previous research on root distribution at different positions around the trunk of apple tree (Li et al., 2019a; Li et al., 2019b). Each soil sample was mixed thoroughly and a subsample was collected in an aluminum box and was then oven-dried at 105 °C to determine the gravimetric soil water content. The remaining soil sample was washed carefully using a 1 mm sieve to obtain fresh root samples. The roots were then scanned on an Epson V700 flatbed scanner (Epson America, Inc.). The scanned images were analyzed with the WinRHIZO image analysis software (Regent Instruments Inc.) to calculate the total root lengths of different diameters in a soil sample. The percentage of fine root (< 2 mm) length in a certain layer was calculated as the fine root length in this layer divided by the total fine root length over the whole soil profile. After scanning, the fresh roots were oven-dried at 60 °C for 72 h and weighed to determine the dry weights. To calculate the soil water storage decrease, the gravimetric soil water content in each layer was multiplied by the ratio of the soil bulk density to pure water density to obtain the volumetric soil water content. Soil bulk density profiles were collected at 20 sites on the Loess Plateau and three of them were sampled to depths of greater than 20 m using a small drill rig (POWERPROBE 9520, AMS Company, USA) in Changwu County and a large drill rig (DPP 100, BJTK Company, CHN) in Weinan City and Haiyuan County.

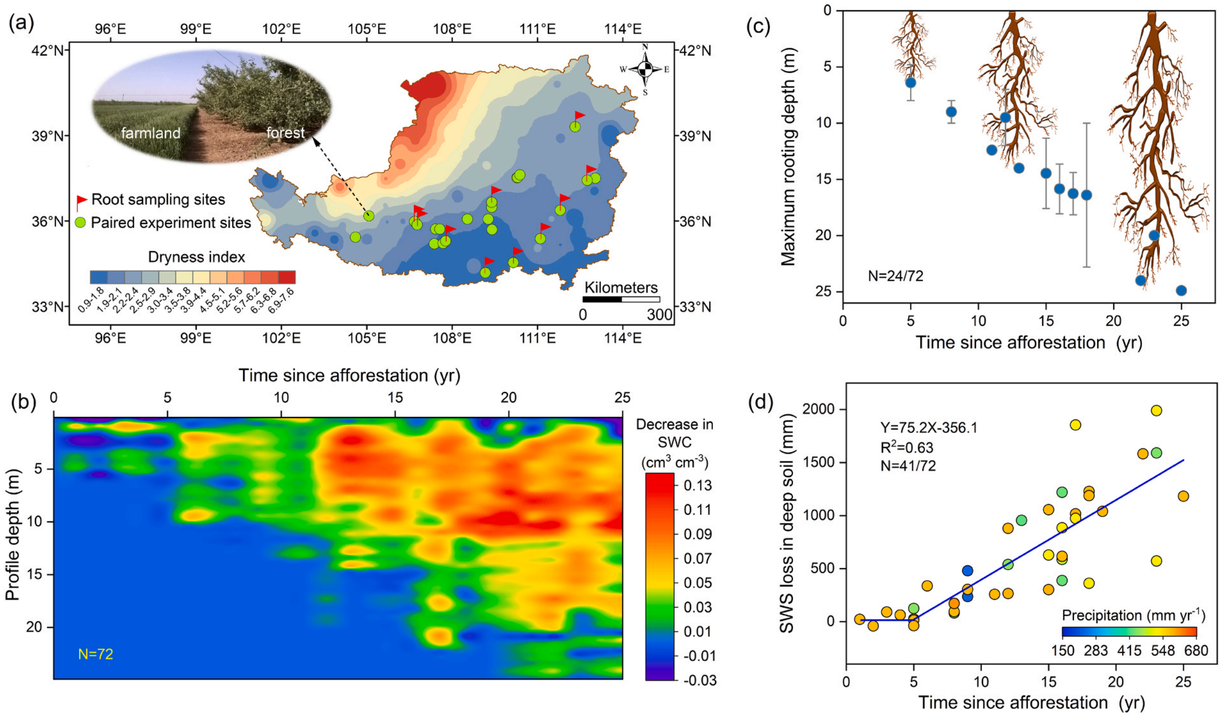

Fig. 1. The study area and sampling sites on the Loess Plateau of China. The 24 green circles represent the sites where 72 pairs of forest and adjacent farmland and grassland soil water profiles were measured. The 10 red flags represent the sites where a total of 24 forest root profiles were collected. (b) Evolution of the decrease of soil water content (SWC) following afforestation in shallow-rooting farmlands and grasslands. The SWC decrease at a given depth was calculated using the soil water content in farm- and grassland areas minus that in the corresponding forest. (c) The maximum rooting depth of trees across stands ages. (d) The decrease of soil water storage (SWS) in deep soil following afforestation. Circles filled with different colors represent different precipitation amount. Because not all sites were sampled to the maximum rooting depth, a total of 41 paired soil water profiles that sampled to the maximum rooting depth were used in the curve fitting.

2.3. Calculation of water loss in deep soil

Water loss in deep soil following afforestation was quantified by the decrease of soil water content (SWC) and soil water storage (SWS). Deep soil refers to the soil with a depth greater than 1 m (Pierret et al., 2016; Germon et al., 2020). We define the decrease of SWC after afforestation as the SWC differences between the farmlands/grasslands and forests. We then calculate the decrease of SWS in deep soil by integrating the SWC decrease over depth in deep soil:

$$\Delta S_t = \int_1^{R_m} (\theta_{SR} - \theta_{DR}) dz \tag{1}$$

where ΔS_t is the total deep soil water storage decrease caused by root water uptake by deep-rooting trees, mm; θ_{SR} and θ_{DR} are the soil water contents under shallow-rooting farmlands or grasslands and deep-rooting trees, m^3 m^{-3}, respectively. R_m is the maximum water depletion depth for trees, m.

3. Results

3.1. Continuous water mining in deep soil following afforestation

Following afforestation, SWC in shallow soil fluctuated greatly, but SWC in deep soil experienced a continuous decrease with stand age (Fig. 1b). We use the term ‘water mining’ here to emphasize that the water extracted by forest roots has not been replenished. Water mining depths gradually increased with increasing stand age, and were deeper than 20 m for trees older than 20 years. The mining front changed with time and coincided with the evolving maximum rooting depth as trees grew (Fig. 1b, c and Fig. S1). No observable water loss occurred beneath the maximum rooting depth. Because of the water mining, the average SWC within 1–25 m depth, relative to that of the farmland or grassland, decreased with stand age, reaching 0.056 ± 0.037 cm^3 cm^{-3} for trees planted 21–25 years (Fig. 1b and Fig. 2), accounting for 25% of the reported field capacity on the Loess Plateau (Wang et al., 2012). For trees older than 15 years, the SWC within 1–10 m depth changed slightly, and thus water mining in the deep soil occurred mainly in the soil layers deeper than 10 m (Fig. 1b).

The intensive water mining in deep soil considerably decreased SWS (Fig. 1d). SWS decreases in deep soil appeared approximately five years after afforestation, and increased linearly from 5 to 25 years ($P < 0.05$, $R^2 = 0.63$) (Fig. 1d). For forests between 5 and 25 years old, available

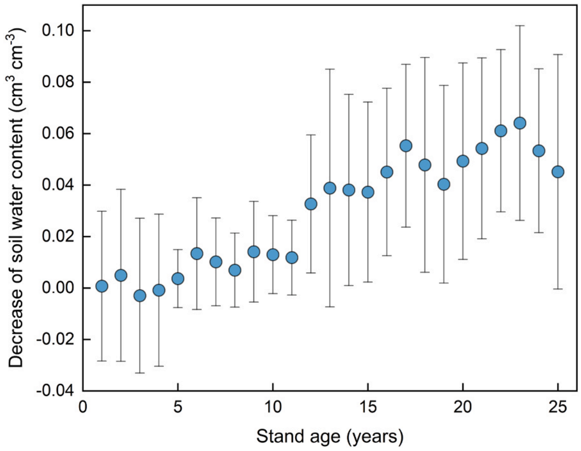

Fig. 2. The decrease of soil water content (SWC) from depths of 1–25 m soil profile for afforested trees with different stand age. Error bars represent the standard deviation. If there is no measured SWC decrease profile at a certain stand age, then linear interpolation was used to derive SWC decrease at this age.

water storage in deep soil decreased by an average of 75.2 ± 9.8 mm yr^{-1}, which accounted for 15% of the mean annual precipitation (503.0 ± 91.7 mm) in the sampling regions. For forests between 21 and 25 years old, accumulated loss of deep SWS accounted for 1393 ± 238 mm, which is 2.8 times as much as the average annual precipitation.

3.2. *Fine root development accompanying water mining in deep soil*

Fine root length was highest in shallow soil (0–1 m) and generally decreased with soil depth (Fig. 3). The maximum forest rooting depth increased at a rate of 1.00 ± 0.06 m yr^{-1} and reached 22.25 ± 3.52 m below the soil surface for trees between 21 and 25 years old (Fig. 3). The rapid deepening of roots resulted in a progressive increase in the fraction of fine root length below 1 m. For trees between 21 and 25 years old, 77% ± 11% of fine root length were found in deep soil, with 50% found at a depth of 6.15 ± 2.25 m (Fig. 3 and Fig. S2). For all 24 sampled root profiles, deep soil had, on average, 62% ± 4% of the fine root length (Fig. 3 and Fig. S2).

Maximum rooting depth had a significant positive correlation with deep soil water storage loss, stand age, and plant density (number of trees per hectare) (Fig. 4). The strongest correlation occurred between maximum rooting depth and deep soil water loss. For trees of 11–15 years old, the maximum rooting depth was 12.8 ± 1.4 m (Fig. 3 and Fig. 5); and water extraction mainly occurred in the upper 10 m soil layers, causing a decrease of 610 ± 100 mm in SWS within 0–10 m depth (Figs. 1b and 5). Thereafter, with the increasing rooting depth, water extraction in deep soil took place mainly below 10 m. For trees between 21 and 25 years old, maximum rooting depth reached 22.2 ± 3.5 m (Figs. 3 and 5), and up to 756 ± 44 mm water was extracted below 10 m by deep roots (Figs. 1c and 5). This suggests that the deeper the roots, the greater the water depletion.

3.3. *Interaction between deep soil water mining and carbon input by root biomass*

The carbon inputs from root biomass generally increased with increasing stand age (Fig. 6a). On average, root biomass carbon input to deep soil was 0.18 ± 0.04 Mg ha^{-1} yr^{-1}. For trees 21–25 years old, the cumulative root biomass carbon input to deep soil was 7.91 ± 2.91 Mg ha^{-1}. Although the root dry weight densities in deep soil were less than those in shallow soil (Fig. 7), the carbon input from the root biomass in

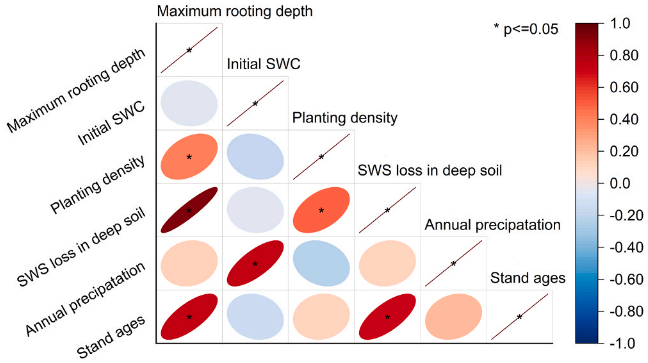

Fig. 4. Pearson rank correlation coefficients among maximum rooting depth, initial soil water content (SWC), planting density, soil water storage (SWS) loss in deep soil, stand ages, and annual precipitation. The 24 paired profiles that were sampled to the maximum rooting depth in the forest were used for correlation analyses. * Represents statistically significant correlations at a confidence of 95%.

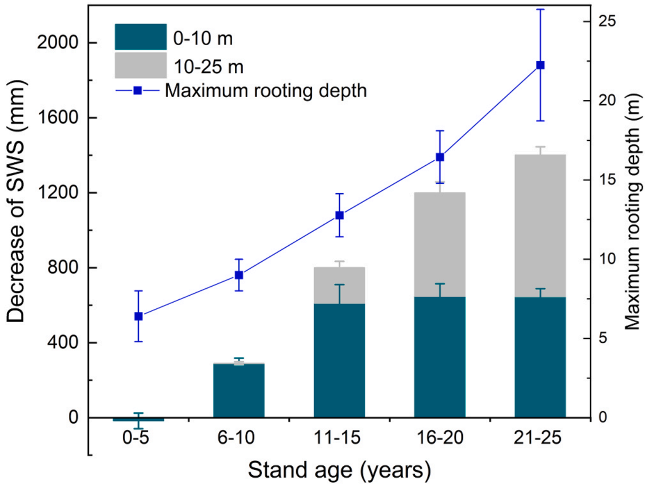

Fig. 5. The decrease of soil water storage (SWS) for 0–10 m and 10–25 m layer, and maximum rooting depth for trees with different stand ages. The error bars represent standard error.

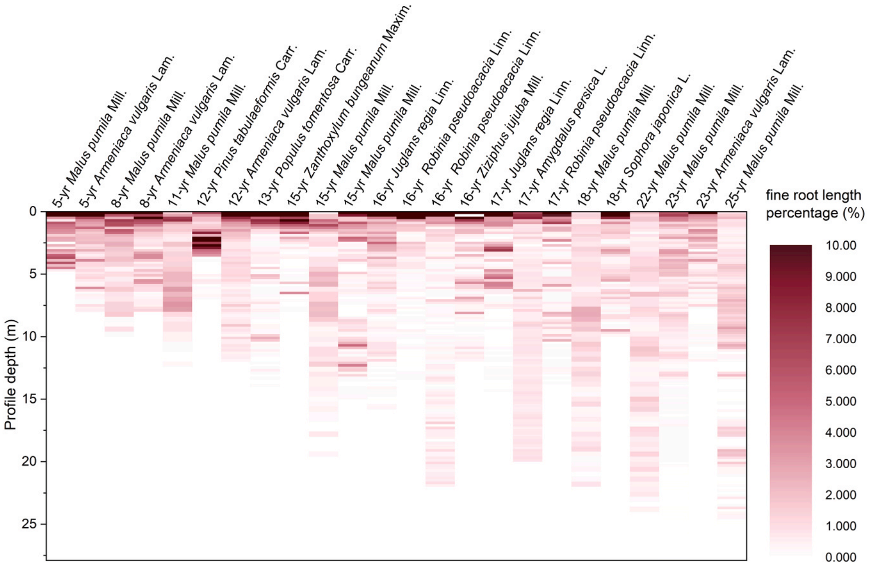

Fig. 3. Vertical profiles of fine root length percentage for the sampled 24 root profiles.

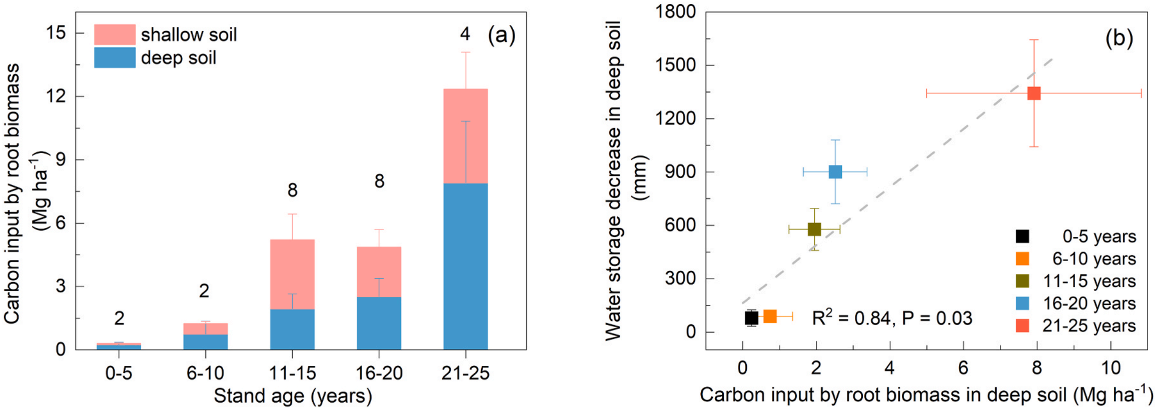

Fig. 6. Carbon inputs by root biomass with increasing stand age (a) and the relationship between carbon inputs by root biomass and water storage decreases in deep soil (b). The error bars represent the standard errors, and the values above the bars represent the corresponding numbers of observations. We assumed a root carbon content of 48.8% (Jackson et al., 1997).

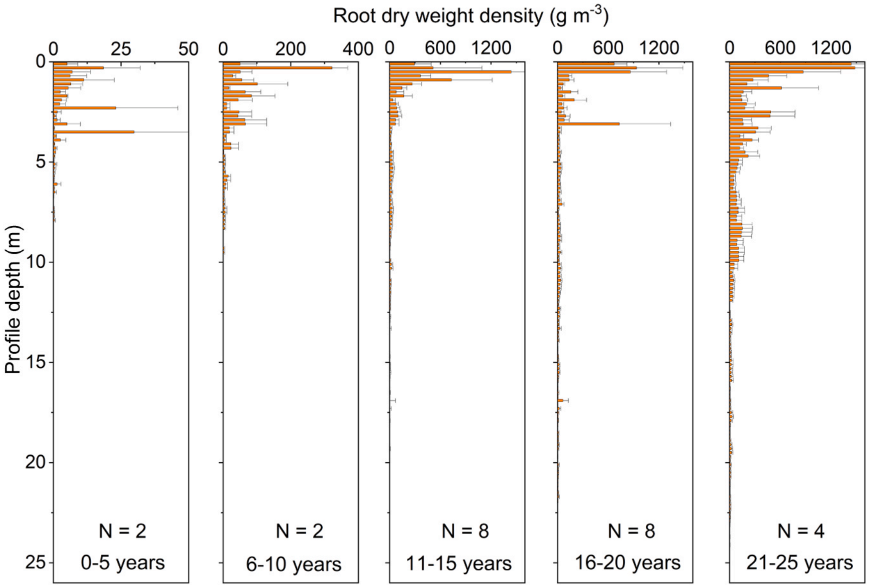

Fig. 7. Vertical distribution of root dry weight density for forest with different stand ages. The error bars represent standard error.

deep soil still accounted for 52% ± 4% of the total carbon (Fig. 6a), due to the great thickness of the root zone (Fig. 7). As shown earlier, rooting depth was correlated to deep soil water depletion (Fig. 4). Therefore, the carbon inputs by root biomass in deep soil were positively correlated with the decreases in soil water storage ($P = 0.03$, Fig. 6b), indicating a water for carbon trade-off in deep soil.

4. Discussion

4.1. Water mining progressively desiccates deep soil

Seasonal water depletion in deep soil has been observed previously in lowland Amazon forests where it enhances tree resilience to drought stress and alters the regional water cycle (Nepstad et al., 1994; Oliveira et al., 2005; Markewitz et al., 2010; Ivanov et al., 2012). Compared to our sites, precipitation in these Amazon systems is abundant and the deep soil from which water is extracted during the dry season are regularly replenished in the following wet season. This enables a sustainable intra-year depletion of deep soil water by trees (Oliveira et al., 2005; Markewitz et al., 2010). In contrast, our observations across the China's Loess Plateau shown that, for deep soil layers, depleted water stores are rarely, if ever replenished, leading to mining of deep soil water. This decreasing soil water further stimulates unsustainable feedback whereby the trees extend their roots to greater and greater depths—to soil water stocks below. The deepening of trees roots finally slows down and ceases due to the greater water transport resistance and gravitational pull for deep roots (Tyree and Zimmermann, 2002) and the large root penetration resistance in deep soil (Gao et al., 2016).

Observed water mining in deep soil appears to be controlled by three converging factors, which can help identify the same process in other regions of the world. The first factor is the dry climate with potential evapotranspiration being 2.08 ± 0.09 times higher than precipitation across the sampling sites, which physically enables exhaustive water use of atmospheric inputs plus soil reserves (Table 1). Recent work in Brazil supports this general notion whereby increasing values of aridity index under Eucalyptus plantation for 19 sites across Brazil resulted in exponential declines in annual catchment runoff ratio (de Ferraz et al., 2019). These findings and our results suggest that drier atmospheric conditions drive utilization of deep soil water by trees. The second factor is the large water storage capacity (ranging from 0.2 to 0.3 $cm^3 cm^{-3}$) (Wang et al., 2012) of loess substrates, helping retain most of the infiltrated water at accessible depths. The retained water is subsequently used for evapotranspiration, consequently leaving little water to recharge deep soil. The third factor is the root depth and deepening rates. Our

Table 1
Hydrometeorological data of the sampling sites.

	P (mm yr^{-1})	PET (mm yr^{-1})	Dryness index	GR (cm yr^{-1})	SWC in farmland/grassland (cm^3 cm^{-3})	PWV (cm yr^{-1})
Mean	503.0	1049.8	2.08	4.0	0.19	21.0
STD	91.7	18.7	0.09	2.7	0.05	8.7

Note: P, precipitation; PET, potential evapotranspiration; GR, groundwater recharge rate (from Wu et al., 2019); SWC, soil water content; PWV, pore water velocity (calculated as GR/SWC).

measured root deepening rate of 1.00 ± 0.06 m yr^{-1} is approximately 5 times as large as the reported pore water velocity of 0.21 ± 0.09 m yr^{-1} (Table 1) on the Loess Plateau. This root deepening rate outpaced the water infiltration, effectively intercepting the infiltration water, which will further diminish the opportunity of precipitation to replenish the depleted deep soil.

Root water uptake influences the water cycle by regulating transpiration, streamflow, and groundwater recharge. However, due to the inaccessibility of deep soil, most previous studies of root water uptake have focused only on shallow soil (Grant and Dietrich, 2017). Our observations showed that water mining in deep soil across the China's Loess Plateau has complemented precipitation inputs with an extra 15% coming from sustained storage depletion over more than two decades. Neglecting water mining in deep soil may considerably underestimate forest transpiration and productivity and overestimate groundwater recharge. On the other hand, it may rise expectations on tree growth and productivity in the long term, since this first generation of trees in previously tree-less sites has been benefiting from an extra source of water that has been exhausted. Our observations showed that soil water storage depletion in deep soil reached eventually 1393 ± 238 mm, 2.8 times of the annual precipitation. This suggests that for the Loess Plateau, apart from intensive atmospheric water demand, the planted trees also suffer from serious water shortage in deep soil. Consequently, the planted forest may experience more drought stress because soil moisture status dominates dryness stress on ecosystem (Liu et al., 2020). Under such conditions, trees may combat drought stress by making physiological adjustments, such as decreasing leaf area to reduce water demand (Zhang et al., 2019), suberizing roots to minimize water loss from roots to desiccated soil (Brunner et al., 2015), and producing abscisic acid to regulate stomatal conductance (Kang and Zhang, 2004). However, whether these adjustments could inhibit hydraulic failure and tree mortality under progressively more depleted deep soil is still unclear and more studies are needed to explore these mechanisms. Collectively, continuous water mining considerably decreased water storage in deep soil, reducing tree resilience to drought stress (Liu et al., 2020), and thus threatening sustainability of artificial forest and secondary forest on Loess Plateau.

4.2. *Deep soil water mining stimulates roots growth into deeper soil layers*

Understanding why and how trees develop deep roots is a research frontier that goes well beyond the China's Loess Plateau and cuts across the disciplines of hydrology, plant physiology and soil science (Schenk, 2008; Fan et al., 2017; Grant and Dietrich, 2017). Soil water availability is a critical external factor that regulates root development and plant resilience to drought stress (Brunner et al., 2015; Rempe and Dietrich, 2018). Episodes of drought or deficits in irrigation can cause plants to extract more water from deeper soil layers (Oliveira et al., 2005; Bruno et al., 2006; Markewitz et al., 2010; Brunner et al., 2015). However, how tree roots respond to long-term (decadal) water availability changes in deep soil remains poorly understood. Our observations show that trees can mine water from deep soil, resulting in a continuous decrease in soil water content within the root zone (Fig. 1b). Therefore, the current root zone fails to provide sufficient water for transpiration and this will likely force deeper vertical exploration of roots to mine water from deeper soil layers where soil water content is high. Therefore, the high water demand may be the main reason why the decrease in SWS in deep soil explained most of the variability in the maximum rooting depth, despite many other factors impacting root growth (Fig. 4). Our study showed that due to the water profitability of deep soil in loessic substrates, water mining in deep soil stimulated planted trees to seek water at depths far greater than the infiltration depths, resulting in mining of past precipitation that had infiltrated into deeper strata many decades earlier (Zhang et al., 2017; Miguez-Macho and Fan, 2021). Hence, water mining in deep soil resulted in a new plant rooting strategy, which should be considered in future root growth models.

4.3. *Water mining results in a single pulse of water for carbon trade-off in deep soil*

Agricultural land on Earth possesses an estimated carbon sink of approximately 128 Pg (Janzen, 2004) and thus alterations in agricultural land use exert a significant influence on the carbon cycles. On the global scale, the conversion of cropland to secondary forest over a span of 100 years can lead to 200% increase in soil organic carbon in the top layer (Kim et al., 2023), while concurrently resulting in about 50% reduction in stream flow (Jackson et al., 2005). In the North China Plain, with an expansion of agricultural land area by 331.2 × 10^3 hectares between 2002 and 2012, evapotranspiration increases by 25.6 × 10^8 cubic meters and net ecosystem CO_2 exchange decreases by 257.9 × 10^4 tons (Zhang et al., 2022). On the Loess Plateau of China, the Grain for Green program, which involves the conversion of croplands into grasslands and forests, is found to induce an annual carbon sink of 18.0 Tg (Lu et al., 2018) and reduced soil water storage at depths of 0–3.2 m by 2.4 ± 0.9 mm yr^{-1} (Feng et al., 2016). These findings highlight a trade-off between the increased carbon sink resulting from the afforestation and the associated intensification of water consumption. In addition, research shows that the carbon sink in deep soil is largely in the form of root biomass in an apple orchard resulting from accessing progressively deep soil water by apple trees. Moreover, the deep soil water is quite "old", having a residence time of over 50 years (Li et al., 2019b) and hard to replenish. Depletion of such 'old' water has important ramification on the sustainability of this "deep" carbon sink. But this finding is only reported at a single location with a single tree species. Therefore, it is crucial to verify the prevalence of water mining in deep soil and understand their impact on this trade-off to ensure sustainable land resources management.

Our intensive field observations on the China's Loess Plateau indicated that trees built a deep stock of C in their roots at the expenses of deep water (Fig. 1b, Fig. 3). Remarkably, carbon inputs by root biomass were positively correlated with water losses, indicating a clear water for carbon trade-off (Fig. 6b). For trees 21–25 years old, the root biomass carbon stocks in the deep soil reached 7.91 ± 2.91 Mg C ha^{-1}, which is equivalent to 15% of the carbon density of global forest aboveground biomass (Santoro et al., 2021) and 14.2% of the overall estimated aboveground and belowground vegetation carbon storage of the forest in China (Fang et al., 2018). Roots are more recalcitrant to degradation compared with topsoil litter, and the mean residence time of root-derived carbon is 2.4 times that of shoot-derived (Rasse et al., 2005). Moreover, deep roots have a lower decomposability than shallow roots due to the lower microbial biomass and oxygen limitations in deep soil (Gonkhamdee et al., 2009; Prieto et al., 2016). For the roots growing in desiccated deep soil, they have to stay alive to transport water mined from deeper strata, which will also prolong the residence time of roots in mineral soils. Therefore, the observed considerable root biomass at depth has great potential to mitigate climate change. While it is worth noting that the continuous water loss in deep soil indicated that deep soil water can only be used once for trading carbon, revealing a single pulse of water for carbon trade-off in deep soil following afforestation.

5. Conclusion

Our field observations of soil water content, root development, and carbon sequestration for the first time systematically, investigate the "hidden" water-root-carbon nexus in deep soil at decades scale. Our findings on water mining and water for carbon trade-off in deep soil reveals the vast potentials of water for carbon tradeoff in deep soil. However, once is exhausted, the deep soil water at a depth will not be replenished, resulting in a single pulsed nature of the water for carbon trade-off. Consequently, when the stand age is greater 25 years, deep soil is desiccated and the potential of using afforestation for climate mitigation is then maximized in deep soil and thus the water for carbon trade off will then be ceased. The resulting desiccated soil may also elevate the risk of tree mortality given the ever-increased drought occurrence and intensity, threatening the sustainability of afforestation. The observed water for carbon trade-off in deep soil on one hand, demonstrates the importance of deep soil in regulating forest water and carbon cycles, and on the other hand, the limited explorable soil water storage reveals the potential risks of afforestation in water limited region as the water mining prevents sustainable carbon sequestration in deep soil, and decreases trees resilience to drought stress.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All data used in this research are available from the corresponding author upon reasonable request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108655.

References

Brunner, I., Herzog, C., Dawes, M.A., Arend, M., Sperisen, C., 2015. How tree roots respond to drought. Front Plant Sci. 6, 547.

Bruno, R.D., da Rocha, H.R., de Freitas, H.C., Goulden, M.L., Miller, S.D., 2006. Soil moisture dynamics in an eastern Amazonian tropical forest. Hydrol. Process. 20, 2477–2489.

Chen, C., Park, T., Wang, X., Piao, S., Xu, B., Chaturvedi, R.K., Fuchs, R., Brovkin, V., Ciais, P., Fensholt, R., Tommervik, H., Bala, G., Zhu, Z., Nemani, R.R., Myneni, R.B., 2019. China and India lead in greening of the world through land-use management. Nat. Sustain. 2, 122–129.

Chen, Y., Wang, K., Lin, Y., Shi, W., Song, Y., He, X., 2015. Balancing green and grain trade. Nat. Geosci. 8, 739–741.

Desa, U.N., 2016. Transforming our world: The 2030 agenda for sustainable development.

Fan, Y., Miguezmacho, G., Jobbágy, E.G., Jackson, R.B., Oterocasal, C., 2017. Hydrologic regulation of plant rooting depth. Proc. Natl. Acad. Sci. USA 114, 10572–10577.

Fang, J., Yu, G., Liu, L., Hu, S., Chapin, F.S.I., 2018. Climate change, human impacts, and carbon sequestration in China. Proc. Natl. Acad. Sci. USA 115, 4015–4020.

Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat. Clim. Chang 6, 1019–1022.

de Ferraz, S.F.B., Rodrigues, C.B., Garcia, L.G., Alvares, C.A., de Lima, W.P., 2019. Effects of Eucalyptus plantations on streamflow in Brazil: moving beyond the water use debate. For. Ecol. Manag. 453, 117571.

Gao, W., Hodgkinson, L., Jin, K., Watts, C.W., Ashton, R.W., Shen, J., Ren, T., Dodd, I.C., Binley, A., Phillips, A.L., Hedden, P., Hawkesford, M.J., Whalley, W.R., 2016. Deep roots and soil structure. Plant Cell Environ. 39, 1662–1668.

Gao, X., Li, H., Zhao, X., Ma, W., Wu, P., 2018. Identifying a suitable revegetation technique for soil restoration on water-limited and degraded land: considering both deep soil moisture deficit and soil organic carbon sequestration. Geoderma 319, 61–69.

Germon, A., Laclau, J.-P., Robin, A., Jourdan, C., 2020. Tamm review: deep fine roots in forest ecosystems: why dig deeper? For. Ecol. Manag. 466, 118135.

Gherardi, L.A., Sala, O.E., 2020. Global patterns and climatic controls of belowground net carbon fixation. Proc. Natl. Acad. Sci. USA 117, 20038–20043.

Gonkhamdee, S., Maeght, J.L., Do, F., Pierret, A., 2009. Growth Dyn. fine Hevea Bras. Roots. a 4. 5-M. Soil Profile 37, 265–276.

Grant, G.E., Dietrich, W.E., 2017. The frontier beneath our feet. Water Resour. Res. 53.

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 Resour. Res. 48.

Jackson, R.B., Mooney, H.A., Schulze, E.D., 1997. A global budget for fine root biomass, surface area, and nutrient contents. Proc. Natl. Acad. Sci. USA 94, 7362–7366.

Jackson, R.B., Jobbágy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K. A., le Maitre, D.C., McCarl, B.A., Murray, B.C., 2005. Trading water for carbon with biological carbon sequestration. Science 310, 1944–1947.

Janzen, H.H., 2004. Carbon cycling in earth systems—a soil science perspective. Agric. Ecosyst. Environ. 104, 399–417.

Johnson, D.M., Sherrard, M.E., Domec, J.-C., Jackson, R.B., 2014. Role of aquaporin activity in regulating deep and shallow root hydraulic conductance during extreme drought. Trees 28, 1323–1331.

Kang, S., Zhang, J., 2004. Controlled alternate partial root-zone irrigation: its physiological consequences and impact on water use efficiency. J. Exp. Bot. 55, 2437–2446.

Kim, D.-G., Kirschbaum, M.U.F., Eichler-Löbermann, B., Gifford, R.M., Liáng, L.L., 2023. The effect of land-use change on soil C, N, P, and their stoichiometries: a global synthesis. Agric. Ecosyst. Environ. 348, 108402.

Li, H., Si, B., Ma, X., Wu, P., 2019a. Deep soil water extraction by apple sequesters organic carbon via root biomass rather than altering soil organic carbon content. Sci. Total Environ. 670, 662–671.

Li, H., Ma, X., Lu, Y., Ren, R., Cui, B., Si, B., 2021. Growing deep roots has opposing impacts on the transpiration of apple trees planted in subhumid loess region. Agric. Water Manag. 258, 107207.

Li, H.J., Si, B.C., Wu, P.T., McDonnell, J.J., 2019b. Water mining from the deep critical zone by apple trees growing on loess. Hydrol. Process. 33, 320–327.

Li, Y., Shi, W., Aydin, A., Beroya-Eitner, M.A., Gao, G., 2020. Loess genesis and worldwide distribution. Earth-Sci. Rev. 201.

Liu, J., Li, S., Ouyang, Z., Tam, C., Chen, X., 2008. Ecological and socioeconomic effects of China's policies for ecosystem services. Proc. Natl. Acad. Sci. USA 105, 9477–9482.

Liu, L., Gudmundsson, L., Hauser, M., Qin, D., Li, S., Seneviratne, S.I., 2020. Soil moisture dominates dryness stress on ecosystem production globally. Nat. Commun. 11, 4892.

Lu, F., Hu, H., Sun, W., Zhu, J., Liu, G., Zhou, W., Zhang, Q., Shi, P., Liu, X., Wu, X., Zhang, L., Wei, X., Dai, L., Zhang, K., Sun, Y., Xue, S., Zhang, W., Xiong, D., Deng, L., Liu, B., Zhou, L., Zhang, C., Zheng, X., Cao, J., Huang, Y., He, N., Zhou, G., Bai, Y., Xie, Z., Tang, Z., Wu, B., Fang, J., Liu, G., Yu, G., 2018. Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. Proc. Natl. Acad. Sci. USA 115, 4039–4044.

Markewitz, D., Devine, S., Davidson, E.A., Brando, P., Nepstad, D.C., 2010. Soil moisture depletion under simulated drought in the Amazon: impacts on deep root uptake. N. Phytol. 187, 592–607.

McCormack, M.L., Dickie, I.A., Eissenstat, D.M., Fahey, T.J., Fernandez, C.W., Guo, D., Helmisaari, H.S., Hobbie, E.A., Iversen, C.M., Jackson, R.B., Leppalammi-Kujansuu, J., Norby, R.J., Phillips, R.P., Pregitzer, K.S., Pritchard, S.G., Rewald, B., Zadworny, M., 2015. Redefining fine roots improves understanding of below-ground contributions to terrestrial biosphere processes. N. Phytol. 207, 505–518.

Miguez-Macho, G., Fan, Y., 2021. Spatiotemporal origin of soil water taken up by vegetation. Nature 598, 624–628.

Molina, A.J., Aranda, X., Llorens, P., Galindo, A., Biel, C., 2019. Sap flow of a wild cherry tree plantation growing under Mediterranean conditions: assessing the role of environmental conditions on canopy conductance and the effect of branch pruning on water productivity. Agric. Water Manag. 218, 222–233.

Nepstad, D.C., de Carvalho, C.R., Davidson, E.A., Jipp, P.H., Lefebvre, P.A., Negreiros, G. H., da Silva, E.D., Stone, T.A., Trumbore, S.E., Vieira, S., 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. Nature 372, 666–669.

Ochsner, Cosh, M.H, Cuenca, R.H., Dorigo, W.A., Draper, C.S., Hagimoto, Y., Kerr, Y.H., Larson, K.M., Njoku, E.G., Small, E.E., 2013. State of the art in large-scale soil moisture monitoring. Soil Sci. Soc. Am. J. 77, 1888–1919.

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. Funct. Ecol. 19, 574–581.

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. Ann. Bot. 118, 621–635.

Prieto, I., Stokes, A., Roumet, C., Mommer, L., 2016. Root functional parameters predict fine root decomposability at the community level. J. Ecol. 104, 725–733.

Rasse, D.P., Rumpel, C., Dignac, M.-F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant Soil 269, 341–356.

Rempe, D.M., Dietrich, W.E., 2018. Direct observations of rock moisture, a hidden component of the hydrologic cycle. Proc. Natl. Acad. Sci. USA 115, 2664–2669.

Santoro, M., Cartus, O., Carvalhais, N., Rozendaal, D.M.A., Avitabile, V., Araza, A., de Bruin, S., Herold, M., Quegan, S., Rodríguez-Veiga, P., Balzter, H., Carreiras, J., Schepaschenko, D., Korets, M., Shimada, M., Itoh, T., Moreno Martínez, Á., Cavlovic, J., Cazzolla Gatti, R., da Conceição Bispo, P., Dewnath, N., Labrière, N., Liang, J., Lindsell, J., Mitchard, E.T.A., Morel, A., Pacheco Pascagaza, A.M., Ryan, C. M., Slik, F., Vaglio Laurin, G., Verbeeck, H., Wijaya, A., Willcock, S., 2021. The global forest above-ground biomass pool for 2010 estimated from high-resolution satellite observations. Earth Syst. Sci. Data 13, 3927–3950.

Schenk, H.J., 2008. Soil depth, plant rooting strategies and species' niches. N. Phytol. 178, 223–225.

Shangguan, W., Hengl, T., de Mende Jesus, J., Yuan, H., Dai, Y., 2017. Mapping the global depth to bedrock for land surface modeling. J. Adv. Model. Earth Syst. 9, 65–88.

Song, X.P., Hansen, M.C., Stehman, S.V., Potapov, P.V., Tyukavina, A., Vermote, E.F., Townshend, J.R., 2018. Global land change from 1982 to 2016. Nature 560, 639–643.

Thorup-Kristensen, K., Halberg, N., Nicolaisen, M., Olesen, J.E., Crews, T.E., Hinsinger, P., Kirkegaard, J., Pierret, A., Dresboll, D.B., 2020. Digging deeper for agricultural resources, the value of deep rooting. Trends Plant Sci. 25, 406–417.

Tyree, M., Zimmermann, M., 2002. Xylem Structure and The Ascent of Sap. & Business Media. Springer Science, p. 2013.

Wang, S., Gao, X., Yang, M., Zhang, L., Wang, X., Wu, P., Zhao, X., 2022. The efficiency of organic C sequestration in deep soils is enhanced by drier climates. Geoderma 415, 115774.

Wang, Y., Shao, M., Liu, Z., 2012. Pedotransfer functions for predicting soil hydraulic properties of the Chinese Loess Plateau. Soil Sci. 177, 424–432.

Wu, Q., Si, B., He, H., Wu, P., 2019. Determining regional-scale groundwater recharge with GRACE and GLDAS. Remote Sens. 11, 154.

Wu, W., Li, H., Feng, H., Si, B., Chen, G., Meng, T., Li, Y., Siddique, K.H.M., 2021. Precipitation dominates the transpiration of both the economic forest (Malus pumila) and ecological forest (Robinia pseudoacacia) on the Loess Plateau after about 15 years of water depletion in deep soil. Agric. For. Meteorol. 297, 108244.

Zhang, Y., Guo, X., Pei, H., Min, L., Liu, F., Shen, Y., 2022. Evapotranspiration and carbon exchange of the main agroecosystems and their responses to agricultural land use change in North China Plain. Agric. Ecosyst. Environ. 338, 108103.

Zhang, Z., Huang, M., Zhao, X., Wu, L., 2019. Adjustments of leaf traits and whole plant leaf area for balancing water supply and demand in Robinia pseudoacacia under different precipitation conditions on the Loess Plateau. Agric. For. Meteorol. 279, 107733.

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. Hydrol. Process. 31, 1196–1201.