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Age- and climate- related water use patterns of apple trees on China's Loess Plateau

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ABSTRACT

The Loess Plateau of China is a major apple-cultivating region, but much of the Plateau is water-limited, and the expansion of apple-growing is putting pressure on soil water resources. Plants' water consumption patterns have been intensively studied to facilitate formulation of robust agricultural strategies, but previous studies have generally applied indirect methods to characterize their water use. Moreover, the few studies that have applied direct (isotopic) methods have mostly focused on shallow (0–200 cm) soil layers, usually in stands of a single age or single climatic region. To avoid these limitations, we have investigated the primary water sources of apple trees of three ages (10, 15 and 22 years) in semiarid and semihumid climatic regions of the Plateau using both natural stable isotopic signatures (δ^2H values) and injections of ^2H_2O into deep soil layers. We found that water content in apple orchards' soil decreased with increases in depth and stand age, and was higher in the semihumid area than in the semiarid area. Nevertheless, patterns of apple trees' water uptake from shallow (0–300 cm) soil layers were similar in the two climatic regions and the main water sources became shallower with increases in stand age. However, water uptake from deep (400–500 cm) soil layers was also detected, particularly in the blossom and young fruit stage in apple orchards of the semiarid area. Moreover, older trees absorbed more water from these layers than younger trees in the semiarid area (but not in the semihumid area) throughout the growing season. Excessive consumption of deep soil water inevitably results in deep soil drying and severely threatens the sustainability of apple cultivation. Our work suggests that it is necessary to take actions (e.g. supplementary irrigation, landscaping and mulching combinations) to reduce the proportion of deep soil water used by apple trees to prevent the development of dried soil layers. It also highlights the need to assess uptake patterns of plants at multiple developmental stages and ages to identify times when and places where interventions may be required or most effective.

1. Introduction

Apples are among the most widely cultivated fruits in the world (Baldi et al., 2013; Li et al., 2013). Large parts of the Loess Plateau of China have abundant light and heat resources, as well as large diurnal temperature ranges, and are thus considered suitable for producing high-quality apples (Wang et al., 2012). Now, the apple industry has become the backbone of the local rural economy (Wang and Wang, 2017) and the Plateau has become the largest area of intensive apple cultivation globally. In 2016, the cover and yield of apple trees in the region amounted to 1.31 million hectares and 22.9 million tons, accounting for 25.2% and 26.3% of global coverage and production, respectively. However, much of the Plateau is water-limited and most orchards in the region are cultivated under rain-fed conditions (Song

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et al., 2017). In many parts the limited precipitation is barely sufficient to meet apple orchards' high water consumption rates. Hence, the large-scale expansion of apple cultivation has changed ecohydrological processes, with profound implications for its sustainability in the region.

In water-limited ecosystems, soil moisture generated by precipitation is a limiting factor governing vegetation dynamics and ecosystem processes (Moreno-de las Heras et al., 2011). In turn, vegetation affects soil water resources, in varying ways depending on the climatic conditions, species and stand ages (Grossiord et al., 2017; Jia et al., 2017; Wang et al., 2017). When water consumption by plants exceeds soil water supplies, water deficits inevitably occur, and prolonged excessive consumption causes soil drying and eventually damage to soil structure that is difficult to ameliorate (Duan et al., 2016; Jian et al., 2015). Apple orchards have already caused such damage, notably formation of dried soil layers (DSL), in parts of the Plateau (Wang et al., 2013; Wang et al., 2015). Therefore, more knowledge of the water consumption patterns of plants, including apple trees, is urgently required to formulate robust strategies for the sustainable use of water resources and vegetation on the Plateau, and similar water-limited regions.

There are several traditional techniques to determine plants' water consumption, generally involving root system excavation and soil water determination (Ma et al., 2019; Wang et al., 2012; Xu and Li, 2006). These methods can provide valuable 'snapshots' of conditions, but provide little information about plants' dynamic water uptake processes, especially in environments where soil water conditions are highly variable and difficult to predict. Moreover, they provide no direct evidence of water uptake by roots. In contrast, tracing stable isotope (δ^2H and δ^{18}O) signatures provides a powerful, reliable and non-destructive approach for studying plants' water uptake and utilization (Dawson and Ehleringer, 1991; Wang et al., 2010). By comparing the isotopic composition of xylem water and potential water sources, we can identify the water sources used by plants and estimate their proportional contributions (Dai et al., 2015; Liu et al., 2010; Wu et al., 2018). Most researchers who have applied this approach have focused on plants' uptake from shallow (0–200 cm or even 0–100 cm) soil layers (Tang et al., 2018; Yang et al., 2015; Zhang et al., 2017a). However, for shrubs or trees with deep root systems this may lead to overestimates of proportional contributions of shallow soil water and neglect of potentially vital contributions of deep soil water, especially in arid and semiarid areas. Uptake of deep soil water by roots is crucial for some plants' normal physiological activities (Bleby et al., 2010; Maeght et al., 2013) and thus must be considered to obtain sufficient understanding of ecohydrological processes. A complication is that vertical profiles of δ^2H or δ^{18}O are often C- or S-shaped when deep soil layers are considered, which must be accounted for in calculations of proportional uptake from different depths (Stahl et al., 2013). A labeling approach that increases the abundance of a monitored isotope in deep soil can provide direct evidence of water uptake from deep layers (Beyer et al., 2016). Therefore, for plants with deep root systems, combining analyses of natural stable isotopic signatures and isotopic labeling might provide more comprehensive information and robust insights. A further limitation of previous studies concerning the variation in plants' water uptake patterns on the Loess Plateau is that they have been mostly restricted to catchment scales or specific stand ages (Tang et al., 2018; Wang et al., 2017). Little is known about the water uptake characteristics of apple trees of different ages under different climatic conditions, although climatic variables (especially precipitation) and stand age clearly affect plants' water use. Thus, there are urgent needs to study their water uptake patterns in more detail to elucidate their age- and developmental stage-dependent effects on ecohydrological processes in water-limited ecosystems and facilitate formulation of sustainable apple cultivation and water conservation strategies.

To address these needs, we have monitored the seasonal variation of water uptake patterns of apple stands of three ages (10, 15 and 22 years) in semiarid and semihumid climatic regions of the Loess Plateau, using both natural stable isotope signatures and isotope labeling of deep layers. There were two specific objectives. First, to identify effects of stand age on apple trees' shallow soil water use in each climatic region. Second, to elucidate differences in deep soil water use of stands of the three ages in the two climatic regions. This was done by measuring stable isotope levels in soil and xylem water samples and soil water content at various depths in apple orchards in the two regions.

2. Materials and methods

2.1. The study area and experimental sites

The study was conducted, in 2016, on the Loess Plateau of China (33°43′–41°16′N, 100°54′–114°33′E), which covers > 620 000 km^2. Annual precipitation on the Plateau ranges from 150 mm in the northwest to 800 mm in the southeast and 55–78% of the total precipitation falls in June to September (Jia et al., 2017). Based on the ratio of mean annual precipitation to potential evapotranspiration (P/ET), the Plateau has been divided into three climatic regions: arid (0.05–0.2), semiarid (0.2–0.5) and semihumid (0.5–0.65) (Scanlon et al., 2006; UNESCO, 1979). The annual average temperature ranges from 3.6 to 14.3 °C. There are rich solar energy resources, with mean annual sunshine hours of 2200–2800 h (Gao et al., 2017). The Plateau's surface is covered by a thick layer of loess, > 100 m thick on average.

Representative sites were selected for sample collection in both the semiarid and semihumid areas of the Plateau, each hosting apple orchards of three stand ages (10, 15 and 22 years). The two sites are located in the Tianhe watershed, Baota district, Yan'an, and the Loess Plateau Experimental Station in Qingyang, respectively, where the P/ET ratios (based on mean precipitation and evapotranspiration from 1995 to 2010 are 0.49 and 0.51, respectively) (Fig. 1). Both sites are located in the main apple cultivation area of the Loess Plateau. At each site, we collected soil and xylem samples from apple orchards of each age. The data gathered from the stands are valid for our comparative purposes, because all orchards at the same site are located in the same small watershed, have similar slopes, aspects and soil texture, and have been subjected to the same management regimes (e.g., no irrigation, with standard clipping and fertilization treatments). Locations of the stands were recorded with a portable GPS receiver. In addition, the height, diameter at breast height and crown dimensions (long and short axes) of 20 randomly selected trees in each stand were measured with a hypsometer, caliper scale and tapeline, respectively. General information on the apple orchards is presented in Table 1.

2.2. Soil water dynamics simulation

2.2.1. Numerical modelling

HYDRUS-2D (version 2.03) is reportedly powerful software for simulating two- or three-dimensional axially symmetric water flow and root water uptake based on finite-element numerical solutions of flow equations (Simunek et al., 2006). Thus, we used it to simulate soil water dynamics in the apple orchards. Ignoring effects of temperature and gas on soil water movement, and assuming that soil is homogeneous and isotropic, its two-dimensional flow is described by the Richards equation (Richards, 1931; Celia et al., 1990):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial r}\left[K(h)\frac{\partial h}{\partial r}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{\partial K(h)}{\partial z} - S(r, z, t) \quad (1)$$

where t is time (d); θ is the volumetric water content (cm^3 cm^{-3}); r is the horizontal coordinate (cm); z is the vertical coordinate, positive upward (cm); h is the pressure head (cm); and $K(h)$ is the unsaturated hydraulic conductivity (cm·d^{-1}).

2.2.2. Root water uptake and boundary conditions

The Feddes function (Feddes et al., 1978) was used to simulate

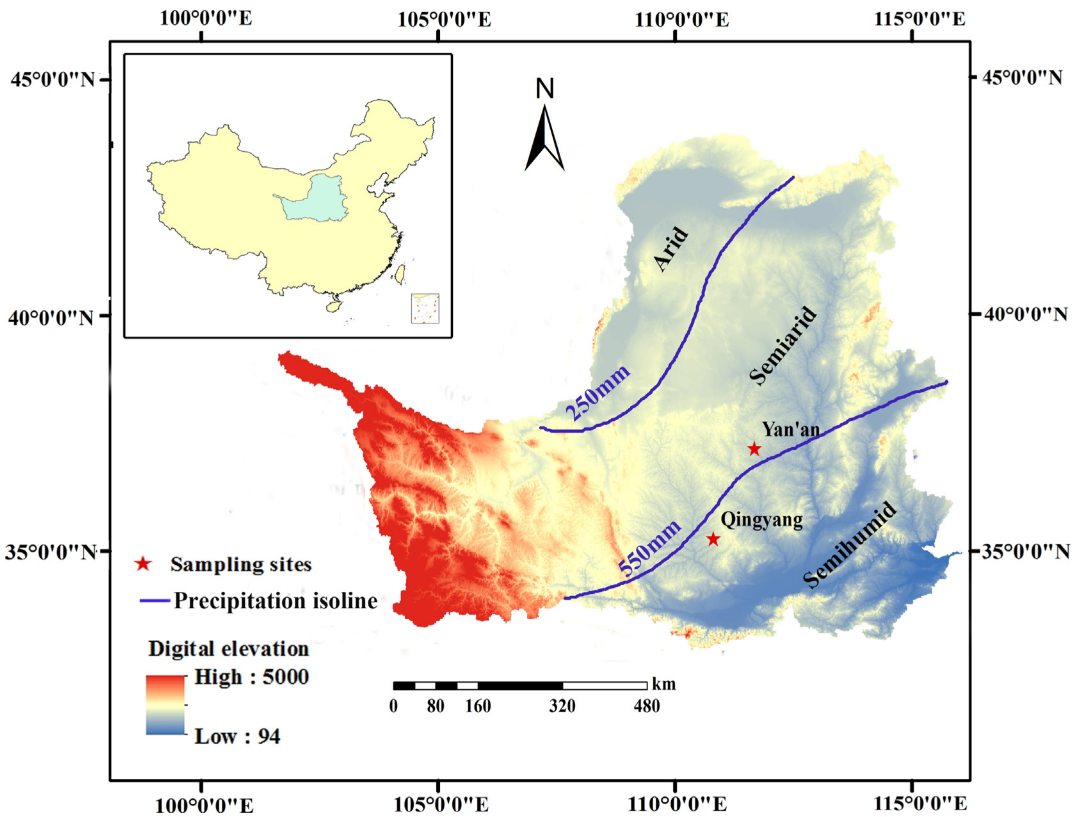

Fig. 1. Locations of the two sampling sites on the Loess Plateau of China.

apple trees' root water uptake:

$$S(z, t) = \alpha(h, z)\beta(z)T_p \tag{2}$$

where α(h, z) is the water stress response equation; β_z is the root water uptake distribution function; and T_p is the potential transpiration rate (cm^{-1}·d).

We set the upper boundary to "atmospheric boundary" conditions, left and right boundaries to "zero flux" conditions, and the bottom boundary to "free drainage boundary" conditions, because the water table in the study area is much lower than the observed soil depth.

2.2.3. Acquisition of model parameters

The soil hydraulic properties were described by the Van Genuchten equation (1980) as follows:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{3}$$

$$K(h) = K_s S_e^1 [1 - (1 - S_e^{1/m})^m]^2 \tag{4}$$

where θ is the volumetric water content (cm^3 cm^{-3}); h is the soil water pressure head (cm^3); θ_r is the residual water content (cm^3 cm^{-3}); θ_s is the saturated water content (cm^3 cm^{-3}); n and m are van Genuchten-Mualem shape parameters and $n = 1/(1\text{-}m)$; α is an empirical parameter (cm^{-3}); K_s is saturated hydraulic conductivity; and S_e is the relative saturation. The initial hydraulic parameters (θ_r, θ_s, α, K_s and n) of different soil layers were estimated using the neural network prediction program in the ROSETTA module, and then optimized by the inverse solution in HYDRUS-2D for these parameters.

2.2.4. Model calibration and evaluation

The volumetric water content of soil in the 10-year-old apple orchard in the semiarid area (Yan'an) was measured using a Portable Time Reflectometry (TDR) system (TRIME-PICO IPH/T3; IMKO, Germany) during the growing seasons in 2016 and 2017. Soil water was measured, at 20 cm intervals to 280 cm depth, once a month, with additional monitoring after rain. The data acquired in 2016 and 2017 were respectively used to calibrate and validate the hydraulic parameters.

'Days' were set as the time units in the numerical simulations, which ran from May 1, 2016 to September 30, 2016 and May 1, 2017 to September 30, 2017. Simulated values were compared with observed values, and values of the calibrated parameters were selected from the run when simulated and observed values were adequately consistent

Table 1
General information on the apple orchards.

Sampling site	Stand age/a	Longitude	Latitude	Altitude/m	Height*/cm	DBH/cm	Crown size/cm
Yan'an	10	109°21′51″E	36°40′23″N	1272	400	14.46	483 × 550
	15	109°20′32″E	36°41′48″N	1269	380	16.46	487 × 551
	22	109°21′51″E	36°40′23″N	1226	382	19.59	570 × 633
Qingyang	10	107°50′12″E	35°39′28″N	1244	394	14.61	457 × 487
	15	107°50′22″E	35°39′30″N	1244	409	16.36	459 × 513
	22	107°50′23″E	35°39′25″N	1244	451	21.98	563 × 597

*Height, DBH (diameter at breast height) and crown size (long and short axes) are mean values of measurements of 20 trees in each stand.

Table 2
Soil hydraulic parameters.

Depth (cm)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_s (cm d^{-1})	l
0–60	0.0823	0.42	0.013	1.78	65	0.5
60–200	0.0823	0.45	0.025	1.6	70	0.5
200–300	0.0823	0.48	0.018	1.6	70	0.5

(He et al., 2018). The soil hydraulic parameters in 2016 (calibration set) and 2017 (validation set) are shown in Table 2. The mean absolute error (MAE), root-mean-square error (RMSE) and coefficient of determination (R^2) were used to assess the consistency between the simulations and observations, as expressed by the following equations.

$$MAE = \frac{\sum_{i=1}^{n} P_i - O_i}{n} \quad (5)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - Q_i)^2}{n}} \quad (6)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (P_i - Q_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \quad (7)$$

where n is the number of compared values, P_i is the predicted value, O_i is the observed value, and $\bar{O}$ is the mean of observed data.

2.3. Isotopic data collection

2.3.1. Fine root collection

Preliminary investigations about the apple trees' root systems distribution were conducted before isotopic sample collection. Root samples of 10-year-old apple trees (0–800 cm) were collected in trisection radiation from the representative tree trunk at 0.5 m distance using a hand auger with 90 mm diameter in May 2016 (Li et al., 2017).

Collected root samples were poured into a sieve (0.2 mm, 25 cm diameter, 7.5 cm height) and then washed carefully with tap water to remove all unnecessary soil. Roots which ≤ 2 mm in diameter are the primary organ of absorbing water and nutrients in forest systems (Ceccon et al., 2011). The fine roots were scanned using a scanner at 300 dpi, and then the fine root length was determined using WinRhizo software (version 5.0 Regent Instruments Inc., Quebec, Canada). The fine root length density (FRLD m m^{-3}) in each sample was then calculated by dividing the obtained length of fine roots by the volume of the sample.

2.3.2. Sampling natural stable isotopes

Plant and soil samples were collected from the orchards in the following three developmental stages in 2016: blossom and young fruit (BYF, May), fruit swelling (FSW, July), and fruit maturation (FTM, September).

On each sampling occasion, three apple trees in each orchard were randomly selected. Xylem and soil samples were collected concurrently between 8:00 and 12:00 when the trees were actively transpiring (Wang et al., 2010). Three suberized twigs (0.3–0.5 cm diameter, ca. 10 cm long and near the tree trunk) were cut from the sunny side of each sampling tree, and the bark, phloem and cambium were removed from them. Then each debarked twig was cut into 1 cm segments, which were immediately placed in vials that were sealed with parafilm, and placed in a box with ice for transportation to the laboratory where they were stored in a refrigerator until water extraction. After xylem sampling, soil samples were collected with a hand auger from shallow soil layers (at 10, 20 and 40 cm intervals from the 0–20, 20–80 and 80–300 cm layers, respectively). The soil samples depth of 300 cm was determined because > 70% of apple tree roots were distributed in the 0–300 cm soil layers and there was a distinct gradient in δ^2H values existed in this layer which meeting requirements for use of isotopic mixing models to distinguish primary water sources. Each soil sample was divided into two parts, one of which was placed in a vial and stored identically to the xylem samples for isotopic determination, while the other was used to obtain the gravimetric soil water content (SWC) by oven-drying.

2.3.3. Isotope labeling experiments

To obtain complementary information on deep soil water use, three trees in each orchard with similar height, crown diameter and diameter at breast height were randomly selected for inclusion in a ^2H_2O tracer experiment in 2016. A day before tracer injection, a 400 cm hole was drilled 50 cm from the trunk of each selected tree using a hand auger. A 400 cm long polyvinyl chloride pipe was inserted into the holes to inject tracer at the target depth (400 cm), then 150 ml of 10% ^2H_2O solution (15 ml 99.99% ^2H_2O plus 135 ml tap water) prepared in advance was injected into each hole. A previous preliminary experiment showed that this treatment increased SWC 24 h after injection by less than 1%, which is negligible for soil hydrological processes. After the ^2H_2O injection, the polyvinyl chloride pipe was removed and the hole was sealed.

We collected xylem samples in the 7 days following each injection to detect possible tracer uptake by the trees. The first ^2H_2O tracer injection was conducted in May, and the xylem samples were collected 2, 4 and 7 days after the injection. Assuming that the ^{2}H concentration in the soil would steadily decline as a result of soil water transport and uptake by roots, in July we applied a second tracer injection (identical to the first in terms of volume and concentration), and collected xylem samples 2 and 7 days later. Xylem samples were also collected from the labeled trees at the end of September. At the same time that xylem samples were collected from labeled trees, corresponding samples were collected from unlabeled trees in the same orchards to acquire background isotope concentrations. If a sample had a ^{2}H concentration that was at least two standard deviations (SD) higher than the background value, tracer was assumed to be present (Kulmatiski et al., 2010).

2.4. Isotopic analysis

The water in xylem and soil samples was extracted using a LI-2000 cryogenic vacuum distillation system (Los Gatos Research, Mountain View, USA), transferred to 5 ml glass vials, and stored at 4 °C until analysis. The stable hydrogen and oxygen isotope ratios of extracted water were then determined using a TIWA-45EP isotope ratio infrared spectroscopy analyzer (Los Gatos Research, Mountain View, USA). Methanol contamination in the plant samples was corrected by correction equation which acquired through calibration test of methanol contamination spectrum, as expressed by the following equations.

$$\delta D_t = \delta D_m - 0.0247(lnM)^3 + 0.0749(lnM)^2 - 1.2613lnM - 1.0182 \quad (8)$$

where δD_t is the true value, δD_m is the measure value, M is the methanol value.

2.5. Determination of plant water sources

The Bayesian isotope mixing model MixSIR 1.0.4, which accounts for uncertainties associated with multiple sources (Moore and Semmens, 2008), was used to calculate proportional contributions of water from considered soil layers to water extracted from the xylem samples. The two study areas are both covered by thick loess soils and groundwater is too deep for plants' roots to absorb. Moreover, all the experimental apple orchards are rainfed. Thus, soil water is the primary water source for plants in the orchards, and on the Plateau generally (Fan et al., 2016). Based on distributions of soil water content (SWC) and δ^2H values, the entire shallow soil profile (0–300 cm) was divided into three potential soil water sources (0–40, 40–160 and 160–300 cm layers). Both SWC and δ^2H values were most variable in the 0–40 layer and most stable in the 160–300 cm layer. The mean δ^2H values and their standard deviations in each of these potential water sources and the xylem samples were respectively used as source and mixture data for the model. The fractionation factor was set to zero because no isotope fractionation is believed to occur during water uptake (Ehleringer and Dawson, 1992).

2.6. Statistics

Distributions of the SWC and δ^2H values (of both xylem and soil water samples) met requirements for analysis of variance (ANOVA). Therefore, differences in δ^2H values of xylem water among sampling dates were evaluated by one-way ANOVA. Two-way ANOVA was applied to detect differences in SWC and δ^2H of soil water between sampling dates and depths, as well as in contributions of the three water sources (soil layers) to xylem water between sampling dates. Least significant difference (LSD) post-hoc tests, with $\alpha = 0.05$, were used to identify significant between-date and between-depth differences.

3. Results

3.1. Precipitation and soil moisture dynamics

Total precipitation in the study year (2016) amounted to 502.2 and 478.4 mm in the semiarid and semihumid areas, respectively, which were both defined as normal precipitation years. In both cases > 90% of the precipitation occurred during the growing season. Additionally, the highest monthly precipitation was 175.4 mm in July in the semiarid area and 105.6 mm in June in the semihumid area. In the highest single precipitation events 89.5 and 66.9 mm of rain fell in these areas, respectively, in both cases in July. The precipitation in 2016 was 28.2% greater than in 2015 in the semiarid area, but 10.6% lower than in 2015 in the semihumid area (Fig. 2).

Fig. 3 shows the observed and simulated soil water dynamics of 10-year-old apple orchard in semiarid area in 2016 and 2017. The results suggest that there is a strong correlation between the simulated and observed volumetric water content for both 5 soil layers. MAE, RMSE and R^2 ranged from 0.5% to 2.1%, 0.5% to 3.2% and 80.0% to 92.4%, respectively (Table 3). These data confirmed the suitability of HYDRUS-2D for simulating water dynamics in the area, at least under the range of precipitation conditions during the monitoring period. Based on the United States Department of Agriculture's classification system, the soils at the two sites are similar silt Loam (with 15.8% clay, 59.4% silt and 18.2% sand contents in Yan'an, and 22.6% clay, 51.5% silt and 26.5% sand contents in Qingyang). Thus, data acquired at the Yan'an site were used to calibrate parameters for numerical simulations with the HYDRUS-2D model of the soil water dynamics of the orchards in both the semiarid and semihumid regions of the Plateau.

The volumetric soil water content (VSWC) of all six orchards displayed clear seasonal and vertical variations throughout the growing season, and differed with stand age and climate (Fig. 4). Due to the typical effects of rainfall infiltration and evapotranspiration, the VSWC showed markedly high temporal variations in 0–100 cm soil layers than in deeper layers. In the semiarid area, desiccation occurred at 160–300, 160–240 and 100–300 cm depths in the 10-, 15- and 22-year-old orchards, respectively. The VSWC of all orchards decreased with increasing stand age in both the semiarid and semihumid areas. Although the total precipitation in the semiarid area was slightly higher than in the semihumid area in 2016, the VSWC in the profile was lower in the semiarid area than in the semihumid area during the BYF stage (from the 121th to 150th day) (Fig. 4). This difference is mainly attributed to the impact of precipitation in the preceding year, which as mentioned above was substantially higher in the semihumid area (534.9 mm) than in the semiarid area (391.7 mm) (Fig. 2). Overall, as expected, orchards in the semihumid area had higher soil water contents than those in the semiarid area.

3.2. δ^2H values in xylem and soil water

The δ^2H values in xylem water from trees in stands of different ages varied substantially during the growth period in the two climatic regions (Fig. 5). The xylem water δ^2H of 10-year-old trees fluctuated most

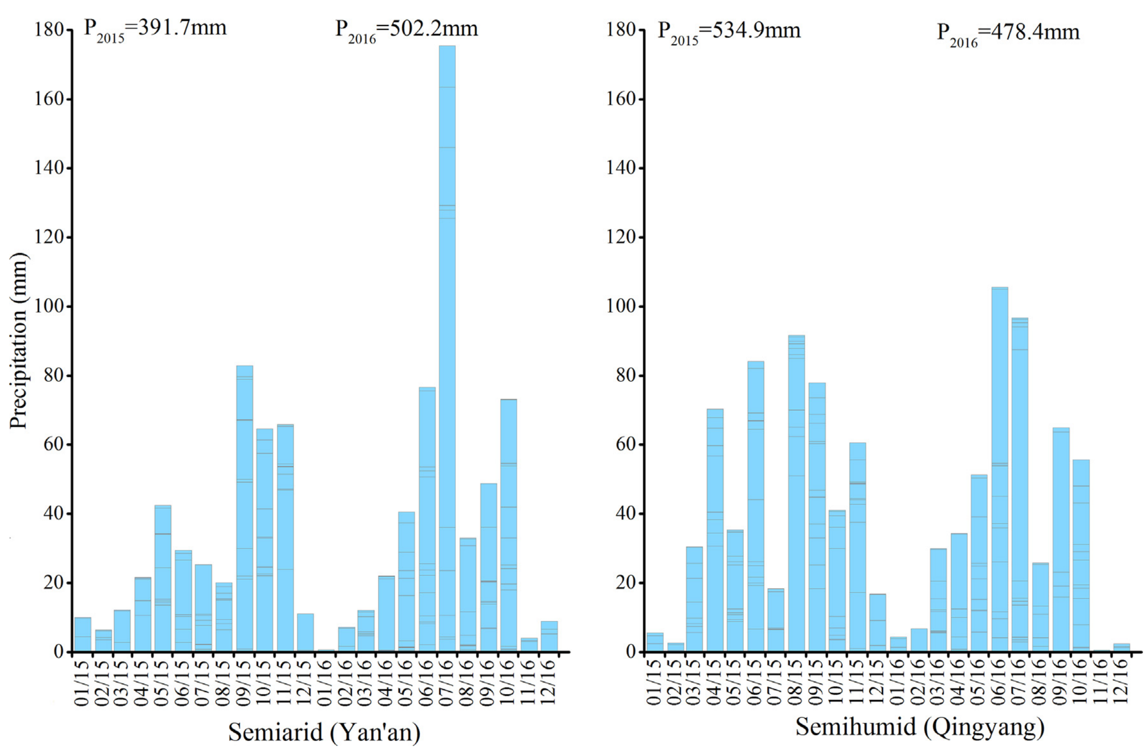

Fig. 2. Monthly precipitation time-series from January 2015 to December 2016 at the sites in the two climatic regions. The intervals in the bars indicate amounts of precipitation in individual events.

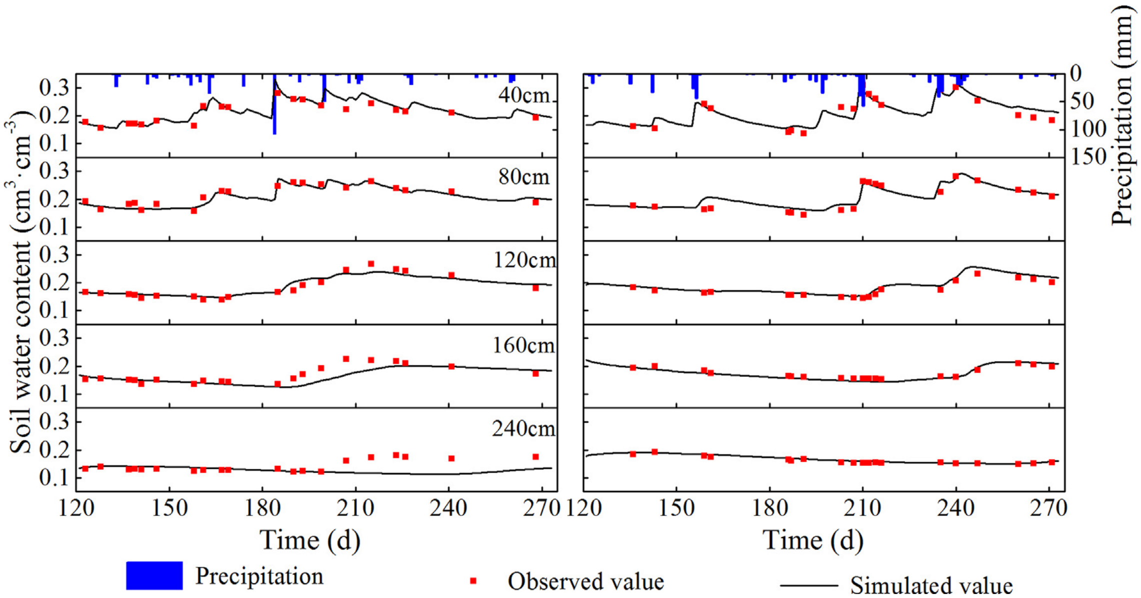

Fig. 3. Simulated and observed soil water contents in the 10-year-old apple orchard at the semiarid site (Yan'an) in 2016 (left) and 2017 (right).

Table 3
Performance of the model in simulating soil water at indicated depths for the calibration (2016) and validation (2017) datasets according to three criteria: MAE, RMSE and R^2 (mean absolute errors, root-mean-square errors and coefficient of determination, respectively, percentages).

Depth (cm)	2016			2017		
	MAE	RMSE	R^2	MAE	RMSE	R^2
40	1.0	1.6	81.2	1.7	2.1	84.7
80	1.2	1.4	84.7	1.4	1.9	83.4
120	1.0	1.4	92.4	1.1	1.2	80.0
160	1.6	2.3	81.6	0.7	0.8	82.7
240	2.1	3.2	80.0	0.5	0.5	80.3

during the growing season, varying from −66.7‰ to −53.3‰ in the semiarid area and from −68.9‰ to −57.3‰ in the semihumid area. The variation in δ^2H in xylem water from the 15- and 22-year-old trees showed similar temporal trends in the two climatic regions, falling between the BYF and FSW stages then increasing between the FSW and FTM stages.

There were marked variations with both depth and sampling date in δ^2H values of shallow soil layers in both climatic regions (Fig. 6). The values were more negative in 40–300 cm layers than in 0–40 cm soil layers of all the orchards in the BYF and FTM stages, but they were more negative in the 0–40 cm layers in the FSW stage, possibly due to infiltration of precipitation with strongly negative values in summer events. Hence, the soil water δ^2H fluctuated more strongly in the upper 40 cm layers (ranging from −69.87‰ to −21.69‰ in the semiarid area and from −87.53‰ to −17.47‰ in the semihumid area) than in the 40–300 cm layers. As soil depth increased, the influences of precipitation weakened. The δ^2H values in the 40–300 cm soil layers were relatively stable and did not significantly differ among sampling dates.

3.3. Water uptake patterns

Analysis of the δ^2H values of xylem and soil water revealed significant variation in contributions of three potential soil water sources of the apple trees throughout the growing season in the two climatic regions (Fig. 7). In the BYF stage, when precipitation was relatively light and evaporation strong, the SWC values in the shallow layers were relatively low and the trees took up correspondingly large proportions of water from deeper layers. For example, 15-year-old trees in the semiarid area took up 48.3% of their xylem water from the 40–160 cm soil layers in the semiarid area. Similarly, 10-year-old trees took up 44.8% of their xylem water from the below 160 cm soil layers in the semiarid area, and the 10- and 15-year-old trees respectively took up 63.4 and 41.8% from the below 160 cm layers in the semihumid area during this stage. As precipitation infiltrated in the FTM stage, 10- and 15-year-old apple trees showed great plasticity in their water uptake patterns, switching their main water source to the 0–40 cm soil layers (which respectively accounted for 43.6 and 44.8% of the xylem water for 10- and 15-year-old trees in the semiarid area, and 63.4 and 41.8% in the semihumid area, respectively) (Fig. 7A–D). The 22-year-old apple trees in the two climatic regions showed similar water uptake patterns. They primarily derived water from 0–160 cm soil layers (73.6 and 71.7% in BYF and FSW stages in the semiarid area, respectively; 71.5 and 89.1% in these stages in the semihumid area, respectively), then switched to 0–40 cm soil layers (48.5 and 58.4% in the semiarid and semihumid areas, respectively) in the FTM stage when the water in the upper layers was replenished (Fig. 7E and F).

3.4. Variations in the isotopic label

The temporal variation in ^{2}H concentrations in the xylem of monitored trees following ^2H_2O injections provided direct evidence of deep root water uptake (Fig. 8), with differences associated with both stand age and climatic region. In the semiarid area, 22-year-old apple trees absorbed water from 400–500 cm soil layers rapidly (Fig. 8A), as manifested by significantly elevated ^{2}H values of samples taken two days after the injections. Then δ^2H values progressively increased, to −43.78‰ (30.8% higher than the background value) by the seventh day. In contrast, no artificial tracer was detected in xylem of 10- and 15-year-old trees 2 and 4 days after labeling, but by the seventh day, their δ^2H values were significantly (18.4 and 21.9%, respectively) higher than the background values. No evidence of uptake of labelled water by the trees was found in the seven days following the second injection, but clear signs of uptake were observed on September 25. No uptake of the labeled water in any of the three apple orchards at any stage of the sampling campaign was detected in the semihumid area (Fig. 8B).

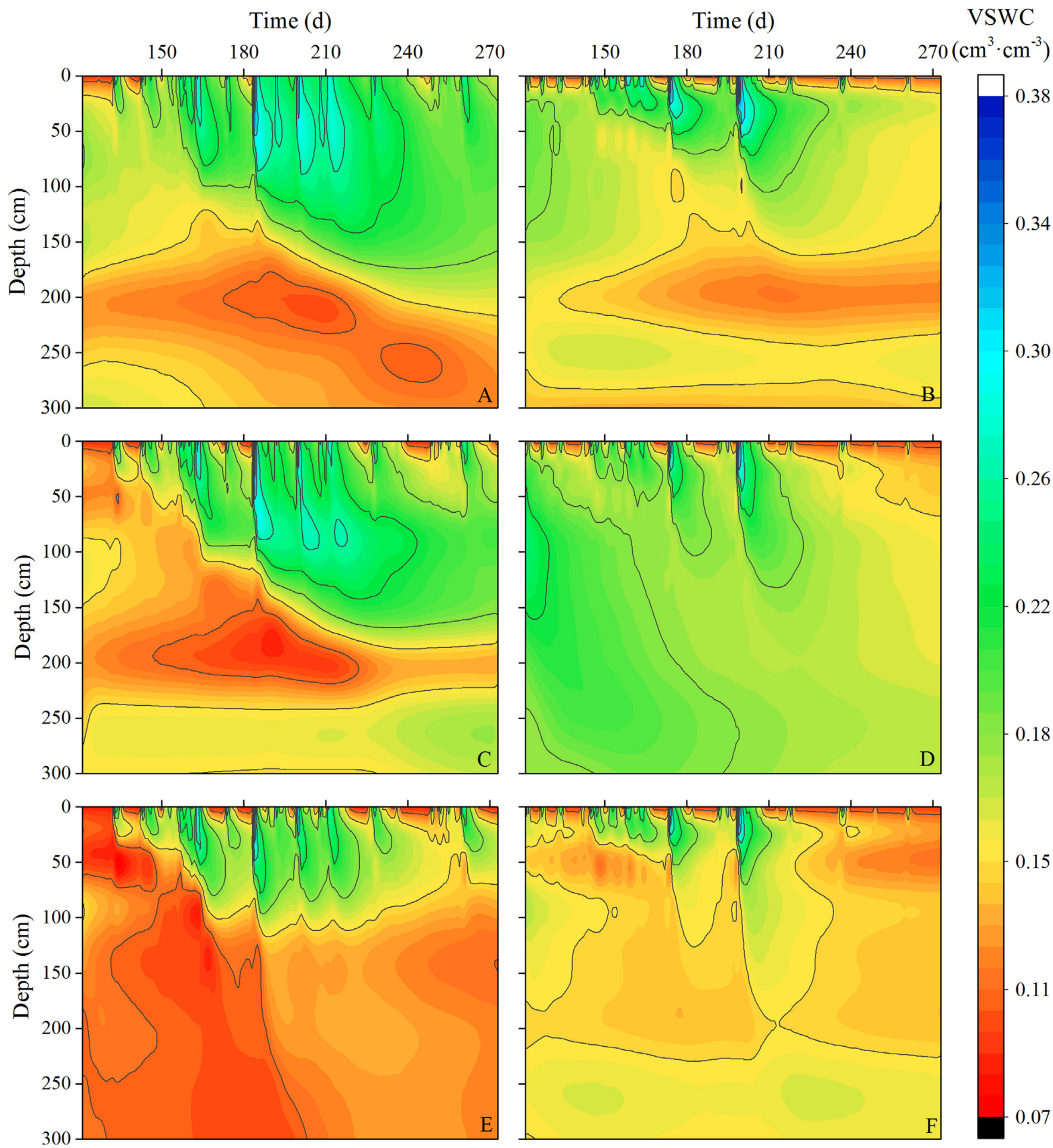

Fig. 4. Seasonal variations in volumetric soil water content (VSWC) in shallow layers (0–300 cm) of the 10-year-old (A and B), 15-year-old (C and D) and 22-year-old (E and F) apple orchards at the semiarid site (Yan'an, A, C and E) and semihumid site (Qingyang, B, D and F).

4. Discussion

4.1. Uncertainty in the soil moisture simulation

HYDRUS-2D accurately captured temporal and spatial dynamics of soil moisture, according to comparison of observed and simulated values, with both MAE and RMSE ≤ 3.2% and R^2 consistently ≥ 80.0% (Table 3). This may be to the reasons of the application of inverse solution in the acquisition of parameters. Nascimento et al. (2018) had demonstrated good similarity between field-measured data and data fitted by inverse solution, and HYDRUS inverse solution is a useful technique for rapid characterization of the unsaturated soil hydraulic properties (Rashid et al., 2015). These results confirm numerous previous demonstrations that HYDRUS-2D has high ability to simulate soil moisture dynamics under diverse conditions (Autovino et al., 2018; Cai et al., 2018; Karandish and Šimůnek, 2019). Nevertheless, there are clearly uncertainties in soil moisture simulations by HYDRUS-2D due to uncertainties in multiple (soil, meteorology and plant) parameters. For example, neural network prediction program in the ROSETTA module was used to predict the soil hydraulic parameters in the Loess Plateau (Lü et al., 2009). Random aspects of sedimentation processes during formation of soils on the Plateau resulted in significant spatial variability in soil physical and chemical properties, which inevitably affect movements of soil moisture and then impact on the simulation effect. Notably, the simulation of soil moisture was less accurate for the 160–300 cm soil layers than for other layers following extreme rainfall (108 mm on July 3, 2016), possibly due to preferential flow leading to increases in soil moisture in the 160–300 cm soil layers that the model did not account for. Moreover, the root distribution is simply described by HYDRUS-2D with just six parameters (maximum rooting depth and

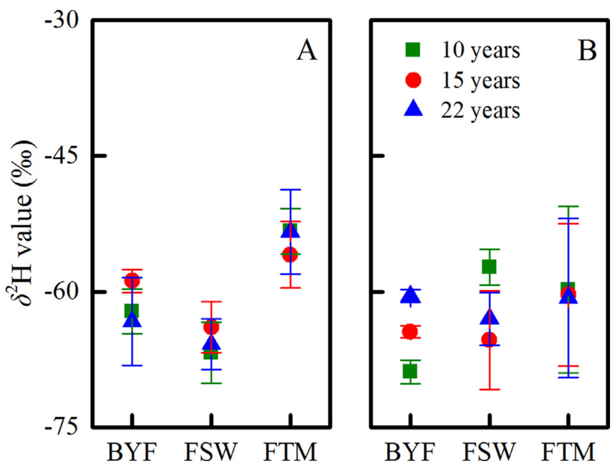

Fig. 5. Seasonal variations of δ^2H values of xylem water of apple trees of indicated ages and developmental stages (blossom and young fruit, BYF; fruit swelling, FSW; and fruit maturation, FTM) at the semiarid site (Yan'an, A) and semihumid site (Qingyang, B). The error bars indicate standard errors of the means (N = 3).

radius, maximum rooting intensity depth and radius, dimensionless parameter P_z and P_x), which is clearly insufficient for detailed simulation of root water uptake.

4.2. Seasonal and regional variations of water uptake patterns

The δ^2H values of soil water in the apple orchards exhibited significant seasonal patterns in both climatic regions (Fig. 6), and they were intimately associated with precipitation infiltration and evaporation, which differed in the two regions. This directly caused variations in δ^2H values of xylem water in the trees throughout the growing season, within and between the two climatic regions (Fig. 5). Therefore, there were distinct seasonal and spatial variations in the trees' water sources, which also varied among orchards of different ages (Fig. 7).

The MixSIR (1.0.4) based analysis detected apparently adaptive water use by the 10- and 15-year-old apple trees in the semiarid area, which switched their primary water sources from 160–300 or 40–160 cm soil layers to 0–40 cm soil layers as the growing season progressed (Fig. 7A and C). This is consistent with findings of several previous studies, that plants absorbed water predominantly from deep soil layers during drought periods (Gao et al., 2018b; Song et al., 2016) and switched to shallow soil layers during other periods (Yang et al., 2015). In contrast, the 22-year-old trees predominately acquired water from 0–160 cm soil layers, and the proportional contribution of water from 160–300 cm layers decreased throughout the growing season. This could be ascribed to relatively low SWC in the 160–300 cm soil layers due to continuous consumption (Fig. 7E). This result partially differs from findings of Zhao et al. (2018), that shallow (0–40 cm) layers were not the primary sources for 22-year-old jujube trees in the semiarid

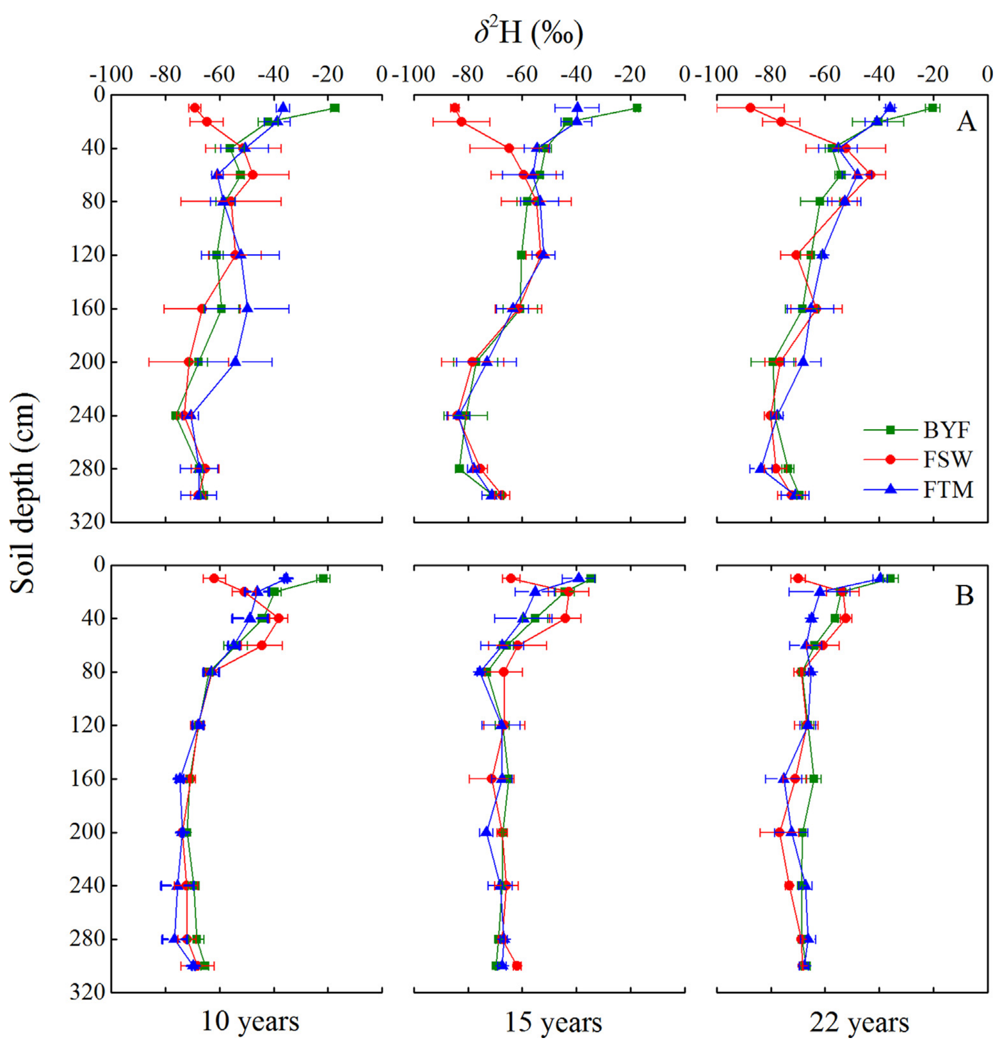

Fig. 6. Seasonal variations of shallow (0–300 cm) soil water δ^2H of the 10-, 15- and 22-year old apple orchards at the semiarid site (Yan'an, A) and semihumid site (Qingyang, B). The error bars indicate standard errors of the means (N = 3).

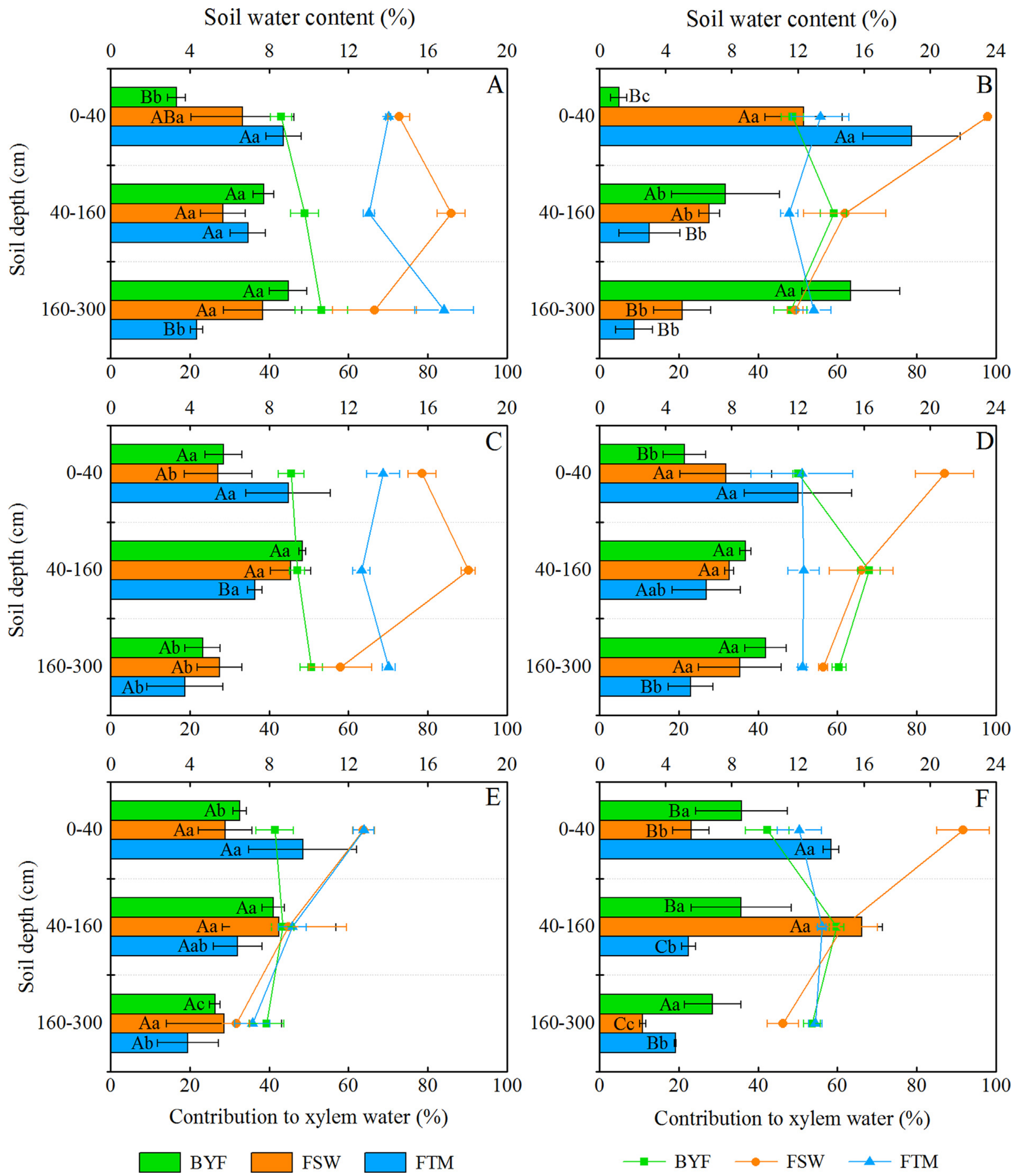

Fig. 7. Average water content of each water source (soil layer) and its contribution to xylem water of the 10-year-old (A and B), 15-year-old (C and D) and 22-year-old (E and F) apple orchards at the semiarid site (Yan'an, A, C and E) and semihumid site (Qingyang, B, D and F). Different uppercase and lowercase characters indicate significant ($P < 0.05$) differences between growing seasons and between soil layers, respectively. The error bars indicate standard errors of the means.

area, possibly due to differences in soil water availability.

Apple trees in the semihumid area showed similar water use patterns to those in the semiarid area. 10- and 15-year-old trees shifted their water sources from the 160–300 cm to 0–40 cm soil layers, and 22-year-old trees mainly exploited water from the 0–160 cm soil layers throughout the growing season (Fig. 7B, D and F). In addition, the proportional contributions of water in the 160–300 cm layers were significantly higher in the BYF stage than in the FTM stage for trees of all three ages ($P < 0.05$). This could be due to relatively low availability of water in the 0–160 cm layers due to relatively high evapotranspiration and low precipitation in the BYF stage (Fig. 7B, D and F). Interestingly, despite SWC in the 0–40 cm soil layers increasing significantly due to heavy rainfall in the FSW stage, the proportional use of shallow water by the 15- and 22-year-old trees did not increase (Fig. 7D and F). Similar studies in water-limited ecosystems have detected a time lag in plants' switches to different water sources following precipitation-mediated increases in water availability in shallow layers (Huo et al., 2018; Wu et al., 2016). Other studies have also detected a time lag between water shortage and plants' responses (Vicente-Serrano et al., 2013; Yang et al., 2015). Nevertheless, the proportional contribution of the 0–40 cm soil water for 10-year-old apple trees increased significantly in the FSW stage, in marked contrast to the observed

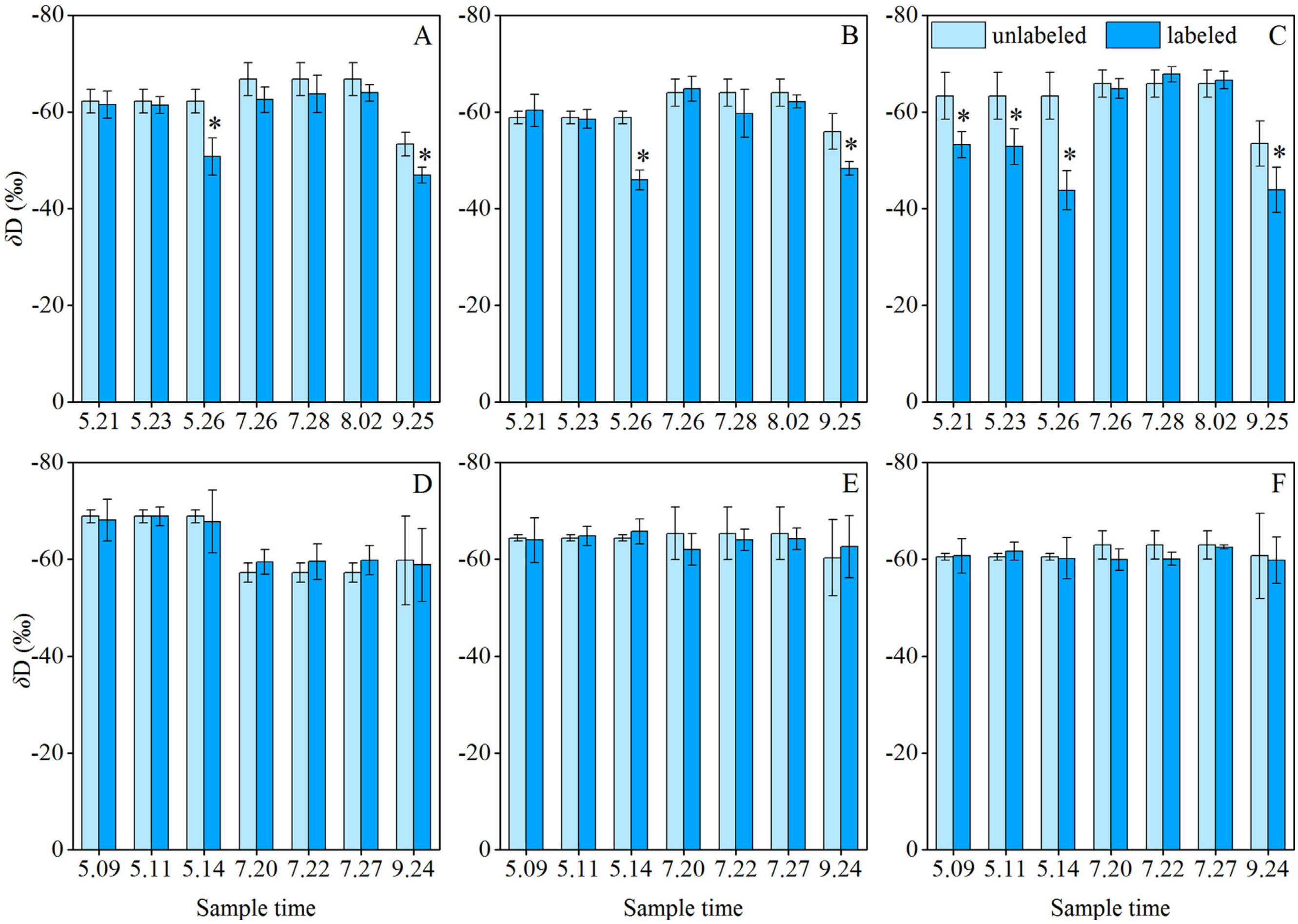

Fig. 8. Dynamics of tracer uptake by trees of 10-year-old (A and D), 15-year-old (C and D) and 22-year-old (E and F) apple orchards at the semiarid site (Yan'an, A, C and E) and semihumid site (Qingyang, B, D and F). The error bars indicate standard errors of the means (N = 6). Asterisks indicate the labeled value is at least two standard deviations higher than the background value.

pattern for older trees (Fig. 7B). This could be partly due to root systems of younger trees having higher sensitivity to water. Skubel et al. (2015) also found that young stands may be more suitable than older stands in warm environments with variable precipitation. Hence, both the likelihood of such time lags and their duration if they occur may be related to stand age. Trees of all three ages obtained the largest proportions of their water from the 0–40 cm soil layers in the FTM age, and the SWC in these layers was correspondingly low (Fig. 7B). Normally, plants' roots obtain resources from upper soil layers (when available) as the energy costs are lower, and both water and nutrient availability are generally high in the upper layers (Schenk, 2008).

4.3. Water uptake dynamics from deep soil layers

The water extracted from deep soil is important for plants' growth, especially in dry periods, and significantly contributes to drought avoidance (Yang et al., 2017). Thus, to obtain more comprehensive information about the trees' water uptake patterns, $^{2}H_2O$ tracer was injected at 400 cm depth and concentrations of ^{2}H in xylem samples were measured to investigate their deep soil water uptake dynamics (Fig. 8).

The artificial tracer was detected in xylem of apple trees, as expected (Fig. 8A), given that roots of apple trees at full productive age could reach depths of 10 m and the roots were deeper as the stand age increasing (Zhang et al., 2017b; Li et al., 2019). Water uptake from deep soil layers (400–500 cm) was detected in BYF in apple orchards of the semiarid area. It maybe because precipitation in BYF was relatively less and evaporation was strong, resulting in relatively low soil water content in shallow layers. Meanwhile, BYF is the critical period of water demand for apple trees. And the SWC in 400 cm depth was higher than its in shallow layers (0–300 cm) (Fig. S1) in this period, so apple trees would take up more deep soil water when shallow soil water rarely suffices the demand. Interestingly, In the semiarid area, 22-year-old apple trees absorbed deep (400–500 cm) soil water rapidly (within 2 days), but the younger trees absorbed it after a longer delay (Fig. 8A), according to the criterion of xylem ^{2}H concentrations being at least two standard deviations (SD) higher than the background value. There are several possible explanations for such uptake. First, some roots capable of taking up water may be present at the labeling depth. Second, hydraulic redistribution of water from deep to upper soil layers may occur, enabling shallow roots to absorb it (Bleby et al., 2010; Scott et al., 2008). Third, deep water may be rapidly accessed and transferred through mycorrhizae (Plamboeck et al., 2007). It should be noted that ^{2}H xylem concentrations increased more rapidly in the 22-year-old trees than in the younger trees, indicating that older trees might have higher transpiration requirements. This inference is consistent with findings by Wang and Wang (2017) that apple trees' daily transpiration and evapotranspiration rates are positively correlated with age. Furthermore, the 22-year-old trees were markedly larger than the younger trees (Table 1), and recent research suggests that canopy cover is the primary driver of orchards' water consumption (Dzikiti et al., 2018). In addition, evidence of uptake of the injected $^{2}H_2O$ was detected in samples from trees in the semiarid area, substantially later, on September 25 (Fig. 8A), possibly because the trees were water-stressed in this period or hydraulic redistribution occurred (Beyer et al., 2016). In contrast, no uptake of the artificial tracer was detected in apple trees in the semihumid area at any sampling date (Fig. 8B). The difference between trees in the two areas could be due to differences in soil water distributions resulting from spatiotemporal heterogeneity of precipitation (Wang et al., 2011). Many trees (including apple trees) have dimorphic root systems, which enable them to switch water sources between shallow and deep soil layers depending on the soil moisture distribution (Liu et al., 2019). Therefore, soil water conditions in shallow layers will strongly affect apple trees' utilization of deep soil water.

4.4. Implications

Knowledge of apple trees' age- and climate-dependent water uptake patterns is crucial for formulating robust sustainable apple cultivation and water management strategies. We found that stands of different ages showed significantly differing responses to water moisture in the semiarid, but not the semihumid, area (Fig. 4). However, uptake patterns of the trees from shallow soil layers were similar in the two climatic regions (Fig. 7). The youngest (10-year-old) trees absorbed the largest proportion of water from the 160–300 cm soil layer (Fig. 7A), while the 15- and 22-year-old trees took up successively more from the shallower layers. However, mean SWC in the 160–300 cm layers decreased with increases in stand age and approached wilting point (5.47%) in the 22-year-old orchard in the semiarid area (Fig. 7E). The variation in shallow soil moisture conditions directly affected the trees' utilization of deep soil water. In the BYF stage, apple trees in the semiarid area increased their water uptake depth and obtained more deep soil water, presumably in responses that alleviated water stress. In addition, the proportion of water they absorbed from deep soil layers (according to the tracer measurements) was positively correlated with their age (Fig. 8A). However, there is virtually no groundwater recharge exist in apple orchards which rooting depth is deeper than 15 m (Li et al., 2018a). So it should be noted that excessive consumption of deep soil water will result in soil drying that is difficult to ameliorate (Wang et al., 2011). If predictions of Huang et al. (2017) and Zhang et al. (2016) are accurate, the climate of the Loess Plateau will become drier and warmer in the future. This would strongly affect water resources, especially soil water availability (Gao et al., 2018a) and accelerate deep soil drying, posing severe challenges to the sustainability of apple orchards. Hence, it is essential to take appropriate action to prevent development of DSL. The critical water demand stage for apple trees is the BYF, and we found strong consumption of water from the 160–300 cm soil layer by young apple trees in this stage. Thus, supplementary irrigation during this period may be appropriate for young orchards. For older apple orchards, mulching (e.g. with straw or plastic film) and landscaping (e.g. creation of fishponds and rainwater collection and infiltration systems) may be good choices for increasing rainfall infiltration and reducing evaporation, especially in the semiarid area (Li et al., 2018b). In addition, climate-smart agroforestry could help to conserve soil nutrients and orchard yields, thereby assisting efforts to cope with climate change (Gao et al., 2018a).

5. Conclusions

In this study, water uptake patterns of apple trees of three ages in two climatic regions of the Loess Plateau were investigated using both natural δ^2H signatures and ^2H_2O labeling. Uptake of shallow (0–300 cm) water showed significant seasonal variation that was similar in both climatic regions. However, there were distinct differences in the trees' utilization of deep (400–500 cm) soil water between the two regions. Apple trees exploited deep (400–500 cm) soil water in the semiarid area, especially in the BYF stage, and uptake of deep water was positively correlated with the trees' age. In contrast, no uptake of deep water was detected at any stage of the growing season in the semihumid area. Excessive consumption of deep soil water profoundly affects the sustainability of apple production, and the Plateau's climate is expected to become drier and warmer, thereby exacerbating soil drying. Hence, we do not recommend development of old apple orchards in the semiarid area. Our results also indicate that supplementary irrigation during the BYF stage may be beneficial for young orchards, and measures such as mulching and landscaping for old orchards.

CRediT authorship contribution statement

Shaofei Wang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft. **Juan An:** Data curation, Visualization. **Xining Zhao:** Conceptualization, Funding acquisition, Validation, Methodology, Visualization, Resources, Data curation. **Xiaodong Gao:** Conceptualization, Funding acquisition, Validation, Project administration, Resources, Data curation, Writing - review & editing. **Pute Wu:** Conceptualization, Funding acquisition, Resources, Supervision. **Gaopeng Huo:** Investigation, Methodology, Software, Data curation. **Brett H. Robinson:** Writing - review & editing.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.124462.

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