Catena 232 (2023) 107474

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Tritium and trees: A bomb peak perspective on soil water dynamics in semi-arid apple orchards

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A R T I C L E I N F O

Keywords:
Agroforest stand age
Soil water recharge
Soil water depletion
Tritium
Transpiration water age
Agroforests

A B S T R A C T

Understanding the relationship between agroforest age and soil water dynamics is crucial for effective land and water resources management. However, the complexities of these dynamics, such as soil water recharge and depletion, hamper in-depth understanding, particularly in water-scarce regions. In this study, we examined soil water recharge and depletion in relation to the stand age of apple trees, a widely planted and representative deep-rooted agroforest, over four years in a semi-arid region on China's Loess Plateau (CLP). We collected soil cores to >20 m depth from four apple orchards (referred to as 'agroforests') with variable stand ages (established in 2008, 2005, 1998, and 1994). For comparison, we selected adjacent cropland as land use prior to agroforestry practices ('control'). We measured soil water content and tritium distributions to model soil water dynamics and estimate water ages across different soil profiles. Our results show that recharge amounts (and depths) in shallow soils were 298.4 mm (7 m), 303.4 mm (6.6 m), 300.6 mm (5.4 m), and 483.1 mm (7.6 m), whereas deep soils had net depletions of 111.1 mm, 391.9 mm, 192.8 mm, and 108.9 mm for AP2008, AP2005, AP1998, and AP1994, respectively. The tritium peak depths, which indicate the 1963 bomb peak depth, significantly differed between agroforested and non-agroforested plots. In particular, agroforestation reduced the seepage velocity of soil water over 20 years. Furthermore, our tritium tracer water age model suggests that the age of transpired deep soil water exceeded 200 years in the oldest orchard. These findings highlight a complex interaction between newly infiltrated water and existing water, possibly due to variations in soil pore size distributions. The results of this study offer valuable insights into the ecohydrological impacts of agroforestation on the CLP and in similar climatic regions.

1. Introduction

In the past six decades, nearly one-third of the global land area has experienced significant transformations (Winkler et al., 2021). This land use has had far-reaching consequences for global sustainability, including climate change, biodiversity loss, and food security (Song et al., 2018). Agroforestry, which was described as a deliberate admixture of woody perennials or trees on the same unit of land as agricultural crops, has been widely adopted worldwide (Nair, 2013). Apple orchards as 'economic forests', dominate agroforestry in China's Loess Plateau, accounting for 22% and 27% of the coverage and fruit production of the global totals, respectively (Gao et al., 2021). However, like afforestation, agroforestry practices also significantly impact regional soil water dynamics and hydrological processes (Evaristo et al., 2019; Li et al., 2019a; Schwärzel et al., 2019), which subsequently affect plant water stress and physiological traits (Yan et al., 2017). Nevertheless, our understanding of how land cover change, particularly in relation to agroforest age, influences soil water dynamics, particularly recharge and depletion, remains limited.

The impact of land cover change on soil water dynamics is complex

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https://doi.org/10.1016/j.catena.2023.107474
Received 6 June 2023; Received in revised form 17 August 2023; Accepted 23 August 2023
Available online 26 August 2023

(Jia et al., 2017). First, land use influences rainfall partitioning, which then modifies net precipitation, that is, water that infiltrates into soils (Miralles et al., 2010). Second, land use changes the water infiltration patterns. Meta-analyses indicate that converting grasslands or croplands to forests increases infiltration rates (Archer et al., 2016; Sun et al., 2018), likely due to altered soil structure and/or root exudates (Bengough, 2012). Higher infiltration rates can enhance water recharge in the unsaturated zone (Archer et al., 2016), increasing evapotranspiration and subsequent soil water depletion (Feng et al., 2016). However, afforestation does not necessarily increase soil water storage in the unsaturated or saturated zones. Compared with crops and herbaceous plants, trees, having deeper roots (Canadell et al., 1996) and higher evapotranspiration, consume more water, leading to drainage to deeper soil layers or groundwater (Kim and Jackson, 2012).

As forests mature, changes in canopy structure, root distribution, and soil properties (Rosenqvist et al., 2010; Scott and Prinsloo, 2008) can affect soil water recharge dynamics. These dynamics, however, are nonlinear, making them challenging to understand, particularly when comparing forests of different ages.

In areas without agroforestry, such as cropland, plants typically use shallow soil water from recent infiltration (referred to as 'young water'), establishing a long-term balance between soil water recharge and evapotranspiration. However, in agroforestry areas, deep roots tend to access 'old water' from deeper parts of the soil. While studies increasingly examine water ages in streams and groundwater (Jasechko et al., 2016; Kirchner, 2016), quantifying soil water age or transpiration water age is uncommon (e.g., Evaristo et al., 2019). Global estimates suggest that ~18% of plants extract water from deeper unsaturated soils or rocks using past precipitation (Miguez-Macho and Fan, 2021). For example, tritium radioactive tracers revealed that transpiration water in mature apple orchards could be several decades old (Zhang et al., 2017). Depleting this 'old' deep soil water could decrease groundwater recharge and streamflow (Li et al., 2019a). Therefore, understanding how agroforest age relates to the age of available water for transpiration is crucial for unraveling the complex interplay between 'new' and 'old' water in the unsaturated zone.

The 'Grain-for-Green Program' implemented on the CLP stands as one of the world's largest ecological engineering and afforestation initiatives. This program effectively promoted regional greening (Chen et al., 2019) and reduced soil and water erosion (Chen et al., 2015). Despite numerous studies assessing its impact on deep soil water depletion (Bai et al., 2020; Zhang et al., 2018b) and regional hydrological processes (Schwärzel et al., 2019; Wang et al., 2011), a considerable knowledge gap exists regarding the interplay between 'new' and 'old' soil water in thick vadose zones. In the deep vadose zone of the CLP, infiltration water is assumed to move via translatory flow or piston flow (Huang et al., 2017; Tao et al., 2021a), displacing the old soil water by recently infiltrated new water. The hydrologic connectivity between precipitation and deep soil water dynamics has been rarely considered, with preferential flow assumed to occur only at the edges of the CLP via macropores, cracks, and fissures (Xiang et al., 2018). In the last decade, several studies have provided evidence supporting the loosely defined 'ecohydrological separation' hypothesis, also known as the 'two water worlds' hypothesis (Brooks et al., 2010; Evaristo et al., 2015). This hypothesis posits that plants use water isotopically distinct from the water recharging the groundwater system and discharging into streams. Among the many unresolved questions regarding the ecohydrological separation hypothesis and soil–plant water relations in general, the interplay between new and old soil water in thick vadose zones remains a significant area of inquiry.

Various studies have suggested slow, piston-like water movement on event or monthly timescales in water-limited areas (Wang and Wang, 2018; Wu et al., 2021). Our study contributes to this existing body of knowledge by conducting a multi-year analysis of soil water dynamics and their relationship with agroforest age. Specifically, we aim to provide clear answers to the following questions: (1) How does agroforest age influence soil water dynamics, particularly in terms of recharge and depletion? (2) What is the 'age' of depleted soil water? (3) How do agroforests affect soil water dynamics in water-limited settings?

2. Materials and methods

2.1. Site description

Our study site was located in the Changwu Tableland on the southern CLP (35°14′ N, 107°41′ E; 1,200 m above sea level, Fig. 1). The site experiences a continental monsoon climate with a seasonal precipitation pattern. Historical annual precipitation (1957–2020) averages 584.6 mm, ranging between 296.0 mm (1995) and 954.3 mm (2003). The majority of rainfall (54%) occurs between July and September. The area's long-term mean annual potential evapotranspiration (1957–2015), calculated using the FAO Penman-Monteith equation (Allen et al., 1998), is 896.9 mm. Mean monthly temperatures hover around 9.3 °C, reaching their lowest in January (–4.6 °C) and peaking in July (22 °C). From 2016 to 2020, there was an increasing trend in precipitation, with amounts from May to October reaching 441, 470, 500, 668, and 518 mm, respectively. The increased precipitation in 2018–2020 exceeded the historical average of 481.5 mm (Fig. 2), suggesting increased water recharge during these years.

The study area features fairly uniform soil physical properties due to horizontal loess soil (Li et al., 2019c). Soil textures and bulk densities display minor changes within the 0–10 m soil layer but fluctuate with depth below 10 m (Fig. 2b).

Exotic apple orchards and non-irrigated cropland form the dominant vegetation at the site. Apple orchards have been cultivated since the 1980s to enhance local income. Orchards planted in different years share similar tree spacing, fertilization patterns, management regimes, and soil physical properties. These make the space-for-time substitution method (Pickett, 1989) applicable for characterizing dynamic water patterns throughout the orchards' lifespan. The orchards' growing period typically spans April (blossom) to October (fruit bearing), with peak water use in June and July (Wang and Wang, 2017). The groundwater table is below 30 m and unavailable for orchard water use.

2.2. Soil sample collection

We selected four apple orchards (*Malus pumila* Mill.), planted in 2008, 2005, 1998, and 1994 (named AP2008, AP2005, AP1998, and AP1994) to represent different orchard ages (see Table 1 for details). We refer to these apple orchards as 'agroforestry' stands. The orchard growth rate increased with orchard age from AP2008 to AP1998, as evidenced by variations in DBH, but declined in AP1994. All the orchards had similar heights due to pruning and dwarfing practices. AP2005 and AP1998 had higher leaf area indices (LAIs) than AP2008 and AP1994 (Table 1), suggesting dense canopy distribution and high productivity during the mature period.

In each orchard, we identified four representative trees with similar growth conditions. Soil cores were collected in October 2020, July 2016, and April 2017 for various analyses. Samples collected in October 2020 and July 2016 were used to compare soil water content and determine soil water dynamics, while samples collected in October 2020 and April 2017 were used to compare soil tritium depths and determine soil porewater velocity.

Three soil cores were taken along the quarter-point at the half diagonal position in October 2020 (Fig. 1c). Fresh soil was sampled at 20 cm intervals using a portable hand auger from the soil surface until no roots were found (13.6, 20, 25.4, and 27 m in AP2008, AP2005, AP1998, and AP1994, respectively). The soils were sampled within a month for a better comparison between orchards. The collected fresh soil samples were oven-dried at 105℃ for at least 24 h to determine the soil gravimetric water content. Volumetric water content was calculated using the bulk density at the corresponding depth, as per Lu et al. (2019). Soil

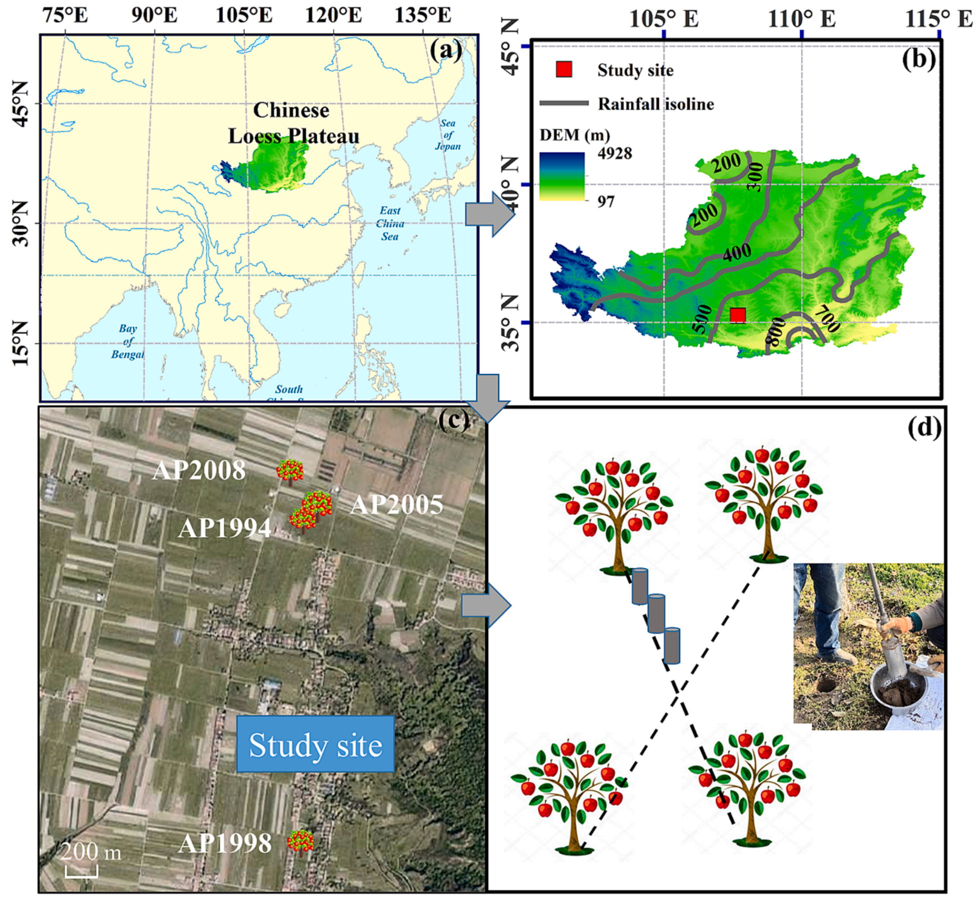

Fig. 1. (a, b) Location of the study site on China's Loess Plateau (CLP); (c) locations of the sampling orchards; (d) distribution of soil cores in each orchard.

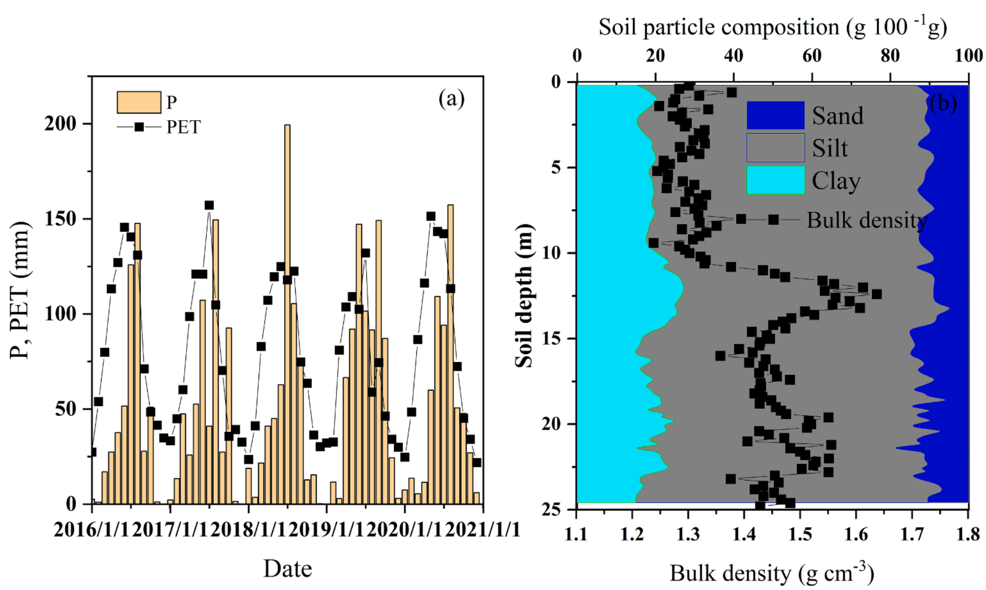

Fig. 2. (a) Monthly precipitation (P) and potential evapotranspiration (PET) from 2016 to 2020; (b) soil texture and bulk density from 0 to 25 m.

cores were also collected in July 2016 and April 2017 to determine fine root distribution, soil water content, and soil water age (Li et al., 2019c). The four-year interval between sampling allows for comparison of soil water recharge and depletion patterns between orchards. Soil cores to a depth were also taken in an adjacent cropland and the same orchards in April 2017. The collected fresh soils were placed into 50 mL air-tight polyethylene bags and stored at −20℃ until analysis. Soil tritium distributions were measured to determine soil water age and porewater velocity.

Table 1
Information on basic vegetation variables in four orchards.

Orchards	DBH (cm)	Height (m)	LAI (m^2 m^{-2})	Root depth (m)	Tree density (plants ha^{-1})
AP2008	13.8	3.2	1.7	9.6–13.6	737
AP2005	16.4	3.1	2.3	11.7–20.0	1003
AP1998	20.5	3.1	2.2	21.7–25.4	793
AP1994	20.4	3.3	1.7	23.2–27.0	1167

DBH, diameter at breast height; LAI, leaf area index. DBH, height, and LAI are the mean of measured values (2016–2020); root depths (unpublished data) are measured values from April 2017 to October 2020.

2.3. Determining soil water age and porewater velocity

In the 1960 s, atomic and hydrogen bomb tests significantly increased atmospheric radioactive tritium, which peaked in 1963. This tritium, with a half-life of 12.3 years (Ojovan et al., 2019), also spiked in the deep unsaturated zones on the CLP and is believed to represent the water recharged by precipitation that year (Shi et al., 2021; Tao et al., 2021a). To determine soil tritium content, we used a cryogenic vacuum distillation system (LICA, LI-2000, China) to extract water from fresh soil, following the technique described by Voltas et al. (2015). This technique has an extraction efficiency of at least 98%.

We extracted approximately 8 mL soil water, mixed it with a scintillation solution (Hisafe3) in an 8:12 ratio, and stored it in the dark for 12 h prior to analysis. The test sample was measured using a low-background liquid scintillation counter (Quantulus 1220, PerkinElmer, Singapore) for 400 min. After correcting for background noise, the measured tritium activities (CPM, count per minute) were transformed into tritium units.

We determined tritium peak depths using Tao et al. (2021a)'s method. This method involves fitting a modified Gaussian function to the soil tritium data through a nonlinear least square procedure. Soil porewater velocity (mean ± SE) was then calculated using the tritium transport depth and time:

$$\upsilon = \frac{d}{n} \quad (1)$$

where υ represents porewater velocity (m yr^{-1}),d is the soil tritium peak depth (m), and n is the number of years between 1963 and the year of soil core collection. Tritium peak depth (d) was averaged over the two periods of soil sampling (April 2017 and October 2020), with n approximated as: $(2020.8 + 2017.3)/2 - 1963 + 1 = 57$ years.

Soil water storage (mm) from depth i (m) to j (m), S_{i-j}, was calculated as:

$$S_{i-j} = \int_i^j \overline{\theta}_{i-j} \times 1000dz \quad (2)$$

where S is soil water storage (mm), and $\overline{\theta}_{i-j}$ is the average soil water content between soil depth i (m) and j (m).

Using the tritium peak-depth method, we determined the soil water age in each soil layer. The depleted deep soil water age (DA, years) was calculated using the deep soil water depletion amount and water age in each soil layer within the soil water depletion zones from 2016 to 2020:

$$DA = \frac{\int_{z_{min}}^{z_{max}} (\theta_{i,2016} - \theta_{i,2020})^* \frac{i}{\upsilon} dz}{\int_{z_{min}}^{z_{max}} (\theta_{i,2016} - \theta_{i,2020}) dz} \quad (3)$$

where z_{min} and z_{max} are the minimum and maximum depths (m) of the deep soil water depletion zone, and i is soil depth (m), $\theta_{i,2016}$ and $\theta_{i,2020}$ are the soil water contents in soil depth i in 2016 and 2020 (m^3/m^{-3}), respectively.

The DA uncertainty mainly originates from υ in Eq. (3) due to the uncertainty of the estimated soil tritium peak depth (d). This uncertainty can be calculated using the first-order perturbation analysis of Eq. (3):

$$SE(DA) = SE(d)^* \frac{n}{d^2} {}^* \frac{\int_{z_{min}}^{z_{max}} (\theta_{i,2016} - \theta_{i,2020})^* i^* dz}{\int_{z_{min}}^{z_{max}} (\theta_{i,2016} - \theta_{i,2020}) dz} \quad (4)$$

3. Results

3.1. Soil water dynamics variability

Soil water content varied considerably from July 2016 to October 2020. There were signs of recharge in shallow soils and depletion in deeper layers depending on orchard age (Fig. 3). Younger orchards (AP2008 and AP2005) experienced soil recharge up to 7 m and 6.6 m, respectively, while AP1998 reached 5.4 m. The oldest orchard (AP1994) had the deepest recharge at 7.6 m. Over time, AP2008 and AP2005 maintained relatively high soil water contents from 0 to 7 m, ranging from 0.2 to 0.25 m^3/m^{-3}. AP1998 and AP1994 had lower water contents from 0 to 10 m, ranging from 0.15 to 0.20 m^3/m^{-3}. By October 2020, AP2008 and AP2005 had stable soil water contents in the upper 7 m (0.25–0.30 m^3/m^{-3}), while soil water in AP1998 and AP1994 decreased gradually in the upper 6 m (0.30–0.17 m^3/m^{-3}). The increase in soil water storage in shallow soils was calculated as 298.4, 303.4, 300.6, and 483.1 mm in AP2008, AP2005, AP1998, and AP1994, respectively.

Despite the recharge in shallow soils from July 2016 to October 2020, deep soil water contents decreased remarkably (Fig. 3), especially in older orchards. The main areas of depletion over the last four years were 7–12 m in AP2008, 6.6–20 m in AP2005, 13–24 m in AP1998, and 22–25 m in AP1994, which decreased deep soil water storage by 111.1, 391.9, 192.8 and 108.9 mm, respectively.

3.2. Soil tritium distribution and water age

Soil tritium concentrations followed a bell-shaped distribution with soil depth (Fig. 4). The tritium displacement depths, averaged over two sampling periods, were 7.25, 7.15, 6.75, 5.70, and 6.15 m in cropland, AP2008, AP2005, AP1998, and AP1994, respectively, over 57 years since 1963 (Fig. 4). This suggests a difference in tritium displacement depths of approximately 1.55 m $(7.25\,m - 5.7\,m = 1.55\,m)$ and an average porewater velocity from 0.13 m yr^{-1} in cropland to 0.10 m yr^{-1} in AP1998 after nearly 20 years of agroforestation.

Assuming uniform piston soil porewater velocities (0.13 m yr^{-1}) across all orchards, each 0.2 m soil increment represents a 1.54-year increment. Applying Eq. (3) to depleted deep soil water content and velocity, we found that the ages of depleted deep soil water were (mean ± SE) 76.0 (±2.3), 107.4 (±3.0), 137.0 (±4.2), and 202.4 (±7.0) years in AP2008, AP2005, AP1998, and AP1994, respectively. The shallower tritium peak depth in orchards suggests a slower soil porewater velocity, less than 0.13 m yr^{-1}, in old orchards, implying that the water used by apple trees is considerably older than the present precipitation.

4. Discussion

4.1. Implications of agroforest age on soil water dynamics

The age of apple trees on the CLP has significant implications for soil water dynamics. Although LAIs of the apple trees changed with stand age, a four-year study showed that the interception difference between 8 and 18 year-old apple orchards is just about 2.4%, which can be negligible (Wang and Wang, 2020). Our study revealed that soil water infiltration varies with the age of apple orchards, resulting in distinct soil moisture patterns. Shallow soils in these orchards (0 to 5.4–7.6 m) likely recharged between July 2016 and October 2021. Liu et al. (2010) reported that an intense precipitation event (954 mm) recharged the soil to a depth of 5 m in a winter wheat field at the same site over a seasonal time scale. However, few studies have demonstrated the cumulative soil water recharge depth reaching below 5 m on the CLP over multiple years (Liu and Shao, 2016; Wang and Wang, 2018). This suggests recharge to

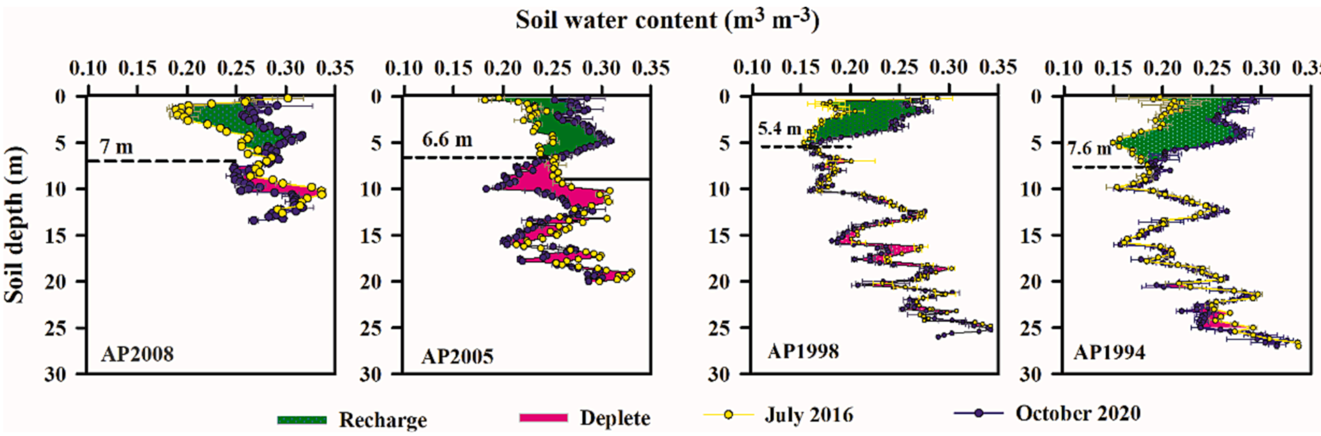

Fig. 3. Soil water distribution in July 2016 and October 2020 in AP2008, AP2005, AP1998, and AP1994. Green area represents soil water recharge, and pink area represents soil water depletion. Dashed lines indicate water recharge depths in the four orchards. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

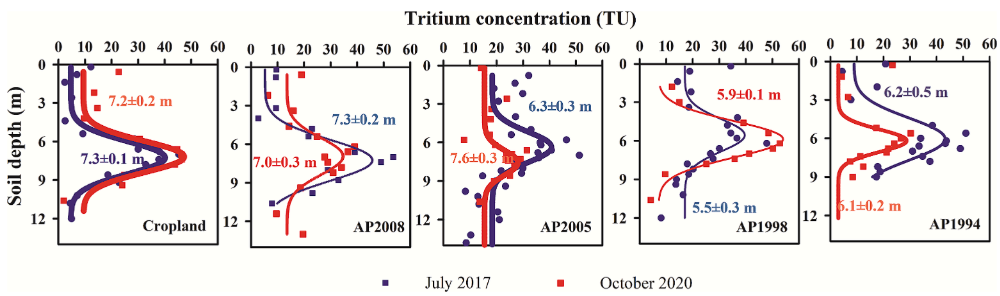

Fig. 4. Tritium distributions in cropland, AP2008, AP2005, AP1998, and AP1994. A modified Gaussian function was fitted to the tritium concentrations to determine tritium peak depths. Uncertainties (±) represent standard errors.

deeper layers during wet years. The greater recharge depths observed in apple orchards could be attributed to higher precipitation and decreased orchard productivity during these years.

Rainfall plays a critical role in controlling soil water status. In 2019, precipitation levels were significantly higher than historical average, which would have increased water content and promoted greater infiltration depth. In addition to the rainfall amount, other rainfall characteristics also influence the soil water dynamics. In 2019, the number of days when rainfall amount >10 mm, an indicator of extreme precipitation (Li et al., 2012), is 25 days. This is greater than the historical average (18.4 days). Also, the total annual precipitation divided by the number of wet days (defined as rainfall amount >1.0 mm) in 2019 is 12.1 mm/day, compared to 8.6 mm/day of historical average. This indicates a higher intensity and duration of extreme rainfall events in 2019. Extreme precipitation promotes greater infiltration into deeper soil layers (Shao et al., 2019). These water infiltration patterns, however, are episodic, and have a fast transit time, which is different from soil matrix flow (Good et al., 2015). In addition, cooler spring temperatures in recent years may have decreased orchard growth and productivity. In 2020, the orchards experienced an almost 50% and 90% decrease in LAI and fruit yield, respectively, compared to a typical growth year (Tao et al., 2021b). It is believed that the reduced number of canopy branches and lower LAI decreased transpiration and enhanced soil water recharge in shallow soils (Ma et al., 2019; Ye et al., 2021). Consequently, higher precipitation and lower water demand may have increased shallow soil water recharge across all orchards at our study site.

While clear recharge was observed in shallow soils, the depths and amounts of recharge varied across the four studied orchards. The water infiltration depth followed a bell-shaped curve with orchard age, with the deepest recharge depths in AP2008 and AP1994. Several factors could contribute to this pattern. First, the shallow soil water content in July 2016 decreased with orchard age, potentially reducing soil hydraulic conductivity and water infiltration depth in older orchards (van Genuchten, 1980). Second, the mature orchards (AP2005 and AP1998) had lower shallow soil water contents than the others, causing more water to fill the soil pores in the upper soil layer and thus reducing the soil water infiltration depth. Third, the older orchard (AP1994) had a lower LAI and, consequently, lower water demand, resulting in more precipitation infiltrating deeper soil layers.

The oldest orchard (AP1994) had the highest water recharge, consistent with an earlier CLP study showing soil water levels rebounding to their original levels (Jia et al., 2017). Meanwhile, soil water depletion was highest in mature orchards, likely due to the higher water demand of mature trees and reduced availability of deep soil water (Tao et al., 2021c). Thus, the overall soil water status and plant water demand determine soil water depletion.

Recharge depths in the orchards reached up to 7 m, while soil water depletion extended beyond 20 m, indicating that recharge water cannot completely compensate for deep soil water depletion. This limitation in water recharge depth can be attributed to low annual precipitation (584.6 mm), with almost half lost through evaporation (Wang and Wang, 2017). Consequently, there is a low likelihood that these non-native apple trees are overusing water. The water recharging the topsoil could be used in the following normal or dry year (Tao et al., 2021b).

This finding contrasts with studies conducted in the humid tropical Amazon, where high annual rainfall (2,000 mm) results in soil water recharge depths exceeding 10 m, thus compensating for any seasonal deficits in deep soil water (Markewitz et al., 2010; Rempe and Dietrich, 2018). Several studies have reported that plants on the CLP can extract soil water from depths >25 m, suggesting the presence of deep root water uptake in a semi-arid setting characterized by a thick vadose zone. Our study supports this observation, providing direct in-situ evidence of deep soil water depletion patterns resulting from agroforestry practices. The depth of deep soil water depletion increases consistently with the one-way water mining patterns reported by Li et al. (2019c).

It is important to note that tree age in our study specifically relates to soil water depletion and does not directly control soil water. Root characteristics directly control deep soil water depletion. Studies on apple trees (Li et al., 2019c) and jujube trees (Wang et al., 2015a) have shown synchronized water consumption and rooting depths. However, fine roots at a specific depth (e.g., 5–10 m) do not guarantee water consumption (as observed in AP1998 and AP1994), as the soil water may have already depleted below the tree's availability level. While a wet year might enhance tree growth and transpiration rates (Brito et al., 2015; Eliades et al., 2018; Zhang et al., 2018a), it may not lead to higher water depletion amounts in deep soil layers because deep soil water depletion is presumed to happen in dry years (Song et al., 2020; Tao et al., 2021b, 2021c).

4.2. *Implications of agroforestation on porewater velocity and soil water age*

The soil tritium peak depths decreased from 7.25 m in cropland to 5.70 m in AP1998 and 6.15 m in AP1994 (Fig. 4). This indicates that the older orchards (AP1998 and AP1994) had lower soil water infiltration depths than the other orchards, suggesting that croplands have greater soil water dynamics, particularly porewater velocities and soil water recharge, than orchards.

Interestingly, the transition from cropland to AP1998 reduced porewater displacement by 1.55 m, or ~ 21%, over nearly 20 years. This finding contrasts the results of Sun et al. (2018), who reported that cropland had lower infiltration rates than forests, attributing it to a physical impermeable layer in cropland and higher organic matter content in forests. However, a relatively old forest had a higher infiltration rate and water storage in a northern temperate climate, allowing rainfall to infiltrate deeper soil layers via preferential flow (Archer et al., 2016).

Our earlier research demonstrated that shallow soil layers in older orchards do not contain denser roots and higher organic matter than younger orchards (Li et al., 2019b, 2019c), suggesting that they may not contribute to a higher infiltration capacity. Furthermore, soil water depletion in older orchards decreased water hydraulic conductance and thus infiltration rates. This is expected because hydraulic conductance is proportional to the soil water potential and soil water content (Van Genuchten, 1980). This also suggests that tritium moved slower in relatively dry soil layers in agroforested plots than in croplands. Multi-year soil water dynamic observations also indicated that annual precipitation only influences the 0–2.0 m for deeper-rooted shrub and pasture, but 0–4.0 m for shallow-rooted crop on the Chinese loessial area (Liu and Shao, 2016). When porewater velocity is reduced, more water would be retained in upper soil layer, which would be available for evapotranspiration, and thus less water available for drainage into deeper layers (Wohling et al., 2012; Wang et al., 2015b; Zhang et al., 2016). Our study indicates that drying of deeper parts of the soil profile leads to an increasing depth of root water uptake to >25 m (e.g. AP1994, Fig. 3). Consequently, agroforestry practices on the CLP decrease porewater velocities.

Root water uptake associated with agroforestry on the CLP appears to reduce potential groundwater recharge. In a 15-year-old apple orchard, rooting depth reached 18.4 m (Li et al., 2019c), suggesting that only a limited amount of infiltrated water could bypass the root zone, with most water transpired into the atmosphere. Consistent with other studies, shifting land use from shallow-rooted to deep-rooted vegetation decreases deep soil water recharge and, consequently, potential groundwater recharge (Allen and Chapman, 2001; Zhang et al., 2018c).

In the Netherlands, soil water recharge decreased with forest age due to increased water interception (Van der Salm et al., 2006). At our study site, the high planting density of apple trees on limited land areas creates similar canopy structures (Table 1), resulting in minimal differences in interception among orchards, given the limited precipitation (Wang and Wang, 2017). Moreover, the soil at our study site is relatively fine; coarser soils may have more significant agroforestry effects on porewater displacement. Agroforestry practices on the CLP, which lead to increased soil desiccation and reduced groundwater recharge, could slow the transport rates of soil pollutants such as nitrates. Indeed, despite the orchards having been heavily fertilized, a recent field study found lower nitrate levels reaching the groundwater than expected (Huang et al., 2021b).

Our findings revealed a soil tritium peak in cropland at 7.25 m, representing the displaced soil depth of the 1963 bomb peak. In contrast, AP1998 had a deep soil water depletion depth below 22 m. The 7.25 m soil tritium depth corresponds to an infiltration rate of 0.13 m yr^{-1}. Further calculations indicated that the orchards used soil water older than 200 years. Considering the adverse effect of agroforestry on porewater velocity, it is likely that the orchards had a higher calculated water age than cropland at the same soil depth and, thus, the depleted deep soil water could be older than our calculated values. While water age does not directly affect root water uptake, apple trees could transpire 'old soil water' that is not readily available. This suggests that apple trees may need to grow deeper roots to fulfill their water requirements, and larger trees could be more vulnerable to the detrimental effects of droughts (Bennett et al., 2015). Our findings align with a previous study suggesting that when shallow soil water is depleted, plants may extract water from deeper soil layers, which likely contain older water (Allen et al., 2019).

4.3. *Heterogeneous water movement patterns evident from soil water dynamics and tritium*

The 'bell-shaped' tritium distribution in each soil profile revealed a piston flow pattern of soil water movement, which is essential for using tritium peaks to determine soil water age and porewater velocity in the unsaturated zone (Huang et al., 2021a). Variations in the soil water profile showed that 'new' water infiltrated to depths over 5 m within four years, whereas resident 'old' water (as indicated by tritium) only moved 6–7 m in nearly 57 years. These patterns suggest that 'new' water has higher velocities than 'old' tritium water. Shallow soils are more prone to saturation, resulting in a faster increase in soil hydraulic conductivity than deep soils. As such, 'new' water in surface and shallow soils is more likely to infiltrate deeper into the soil profile. In contrast, the movement of 'old' tritium water decreases as less 'new' water infiltrates deeper into the soil profile.

The heterogeneity in porewater velocities for soil water and tritium water may arise from different water movement patterns in soil pore classes. Tritium water tends to remain in smaller pores, while infiltrated precipitation is more likely to be transported through larger pores, bypassing the smaller ones. This is because the water in large pores is more readily available for plant uptake due to lower matric tension.

In saturated soils, hydraulic conductivity is related to the fourth power of the pore radius (Vervoort and Cattle, 2003), with larger pores the dominant pathway for precipitation movement through the soil profile. When soils are below field capacity, large pores that drain with the least tension become empty, while the remaining soil water in small pores has matric potentials that are lower than what gravity can drain (Brooks et al., 2010). As a result, the tritium water in small pores has a longer residence time than newly infiltrated precipitation. This phenomenon aligns with the 'ecohydrological separation' concept, suggesting a dichotomy between fast-moving water and slow water stored in presumably smaller pore spaces (Brooks et al., 2010). Our findings are consistent with the study by Zhang et al. (2019) that found chloride in small pores and infiltrated water in big pores. Hence, chemical tracers such as chloride can be used to quantify piston and preferential water velocities in deep soil profiles. Although tritium is considered an ideal tracer for indicating soil water age following agroforestation on the CLP (Shi et al., 2021; Xiang et al., 2020), our study suggests that soil tritium water is more likely to represent water moving in small pores.

4.4. Study limitations and implications

Our study has several limitations that should be considered. First, the timing of our soil sample collection (April/July and October) may introduce some variability due to differences in meteorological conditions, such as precipitation. However, we believe that the impact on our results is minimal as we compared cumulative soil water dynamics and porewater velocity across orchards at the same time interval, and the samples were collected almost simultaneously from all orchards. In addition, the effects of monthly weather patterns on deep soil water movement and depletion are expected to be limited in water-limited areas with apple trees.

Another limitation concerns the challenges associated with the available measurement tools for observing in-situ deep soil water dynamics at shorter timescales Techniques such as oven-drying and neutron probe methods present challenges. Notably, obtaining accurate observations of deep soil water dynamics is particularly challenging for mature apple trees, exemplified by AP1998 and AP1994. This presents some real-world constraints associated with field studies such as ours. Several studies have reported that deep soil water content on the CLP does not change within a year (Li et al., 2019b; Suo et al., 2018; Wu et al., 2021). Meanwhile, we compared the soil water dynamics and porewater movement at orchard trees of different stand ages, using space-for-time substitution method. We believe that our approach helps to clarify the ecohydrological impacts of agroforestation relative to stand age. Thus, we focused on cumulative soil water variations and movement to illustrate changes in hydrological processes in the deep vadose zone due to agroforestry on the CLP.

Using the space-for-time substitution method is suitable for examining the impact of tree age on soil water dynamics. Nonetheless, our study faces a limitation in understanding in-situ deep soil water dynamics at more refined temporal resolutions, such as seasonal variations. To overcome this limitation, future researchers should capitalize on advancements in sampling techniques, focusing on deep soils. Alternatively, they could refine the space-for-time substitution approach employed in our study to better understand the seasonal variations of soil water dynamics under these apple orchards.

Sampling at the most extreme part of the year helped magnify orchard differences in soil water dynamics. Future studies incorporating high-accuracy instruments for soil water content measurements and fine root observations could provide further insights into the mechanisms underlying deep soil water depletion.

It is important to note that while land cover changes, such as agroforestry and afforestation, offer benefits in terms of climate change mitigation, our study suggests that agroforestry may not always favor regional water resources. On the CLP, afforestation in water-limited environments contributes to global greening (Chen et al., 2019), but could also reduce groundwater recharge and streamflow generation (Feng et al., 2016; Wang et al., 2011), exacerbating water scarcity (Feng et al., 2016). Conversely, afforestation in energy-limited environments could increase groundwater recharge and dry season flows (Calder, 2007).

The radioactive tracer indicated that the depleted soil water could be hundreds of years old, implying that soil water recovery might take centuries, particularly for deeper soil layers with longer surface flow paths and greater evapotranspiration losses.

Furthermore, the hydrological effects of land cover change can vary over time as agroforests mature, influencing ecohydrological dynamics. Factors such as forest management, tree species, forest structure, and forest density can influence seasonal and annual water yields from forested areas (Brooks et al., 2010; Zhang and Wei, 2021). Our study found differences in soil water recharge dynamics and movement rates likely associated with agroforest age, a common observation on the CLP. For example, a large-scale study that collected 9,263 soil samples from 128 profiles of 7–25 m deep soil under various climates, soil textures, and plant types (shallow or deep roots) on the CLP found that plant age and normalized difference vegetation index (NDVI) dominated the vertical variability of soil water (Huang et al., 2021a). However, our understanding of apple tree water consumption per vegetation period is limited, and further research is needed to explore the relationship between soil water dynamics and transpiration amounts and rates. Nevertheless, it is conceivable that vegetation, such as grasses, between apple trees consumes some of the soil water, with variability in transpiration amounts and rates affecting the soil water dynamics below the rooting zone. While we revealed differences in LAI values between orchards, we do not explain how LAI directly relates to soil water dynamics. High LAI values could be associated with high actual evapotranspiration and, thus, lower amounts of infiltration below the rooting zone.

As we calculated volumetric water content to determine recharge and depletion using the bulk density at the corresponding depth, a possible source of uncertainty – and a caveat to the interpretation of our findings – is the dependency of volumetric water content on bulk density.

Determining water age in streamflow (Cartwright and Morgenstern, 2018) or groundwater (Jasechko, 2019) is relatively common, but non-uniform water flow in the vadose zone affects the accuracy of these measurements. However, methods such as introduced Cl^- or NO_3^- fertilizers and radioactive ^3H tracers can effectively model soil water movement to determine soil water age in deep vadose settings (Chen et al., 2023; Huang et al., 2016; Shi et al., 2021), providing an effective tool for understanding deep hydrological processes following land use changes.

5. Conclusions

Our study revealed that the age of apple orchards on the CLP significantly affects soil water dynamics, including soil water recharge and depletion patterns. Shallow soil water had recharge depths ranging from 5.4 to 7.6 m. Moreover, older orchards had greater depth and age of deep soil water depletion than younger orchards, with depths exceeding 22 m and water ages surpassing 200 years. Interestingly, older orchards had shallower tritium peak depths, indicating slower soil water velocities following agroforestation. These varied water movement patterns within agroforestry areas suggest the presence of flow path heterogeneities. Overall, our research offers valuable insights into the impact of agroforest age on soil water dynamics, with more noticeable reductions in infiltration rates and deep soil water recharge in agroforestry areas than non-agroforestry areas on the CLP. Future research should investigate the mechanisms underlying these water dynamics and explore sustainable approaches to optimize water use efficiency in agroforestry systems.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Data availability

Data will be made available on request.

Acknowledgments

Professor Bing Si was funded by National Natural Science Foundation of China (41877017 & 42201051). Ze Tao was funded by Natural Science Foundation of Hebei Province (E2022201018). The soil samples were collected by Ze Tao, which was funed by National Natural Science Foundation of China (41877017 & 42201051). Samples measurements and further data processing were accomplished when Ze Tao was working in Hebei, which were funded by the National Natural Science Foundation of China (41877017 & 42201051) and Natural Science Foundation of Hebei Province (E2022201018). We thank Jingjing Jin, lab manager from the Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A&F University, for her assistance in performing sample analyses. We also extend our appreciation to Dong He, Yanli Fan, Peng Li, Wei Xiang and Xin Liu, for their assistance in the field.

References

Allen, A., Chapman, D., 2001. Impacts of afforestation on groundwater resources and quality. Hydrgeol. J. 9 (4), 390–400. https://doi.org/10.1007/s100400100148.

Allen, S.T., Kirchner, J.W., Braun, S., Siegwolf, R.T., Goldsmith, G.R., 2019. Seasonal origins of soil water used by trees. Hydrol. Earth Syst. Sci. 23 (2), 1199–1210. https://doi.org/10.5194/hess-23-1199-2019.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56.

Archer, N.A.L., et al., 2016. Rainfall infiltration and soil hydrological characteristics below ancient forest, planted forest and grassland in a temperate northern climate. Ecohydrology 9 (4), 585–600. https://doi.org/10.1002/eco.1658.

Bai, X., Jia, X., Jia, Y., Shao, M., Hu, W., 2020. Modeling long-term soil water dynamics in response to land-use change in a semi-arid area. J. Hydrol. 585, 124824 https://doi.org/10.1016/j.jhydrol.2020.124824.

Bengough, A.G., 2012. Water dynamics of the root zone: rhizosphere biophysics and its control on soil hydrology. Vadose Zone J. 11 (2), 460. https://doi.org/10.2136/vzj2011.0111.

Bennett, A., McDowell, N., Allen, C., Anderson-Teixeira, K., 2015. Larger trees suffer most during drought in forests worldwide. Nat. Plants 1 (10), 15139. https://doi.org/10.1038/NPLANTS.2015.139.

Brito, P., et al., 2015. Canopy transpiration of a semi arid Pinus canariensis forest at a treeline ecotone in two hydrologically contrasting years. Agric. For. Meteorol. 201, 120–127. https://doi.org/10.1016/j.agrformet.2014.11.008.

Brooks, J.R., Barnard, H., Coulombe, R., McDonnell, J., 2010. Ecohydrologic separation of water between trees and streams in a Mediterranean climate. Nat. Geosci. 3, 100–104. https://doi.org/10.1038/NGEO722.

Calder, I., 2007. Forests and water – ensuring benefits outweigh water costs. For. Ecol. Manage. 251, 110–120. https://doi.org/10.1016/j.foreco.2007.06.015.

Canadell, J., et al., 1996. Maximum rooting depth of vegetation types at the global scale. Oecologia 108 (4), 583–595. https://doi.org/10.1007/BF00329030.

Cartwright, I., Morgenstern, U., 2018. Using tritium and other geochemical tracers to address the "old water paradox" in headwater catchments. J. Hydrol. 563, 13–21. https://doi.org/10.1016/j.jhydrol.2018.05.060.

Chen, Y., et al., 2015. Balancing green and grain trade. Nat. Geosci. 8 (10), 739–741. https://doi.org/10.1038/ngeo2544.

Chen, C., et al., 2019. China and India lead in greening of the world through land-use management. Nat. Sustainability 2 (2), 122–129. https://doi.org/10.1038/s41893-019-0220-7.

Chen, G., et al., 2023. Quantitative partitioning of temporal origin of transpiration into pre- and post-plantation under deep-rooted vegetation on the Loess Plateau of China. J. Hydrol. 617, 128964 https://doi.org/10.1016/j.jhydrol.2022.128964.

Eliades, M., et al., 2018. The water balance components of Mediterranean pine trees on a steep mountain slope during two hydrologically contrasting years. J. Hydrol. 562, 712–724. https://doi.org/10.1016/j.jhydrol.2018.05.048.

Evaristo, J., et al., 2019. Characterizing the fluxes and age distribution of soil Water, plant Water, and deep percolation in a model tropical ecosystem. Water Resour. Res. 55 (4), 3307–3327. https://doi.org/10.1029/2018wr023265.

Evaristo, J., Jasechko, S., McDonnell, J.J., 2015. Global separation of plant transpiration from groundwater and streamflow. Nature 525 (7567), 91–94. https://doi.org/10.1038/nature14983.

Feng, X., et al., 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat. Clim. Chang. 6, 1019–1022. https://doi.org/10.1038/nclimate3092.

Gao, X., et al., 2021. The economic–environmental trade-off of growing apple trees in the drylands of China: a conceptual framework for sustainable intensification. J. Clean. Prod. 296, 126497 https://doi.org/10.1016/j.jclepro.2021.126497.

Good, S., Noone, D., Bowen, G., 2015. Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. Science 349 (6244), 175–177. https://doi.org/10.1126/science.aaa5931.

Huang, Y., Li, B., Biswas, A., Li, Z., 2021a. Factors dominating the horizontal and vertical variability of soil water vary with climate and plant type in loess deposits. Sci. Total Environ. 811, 152172 https://doi.org/10.1016/j.scitotenv.2021.152172.

Huang, Y., Li, B., Li, Z., 2021b. Conversion of degraded farmlands to orchards decreases groundwater recharge rates and nitrate gains in the thick loess deposits. Agr. Ecosyst. Environ. 314 (2), 107410 https://doi.org/10.1016/j.agee.2021.107410.

Huang, T., Yang, S., Liu, J., Li, Z., 2016. How much information can soil solute profiles reveal about groundwater recharge? Geosci. J. 20 (4), 495–502. https://doi.org/10.1007/s12303-015-0069-3.

Huang, T., Pang, Z., Liu, J., Ma, J., Gates, J., 2017. Groundwater recharge mechanism in an integrated tableland of the Loess Plateau, northern China: insights from environmental tracers. Hydrgeol. J. 25 (7), 2049–2065. https://doi.org/10.1007/s10040-017-1599-8.

Jasechko, S., 2019. Global isotope hydrogeology-Review. Rev. Geophys. 57 (3), 835–965. https://doi.org/10.1029/2018rg000627.

Jasechko, S., Kirchner, J.W., Welker, J.M., McDonnell, J.J., 2016. Substantial proportion of global streamflow less than three months old. Nat. Geosci. 9, 126–129. https://doi.org/10.1038/ngeo2636.

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

Kim, J.H., Jackson, R.B., 2012. A global analysis of groundwater recharge for vegetation, climate, and soils. Vadose Zone J. 11 (1) https://doi.org/10.2136/vzj2011.0021RA.

Kirchner, J.W., 2016. Aggregation in environmental systems: seasonal tracer cycles quantify young water fractions, but not mean transit times, in spatially heterogeneous catchments. Hydrol. Earth Syst. Sci. 20 (1), 279. https://doi.org/10.5194/hessd-12-3059-2015.

Li, H., Si, B., Ma, X., Wu, P., 2019b. 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. https://doi.org/10.1016/j.scitotenv.2019.03.267.

Li, H., Si, B., Wu, P., McDonnell, J.J., 2019c. Water mining from the deep critical zone by apple trees growing on loess. Hydrol. Process. 33 (2), 320–327. https://doi.org/10.1002/hyp.13346.

Li, B., Wang, Y., Hill, R.L., Li, Z., 2019a. Effects of apple orchards converted from farmlands on soil water balance in the deep loess deposits based on HYDRUS-1D model. Agr Ecosyst Environ 285, 106645. https://doi.org/10.1016/j.agee.2019.106645.

Li, Z., Zheng, F.-L., Liu, W.-Z., Jiang, D.-J., 2012. Spatially downscaling GCMs outputs to project changes in extreme precipitation and temperature events on the Loess Plateau of China during the 21st Century. Global Planet. Change 82–83, 65–73. https://doi.org/10.1016/j.gloplacha.2011.11.008.

Liu, W., et al., 2010. Soil water dynamics and deep soil recharge in a record wet year in the southern Loess Plateau of China. Agric. Water Manag. 97 (8), 1133–1138. https://doi.org/10.1016/j.agwat.2010.01.001.

Liu, B., Shao, M., 2016. Response of soil water dynamics to precipitation years under different vegetation types on the northern Loess Plateau, China. J. Arid Land 8 (1), 47–59. https://doi.org/10.1007/s40333-015-0088-y.

Lu, Y., Si, B., Li, H., Biswas, A., 2019. Elucidating controls of the variability of deep soil bulk density. Geoderma 348, 146–157. https://doi.org/10.1016/j.geoderma.2019.04.033.

Ma, L., et al., 2019. Canopy pruning as a strategy for saving water in a dry land jujube plantation in a loess hilly region of China. Agric. Water Manag. 216, 436–443. https://doi.org/10.1016/j.agwat.2018.12.007.

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. New Phytol. 187 (3), 592–607. https://doi.org/10.1111/j.1469-8137.2010.03391.x.

Miguez-Macho, G., Fan, Y., 2021. Spatiotemporal origin of soil water taken up by vegetation. Nature 598 (7882), 1–5. https://doi.org/10.1038/s41586-021-03958-6.

Miralles, D., Gash, J., Holmes, T., de Jeu, R., Dolman, H., 2010. Global canopy interception from satellite observations. J. Geophys. Res. 115, 8. https://doi.org/10.1029/2009JD013530.

Nair, P., 2013. Agroforestry: trees in support of sustainable agriculture. Reference Module in Earth Systems and Environmental Sciences. https://doi.org/10.1016/B978-0-12-409548-9.05088-0.

Ojovan, M.I., Lee, W.E., Kalmykov, S.N., 2019. Chapter 11 - Short-Lived Waste Radionuclides. In: Ojovan, M.I., Lee, W.E., Kalmykov, S.N. (Eds.), An Introduction to Nuclear Waste Immobilisation. Elsevier, pp. 145–154. https://doi.org/10.1016/B978-0-08-102702-8.00011-X.

Pickett, S.T.A., 1989. Space-for-time substitution as an alternative to long-term studies. In: Likens, G.E. (Ed.), Long-term Studies in Ecology. Springer, New York, pp. 110–135. https://doi.org/10.1007/978-1-4615-7358-6_5.

Rempe, D.M., Dietrich, W.E., 2018. Direct observations of rock moisture, a hidden component of the hydrologic cycle. Proc. Natl. Acad. Sci. 33 (2), 2664–2669. https://doi.org/10.1073/pnas.1800141115.

Rosenqvist, L., Hansen, K., Vesterdal, L., van der Salm, C., 2010. Water balance in afforestation chronosequences of common oak and Norway spruce on former arable land in Denmark and southern Sweden. Agric. For. Meteorol. 150 (2), 196–207. https://doi.org/10.1016/j.agrformet.2009.10.004.

Schwärzel, K., Zhang, L., Montanarella, L., Wang, Y., Sun, G., 2019. How afforestation affects the water cycle in drylands: A process-based comparative analysis. Glob. Chang. Biol. 26 (2), 944–959. https://doi.org/10.1111/gcb.14875.

Scott, D., Prinsloo, F., 2008. Longer-term effects of pine and eucalypt plantations on streamflow. Water Resour. Res. 44 (7), W00A08. https://doi.org/10.1029/2007WR006781.

Shao, J., Si, B., Jin, J., 2019. Rooting depth and extreme precipitation regulate groundwater recharge in the thick unsaturated zone: a case study. Water 11 (6), 1232. https://doi.org/10.3390/w11061232.

Shi, P., et al., 2021. Impacts of deep-rooted fruit trees on recharge of deep soil water using stable and radioactive isotopes. Agric. For. Meteorol. 300 (23), 108325 https://doi.org/10.1016/j.agrformet.2021.108325.

Song, X.-P., et al., 2018. Global land change from 1982 to 2016. Nature 560. https://doi.org/10.1038/s41586-018-0411-9.

Song, X., et al., 2020. Drought responses of profile plant-available water and fine-root distributions in apple (*Malus pumila* Mill.) orchards in a loessial, semi-arid, hilly area of China. Sci. Total Environ. 723, 137739 https://doi.org/10.1016/j.scitotenv.2020.137739.

Sun, D., et al., 2018. The effects of land use change on soil infiltration capacity in China: a meta-analysis. Sci. Total Environ. 626, 1394–1401. https://doi.org/10.1016/j.scitotenv.2018.01.104.

Suo, L., Huang, M., Zhang, Y., Duan, L., Shan, Y., 2018. Soil moisture dynamics and dominant controls at different spatial scales over semiarid and semi-humid areas. J. Hydrol. 562, 635–647. https://doi.org/10.1016/j.jhydrol.2018.05.036.

Tao, Z., Li, H., Neil, E., Si, B., 2021a. Groundwater recharge in hillslopes on the Chinese Loess Plateau. J. Hydrol.: Reg. Stud. 36 (1), 100840 https://doi.org/10.1016/j.ejrh.2021.100840.

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

Tao, Z., Neil, E., Si, B., 2021c. Determining deep root water uptake patterns with tree age in the Chinese loess area. Agric. Water Manag. 249, 106810 https://doi.org/10.1016/j.agwat.2021.106810.

Van der Salm, C., Denier van der Gon, H., Wieggers, R., Bleeker, A., van den Toorn, A., 2006. The effect of afforestation on water recharge and nitrogen leaching in The Netherlands. For. Ecol. Manage. 221 (1), 170–182. https://doi.org/10.1016/j.foreco.2005.09.027.

Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils1. Soil Sci. Soc. Am. J. 44 (5), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x.

Vervoort, R.W., Cattle, S.R., 2003. Linking hydraulic conductivity and tortuosity parameters to pore space geometry and pore-size distribution. J. Hydrol. 272 (1), 36–49. https://doi.org/10.1016/S0022-1694(02)00253-6.

Voltas, J., Lucabaugh, D., Chambel, M.R., Ferrio, J.P., 2015. Intraspecific variation in the use of water sources by the circum-Mediterranean conifer *Pinus halepensis*. New Phytol. 208 (4), 1031–1041. https://doi.org/10.1111/nph.13569.

Wang, Y., et al., 2011. Annual runoff and evapotranspiration of forestlands and non-forestlands in selected basins of the Loess Plateau of China. Ecohydrology 4 (2), 277–287. https://doi.org/10.1002/eco.215.

Wang, Y., Shao, M., Liu, Z., Zhang, C., 2015b. Characteristics of dried soil layers under apple orchards of different ages and their applications in soil water managements on the loess plateau of China. Pedosphere 25 (4), 546–554. https://doi.org/10.1016/S1002-0160(15)30035-7.

Wang, D., Wang, L., 2017. Dynamics of evapotranspiration partitioning for apple trees of different ages in a semiarid region of northwest China. Agric. Water Manag. 191, 1–15. https://doi.org/10.1016/j.agwat.2017.05.010.

Wang, D., Wang, L., 2018. Soil water dynamics in apple orchards of different ages on the Loess Plateau of China. Vadose Zone J. 17 (1), 180049 https://doi.org/10.2136/vzj2018.03.0049.

Wang, D., Wang, L., 2020. Rainfall partitioning and its effects on regional water balances: evidence from the conversion of traditional cropland to apple orchards in a semi-humid region. Hydrol. Process. 34 (24), 4628–4639. https://doi.org/10.1002/hyp.13891.

Wang, X., Zhu, D., Wang, Y., Wei, X., Ma, L., 2015a. Soil water and root distribution under jujube plantations in the semiarid Loess Plateau region, China. Plant Growth Regul. 77 (1), 21–31. https://doi.org/10.1007/s10725-015-0031-4.

Winkler, K., Fuchs, R., Rounsevell, M., Herold, M., 2021. Global land use changes are four times greater than previously estimated. Nat. Commun. 12, 2501. https://doi.org/10.1038/s41467-021-22702-2.

Wohling, D., Leaney, W., F., Crosbie, R.,, 2012. Deep drainage estimates using multiple linear regression with percent clay content and rainfall. Hydrol. Earth Syst. Sci. 16, 563–572. https://doi.org/10.5194/hess-16-563-2012.

Wu, W., et al., 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 https://doi.org/10.1016/j.agrformet.2020.108244.

Xiang, W., Si, B., Biswas, A., Li, Z., 2018. Quantifying dual recharge mechanisms in deep unsaturated zone of Chinese Loess Plateau using stable isotopes. Geoderma 337, 773–781. https://doi.org/10.1016/j.geoderma.2018.10.006.

Xiang, W., Evaristo, J., Li, Z., 2020. Recharge mechanisms of deep soil water revealed by water isotopes in deep loess deposits. Geoderma 369, 114321. https://doi.org/10.1016/j.geoderma.2020.114321.

Yan, W., Zhong, Y., Shangguan, Z., 2017. Responses of different physiological parameter thresholds to soil water availability in four plant species during prolonged drought. Agric. For. Meteorol. 247, 311–319. https://doi.org/10.1016/j.agrformet.2017.08.017.

Ye, M., et al., 2021. Measurements and modeling of hydrological responses to summer pruning in dryland apple orchards. J. Hydrol. 594, 125651 https://doi.org/10.1016/j.jhydrol.2020.125651.

Zhang, Q., et al., 2018a. Sap flow of black locust in response to short-term drought in southern Loess Plateau of China. Sci. Rep. 8 (1), 6222. https://doi.org/10.1038/s41598-018-24669-5.

Zhang, S., et al., 2018b. Excessive afforestation and soil drying on China's Loess Plateau. J. Geophys. Res. Biogeo. 123 (3), 923–935. https://doi.org/10.1002/2017jg004038.

Zhang, Z., Evaristo, J., Li, Z., Si, B., McDonnell, J.J., 2017. Tritium analysis shows apple trees may be transpiring water several decades old. Hydrol. Process. 31 (5), 1196–1201. https://doi.org/10.1002/hyp.11108.

Zhang, Z., Li, M., Si, B., Feng, H., 2018c. Deep rooted apple trees decrease groundwater recharge in the highland region of the Loess Plateau, China. Sci. Total Environ. 622–623, 584–593. https://doi.org/10.1016/j.scitotenv.2017.11.230.

Zhang, Z., Si, B., Li, H., Li, M., 2019. Quantify piston and preferential water flow in deep soil using Cl− and soil water profiles in deforested apple orchards on the Loess Plateau, China. Water 11 (10), 2183. https://doi.org/10.3390/w11102183.

Zhang, M., Wei, X., 2021. Deforestation, forestation, and water supply. Science 371 (6533), 990. https://doi.org/10.1126/science.abe7821.

Zhang, Y., Xiao, Q., Huang, M., 2016. Temporal stability analysis identifies soil water relations under different land use types in an oasis agroforestry ecosystem. Geoderma 271, 150–160. https://doi.org/10.1016/j.geoderma.2016.02.023.