

Short-term changing patterns of stem water isotopes in shallow soils underlain by fractured bedrock

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ABSTRACT

Knowledge is limited on the changes in tree water uptake over short timescales in shallow soils underlain by fractured rocks under humid climate conditions. This study explored the changing patterns of tree water uptake at two forests (camphor) and two orchards (peach and tea) over multi-day timescales. We collected water isotopic samples (δD and $\delta^{18}O$) from rainfall, spring, tree branch, soil and fissure between two rain events (8-day duration). The trees in the forest lands exhibited a larger variability in stem water isotopic composition than the trees in the orchards. Significantly different changing patterns of stem water isotopic composition were found between the orchards and the forest lands. On average, the fissure contributed most of the tree water uptake ($46.1 \pm 20.8\%$) compared to the soil layer ($33.9 \pm 17.7\%$) and shallow groundwater ($20.0 \pm 13.5\%$). Main water sources for the trees in this study shifted at a daily timescale. Compared to orchards, forest trees had a relatively large range of source water and a good water use strategy in the shallow soil-rock profile under humid climate conditions. This study emphasizes the importance of characterization of the changing patterns of stem water isotopic composition over short timescales.

Key words | changing pattern, dual stable isotopes, isotopic shift, shallow soil, tree water uptake

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INTRODUCTION

Soil water is a key factor controlling plant growth and ecological and hydrological processes across multiple spatial scales in terrestrial ecosystems (Dawson 1993; Brooks *et al.* 2002; Zehe *et al.* 2010; Vereecken *et al.* 2014; Tang *et al.* 2015; Zhao *et al.* 2016a). The soil profile is one of the most important areas of water storage (de Boer-Euser *et al.* 2016; Yang *et al.* 2018). However, many areas are characterized by shallow soils underlain by fractured bedrock with fissures filled with moisture, soil particles and plant roots (Zwieniecki & Newton 1995; Schwinning 2010; Hasenmueller *et al.* 2017; Rempe & Dietrich 2018). Water stored in shallow soils is limited and prone to loss (Gaines *et al.* 2016; Fischer *et al.* 2017). Given the shallow soil and the developed fissure networks, rainwater can easily pass through the bedrock and then be discharged (Rempe & Dietrich 2018). It is

common that plants use water from the fractured bedrock on sites with shallow soils under semi-arid climate conditions (Zwieniecki & Newton 1995; Rempe & Dietrich 2018). In contrast, under humid climate conditions, the tree water uptake in shallow soils underlain by fractured rocks remains unclear.

Generally, soil water decreased consistently by evapotranspiration during drought periods (Anderson *et al.* 2009). Meanwhile, the taproots and lateral roots of trees can transfer water between soil layers (hydraulic redistribution), thereby significantly affecting the distribution and availability of water in the soil profile (Burgess *et al.* 1998; Brooks *et al.* 2002). The complex interactions reflect the possible different responses of the tree water uptake to variations in the potential water sources (Flanagan *et al.* 1992;

Ellsworth & Williams 2007; Schwinning 2008; Nie *et al.* 2011), and thus resulted in different changing patterns of water uptake (Brooks *et al.* 2002; Oliveira *et al.* 2005; Schlesinger & Jasechko 2014; Good *et al.* 2015).

In shallow soils underlain by thick fractured bedrock, trees could obtain water both in shallow soil and water held in deep bedrock (Zwieniecki & Newton 1995, 1996; Schwinning 2010; Nie *et al.* 2012). Trees in humid temperate climates are believed to rely mainly on shallow roots to obtain water in areas with frequent precipitation and abundant shallow soil water (Guswa 2008; Schenk 2008; Gaines *et al.* 2016), but this case needs to be further explored in shallow soils underlain by thick bedrock under humid climate conditions. Besides, tree water isotope ratios shifted significantly after intervening rain events (Schwinning 2008). Schwinning (2008) found that stem water isotope ratios also shifted after the summer-drought-ending rain event, and species effects were again non-significant. Nie *et al.* (2012) found the water source shift for woody plants growing on dolomite outcrops and nearby soils during dry seasons in karst region at monthly timescales. Ehleringer *et al.* (1991) found that, by fall, when the moisture from the summer rains was essentially depleted, woody perennials had shifted between possible water sources.

The isotopic fingerprint has significantly improved our understanding of many hydrological and ecological processes (Dawson & Ehleringer 1991; Ehleringer & Dawson 1992; Jackson *et al.* 1995; Tetzlaff *et al.* 2015; Allen *et al.* 2016; Priyadarshini *et al.* 2016). The dual stable isotopes (δD and $\delta^{18}\text{O}$) are widely used to investigate the depth and source of tree water uptake by the end member mixing model (e.g. IsoSource, MixSIAR) (Phillips & Gregg 2003; Hu *et al.* 2015; Rothfuss & Javaux 2016; Sprenger *et al.* 2016; Wang *et al.* 2017), including a wide range of environmental conditions differing in climate, soil type and vegetation type (Dawson 1996; Meinzer *et al.* 1999; McCole & Stern 2007; Manzoni *et al.* 2014; Rothfuss & Javaux 2016). For example, an investigation of the seasonal variations in the water uptake patterns of three representative plant species in a semi-arid area revealed that the plant water was mainly derived from 0–120-cm soils (Wang *et al.* 2017). In contrast, under humid climate conditions, trees in a central Pennsylvania catchment were found to mostly obtain water from a ~60-cm soil depth

during dry portions of the growing season throughout the catchment and to generally lack the deep root function necessary for hydraulic redistribution (Gaines *et al.* 2016; Hasenmueller *et al.* 2017). Most studies using stable isotopes in exploring tree water uptake have been conducted in seasonally dry or arid environments (Dawson & Ehleringer 1991; Dawson & Pate 1996; Gaines *et al.* 2016; Wang *et al.* 2017). However, few studies have combined the situation of shallow soil and humid climate conditions and investigated the changing patterns of tree water uptake over short timescales, which is vital for the improvement of hydrologic and land-surface models considering the soil–rock profile.

Small-timescale experiments help to gain insight into the tree water isotope shift and tree water use strategy in response to source water change. The main objectives of this study were to: (1) identify the changing patterns of stem water isotopic compositions; and (2) identify the variations in the proportions of water uptake over a short timescale in shallow soils underlain by fractured rocks in eastern China. This study also provides evidence on whether the water stable isotopic composition can be used to reveal the variations in plant water sources on such a short timescale.

MATERIALS AND METHODS

Site description

The experimental sites are situated in a typical peri-urban catchment (~29 km²) in Ningbo city, eastern China (29°48'N, 121°19'E) (Figure 1). The soil types are mainly red, yellow and paddy soil (entisols). The soil in the catchment is shallow (~30 cm on average) and is dominated by a silt loam in the 0–20-cm soil profile and a sandy loam in the 20–30-cm soil profile. Beneath the shallow soil (>30 cm) are frequently fractured rocks with developed fissures. This bedrock profile (unsaturated zone) can reach depths of >19 m according to the borehole records. A typical soil–rock profile is shown in Figure 1. The parental materials of the bedrock are mainly silicate and aluminosilicate rocks and carbonate and aluminosilicate clastic rocks. The region has a moderate subtropical monsoon climate that is warm and humid during April to September

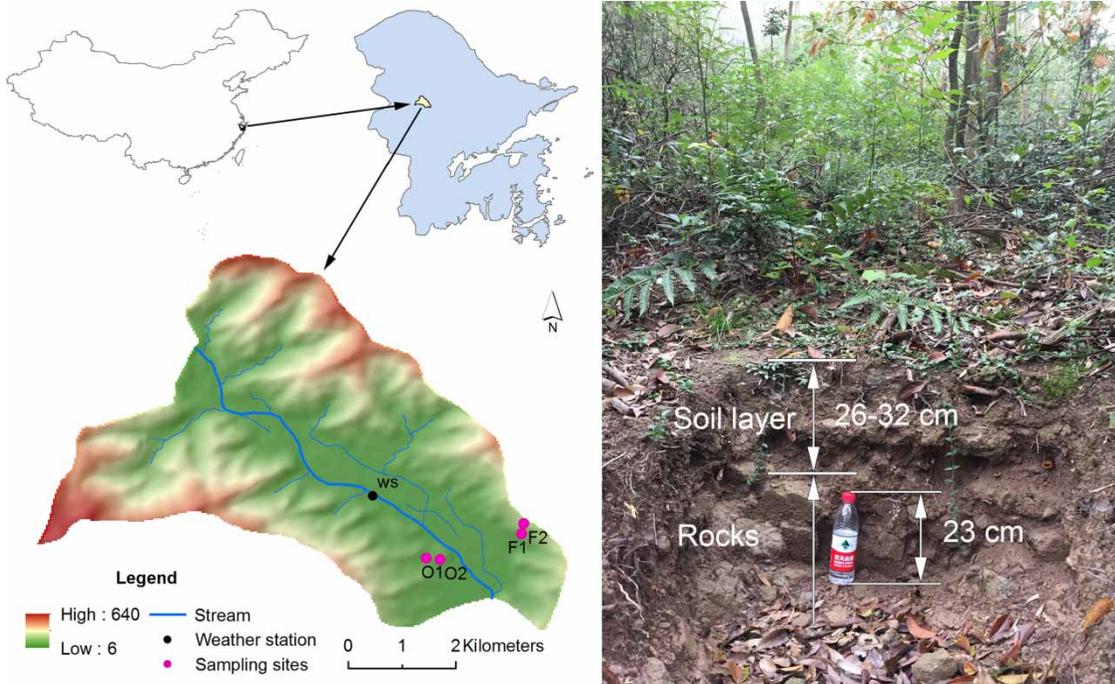


Figure 1 | Location of the study area and experimental sites and a typical soil–rock profile. Four experimental sites include two orchards (O1, peach; O2, tea) and two forest lands (F1, camphor1; F2, camphor2).

(Zhu et al. 2017; Li et al. 2018; Xiang et al. 2018). The region has an annual mean temperature of 17.4 °C and a mean annual precipitation of 1,463 mm. The evapotranspiration is approximately 730 mm and 45% of that in summer (Jun–Aug). Four representative sites were selected covering two type of land uses (forests and orchards), namely, forest1 and forest2 (*Cinnamomum bodinieri* Levl.) and orchard1 (peach, *Amygdalus persica* L.) and orchard2 (tea, *Camellia sinensis*).

Sample collection and preparation in the field

Water for the δD and $\delta^{18}\text{O}$ analysis was collected from rainfall, a nearby spring (~2.6 km away), soils, and tree branches. Rainwater samples were collected during rainfall by using a glass funnel (diameter: 10 cm) connected to a polyethylene bottle (0.6 L). A table tennis ball was placed in the funnel to reduce evaporation (Zhao et al. 2016b). Seepage spring water was collected five times, corresponding to the soil and plant sampling campaigns (total of six spring samples because two samples were collected at the first sampling campaign). In the study area, trees are likely to

rely on deep roots and extract shallow groundwater. Spring water is the easily accessible source for shallow groundwater (Nie et al. 2012). Thus, the isotopic composition of spring water could be used to represent that of shallow groundwater potentially obtained by trees.

Soil samples used for the δD and $\delta^{18}\text{O}$ analysis were collected five times between two typical rainfall events (amount: 6.7 and 8 mm, maximal precipitation rate: 3.2 and 3.8 mm h⁻¹, duration: 3 and 3.5 h, respectively), from 1st November to 8th November 2016. The former four samplings were conducted at 2-day intervals, and the last (fifth) sampling was conducted on the day after the fourth sampling (Figure 2). The soil samples were collected in three replicates using a hand soil auger from three soil layers (0–10, 10–20 and 20–30 cm) for forest2, orchard1 and orchard2, and two soil layers (0–10 and 10–20 cm) for forest1 where the soil depth was only approximately 22 cm. Because of the difficulty of sample collection from the fissures, only two fissure samples were collected for each site. Thus, the isotopic compositions of fissure sources were assumed to be stable.

Tree samples were collected simultaneously with soil sampling campaigns. For each sampling campaign, three

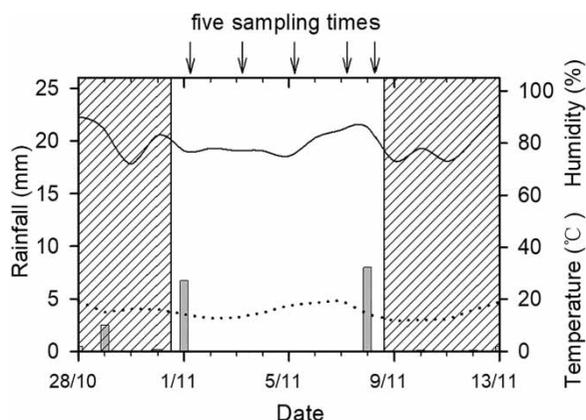


Figure 2 | Daily rainfall (bar), mean daily air temperature (dot line), and mean daily humidity (solid line) before, during, and after (shaded) the experimental period.

replicates of tree samples were taken (one for each tree) from the suberized xylem (main branches) and at least 1 cm away from any nodes of leaves, and the bark was removed (Ehleringer & Dawson 1992; Nie *et al.* 2011). The tree samples were collected from the same main branches of the investigated trees in all of the campaigns to ensure the same route of water uptake. We assume that branch water represents stem water (Tang & Feng 2001; Brooks *et al.* 2010). All collected samples were placed in 50-mL centrifuge tubes and sealed with parafilm, and placed in an ice-box for transportation.

Sample preparation in the laboratory

In the laboratory, solid samples were stored at -20°C and water samples were stored at 4°C . Water was extracted from the plant and soil samples using a cryogenic vacuum distillation system (LI-2100, LICA, Beijing, China), an automatic machine with standard parameter settings (Wang *et al.* 2017). The extraction process required 2.0–3.5 h, depending on the sample materials and the water content of the samples. Rain and extracted water were filtered using $0.22\text{-}\mu\text{m}$ organic-phase pin-type filters to eliminate impurities and organic contamination (Wang *et al.* 2017).

The δD and $\delta^{18}\text{O}$ in the stem water were measured using a Thermo Scientific MAT 253 isotope ratio mass spectrometer with a Flash 2000 HT elemental analyzer (precision of $\pm 1.0\text{‰}$ for δD ; $\pm 0.2\text{‰}$ for $\delta^{18}\text{O}$). Water samples from rainfall, spring, soil, and fissures were

analyzed with a Los Gatos Research 912-0008 laser isotope analyzer following the standard measurement protocol (precision of $\pm 0.4\text{‰}$ for δD ; $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$). All δD and $\delta^{18}\text{O}$ values (δ notation, ‰) are expressed relative to Vienna Standard Mean Ocean Water (Brooks *et al.* 2010; Tetzlaff *et al.* 2014).

All of the soil samples for the δD and $\delta^{18}\text{O}$ analysis were weighed before and after the water extraction. After cryogenic extraction, the samples were oven-dried at 110°C for more than 48 h to obtain the soil water content, check the efficiency of the water extraction (no change in the weight of the extracted sample denoted 100% efficiency of water extraction). The water extraction for the soil samples was re-conducted if the water extraction efficiency was less than 98.0% (West *et al.* 2006).

Mixing model calculations

Deep groundwater was not used as a potential water resource because in this area it is buried deep ($>19\text{ m}$). Thus, soil water, fissure water, and shallow groundwater were regarded as the three water sources for tree water uptake. A three end-member mixing model was used to estimate the contributions of soil water, fissure water, and shallow groundwater to the plant water:

$$C_s X_s + C_f X_f + C_g X_g = X_p \quad (1)$$

$$C_s + C_f + C_g = 1 \quad (2)$$

where X_p is the isotopic composition in the plants (δD or $\delta^{18}\text{O}$); X_s , X_f , and X_g are the isotopic compositions (δD or $\delta^{18}\text{O}$) in the soil water, fissure water and shallow groundwater; and C_s , C_f and C_g are the contributions of the soil water, fissure water and shallow groundwater to tree water uptake, respectively. The calculation was performed by the IsoSource model (Phillips & Gregg 2003).

Soil properties

Soil bulk density was measured in triplicate using steel rings (diameter: 5 cm; height: 5 cm) by the oven-drying method (Mandal *et al.* 2008; Sun *et al.* 2016b). Antecedent soil moisture content was determined using the oven-drying method

(Sun *et al.* 2016a). The soil particle size distribution of each soil sample was determined using a Mastersizer 2000 (Malvern Instruments, Malvern, UK), following the USDA soil taxonomy classification system (Sun *et al.* 2013, 2016a). The capillary porosity and total porosity of the soil samples were determined using the water saturation method (Chen *et al.* 2004; Liu *et al.* 2011). Basic information on these sites is presented in Table 1. The meteorological parameters were determined using a weather station near the experimental sites. The variations in rainfall and humidity for the study period are shown in Figure 2.

Statistical analysis

The Kolmogorov–Smirnov (K–S) test was performed to determine the normality of the raw data (Sun *et al.* 2016b). Differences in the hydrogen isotopic ratios of the stem water between different sites were detected using the non-parametric Kruskal–Wallis tests. A paired *t*-test was used to detect the difference in the changing patterns and proportions of tree water uptake among the different tree species. Statistical results were considered significant at $p < 0.05$. The statistical analyses were carried out in IBM SPSS Statistics 23.0.

RESULTS

Variations in stem water isotopic compositions

The isotopic compositions of the stem water were significantly lower compared to the soil water (Table 2). For the

four sites, the values of the averaged-mean soil water δD were -39.3 , -42.4 and -43.2 ‰ and those of $\delta^{18}O$ were -5.6 , -6.0 and -6.2 ‰, for 0–10, 10–20, and 20–30 cm soil layers, respectively. The value of the averaged-mean stem water δD was -54.1 ‰ and that of $\delta^{18}O$ was -7.8 ‰ for the four sites. For an overall comparison between the four sites, the stem water δD during the study period ranged from -45.2 to -60.1 ‰ for orchard1 (peach), -42.4 to -62.0 ‰ for orchard2 (tea), -49.2 to -67.9 ‰ for forest1 (camphor) and -44.6 to -72.2 ‰ for forest2 (camphor); the stem water $\delta^{18}O$ ranged from -7.0 to -8.1 ‰ for orchard1, -7.7 to -9.5 ‰ for orchard2, -8.2 to -10.1 ‰ for forest1 and -8.1 to -10.3 ‰ for forest2. The mean values of isotopic compositions of the spring water (δD : -43.03 , $\delta^{18}O$: -6.24) were similar to the rainwater (δD : -42.49 , $\delta^{18}O$: -7.05).

Distinct variations (variable ranges) were found in stem water isotopic compositions, particularly for the trees in orchard1 and forest1 (Figure 3). The boxes gradually enlarged the amplitude of variation, particularly in the bottom half, in the following order: orchard1, orchard2, forest1, and forest2. The stem water isotopic compositions of orchard1 had the lowest variable range. Trees in forest2 had the largest range of hydrogen isotopic ratios. Compared with the upper boundaries of the boxes, the lower boundaries of the boxes exhibited relative great variations.

Changing patterns of stem water isotopic composition

The obvious differences in the changing patterns of stem water δD and $\delta^{18}O$ between the orchard and forest sites

Table 1 | Study site characteristics

Site (tree)	Age (year)	Altitude (m)	Slope		Dominant soil texture for 0–30 cm	Soil porosity		Antecedent gravimetric moisture content (%)	Soil bulk density ($g\ cm^{-3}$)
			Aspect	(°)		Total (%)	Capillary (%)		
Orchard1 (Peach)	~10	44	SE	2.8	Silt loam	44.51 ± 1.76	10.89 ± 1.06	20.76 ± 0.91	1.17 ± 0.03
Orchard2 (Tea)	~20	41	S	5	Sandy loam	37.99 ± 5.30	5.71 ± 1.75	20.79 ± 4.86	1.27 ± 0.09
Forest1 (Camphor)	~18	124	S	14.9	Sandy loam	44.15 ± 5.77	15.43 ± 6.32	19.30 ± 2.28	1.16 ± 0.10
Forest2 (Camphor)	~20	183	S	9.7	Sandy loam	68.44 ± 5.41	18.56 ± 3.91	21.52 ± 0.63	0.87 ± 0.02

Dominant soil texture is regarding to the most frequency texture for three soil layers (0–10, 10–20, and 20–30 cm). Basic soil properties are the mean value of triplicates and shown as mean \pm St. Dev.

Table 2 | Summary statistics of hydrogen and oxygen isotopic ratios for the study period

Water extraction	Number	Mean		Min		Max		St. Dev.			
		δD (‰)	$\delta^{18}O$ (‰)								
Rainwater ^a	16	-43.03	-6.24	-59.23	-8.74	-10.36	-2.65	15.42	1.80		
Rainwater (during study period)	8	-36.94	-5.17	-38.20	-5.22	-36.01	-4.82	0.82	0.21		
Spring	6	-42.49	-7.05	-43.08	-7.22	-41.97	-6.86	0.37	0.12		
Plant	Orchard1	15	-51.92	-7.03	-60.07	-8.11	-45.16	-6.39	4.27	0.56	
	Orchard2	15	-51.09	-7.73	-62.00	-9.51	-42.42	-6.13	5.40	0.87	
	Forest1	15	-57.10	-8.18	-67.90	-10.06	-49.24	-6.82	6.47	1.24	
	Forest2	15	-56.30	-8.14	-72.23	-10.33	-44.63	-6.27	8.68	1.39	
Soil	Orchard1	0–10 cm	15	-36.35	-5.02	-52.90	-7.07	-29.56	-4.04	7.05	0.92
		10–20 cm	15	-41.65	-5.77	-49.08	-7.06	-37.08	-4.81	3.72	0.60
		20–30 cm	15	-45.12	-6.24	-54.51	-8.22	-35.02	-4.73	4.69	0.89
	Orchard2	0–10 cm	15	-39.36	-5.21	-50.18	-6.83	-34.54	-4.35	4.02	0.68
		10–20 cm	15	-41.94	-5.80	-59.26	-8.27	-35.05	-4.82	5.94	0.88
		20–30 cm	15	-44.99	-6.19	-53.12	-6.98	-37.28	-4.70	3.63	0.60
	Forest1	0–10 cm	15	-44.12	-6.50	-55.09	-8.11	-29.70	-4.48	6.80	0.98
		10–20 cm	15	-46.64	-6.88	-60.62	-8.81	-39.99	-5.96	6.71	0.99
	Forest2	0–10 cm	15	-37.35	-5.68	-55.64	-8.38	-31.11	-4.64	5.75	0.84
		10–20 cm	15	-39.30	-5.73	-47.82	-7.15	-31.29	-4.47	4.52	0.63
		20–30 cm	15	-47.09	-6.73	-59.64	-8.42	-38.99	-5.50	5.21	0.83
	Fissures	Orchard1	30–65 cm	2	-62.51	-8.95	-64.34	-9.03	-60.67	-8.88	\
Orchard2		30–60 cm	2	-63.17	-9.09	-65.86	-9.72	-60.47	-8.46	\	\
Forest1		25–60 cm	2	-69.52	-9.79	-71.19	-9.97	-67.84	-9.60	\	\
Forest2		30–75 cm	2	-73.61	-10.58	-75.00	-10.84	-72.23	-10.33	\	\

^aThe rainwater is based on the sixteen precipitation data in 2016.

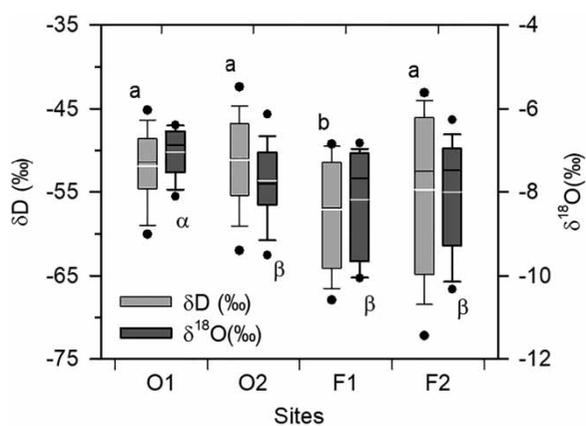


Figure 3 | Variation in δD and $\delta^{18}O$ of stem water for orchard1 (peach, O1), orchard2 (tea, O2), forest1 and forest 2 (camphor, F1 and F2) with each box gathered data of five sampling campaigns. Different letters (a,b; α , β) denote the significant differences between sites at $p < 0.05$. The bottom/top of the box denote 25th/75th percentiles. Whiskers denote 5th/95th percentiles. Black points denote outliers. The white lines denote the mean values, and the black lines denote the medians.

are shown in Figure 4. The changing trends of stem water δD and $\delta^{18}O$ in the orchards showed a pattern of first an increase and then a decrease, while the forest lands

showed first a decrease and then an increase. A comparison of land uses (or plant species) revealed that the stem water isotopes in the orchards and the forest lands had significant differences (δD , $p = 0.011$; $\delta^{18}O$, $p = 0.013$). Before the second rainfall, a significant decreasing trend of the stem water isotopic composition for the forest lands was found. The mean stem water δD and $\delta^{18}O$ on 7th November decreased by 14.5 and 2.0‰, respectively, compared with the mean values on 1st November. However, the stem water δD and $\delta^{18}O$ in the orchards significantly increased after the first rainfall, and the mean stem water δD and $\delta^{18}O$ increased by 7.4 and 1.0‰, respectively, compared with the mean values on 1st November. The isotopic composition of stem water sampled immediately after the rainfall was significantly different from those of the other sampling campaigns (Figure 4). These findings suggested the evident response of stem water δD and $\delta^{18}O$ to rainfall. The stem water δD and $\delta^{18}O$ for the forest lands showed higher error bars than for the orchards. The highest error bar was

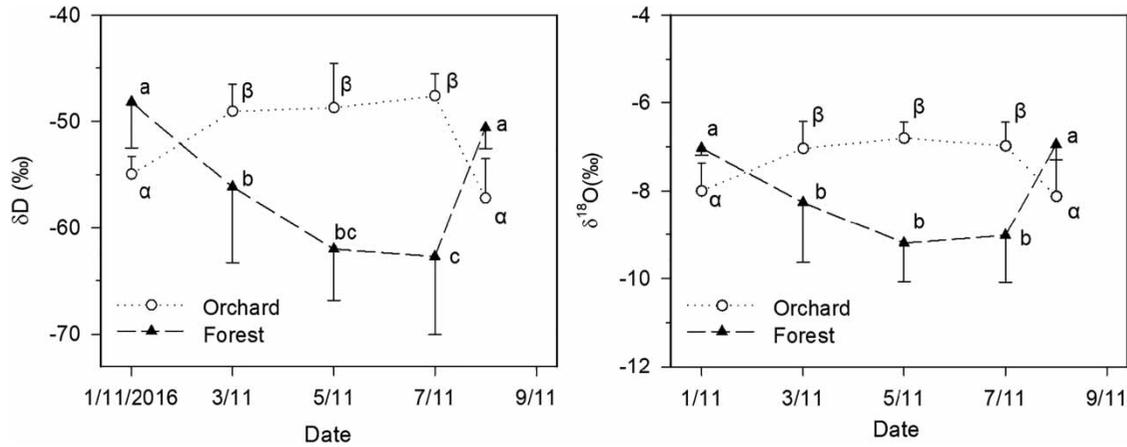


Figure 4 | Changing patterns of stem water isotopic compositions of two land uses. Different letters (a,b; α,β) behind the legend names and points denote the significant differences at $p < 0.05$. For ease of reading, only single error bar for each point is shown.

presented for the second sampling campaign. On average, the error bars for the forest lands were larger than those for the orchards.

The time series of isotopic compositions of rainwater, soil water, fissure water, and spring water (groundwater) is shown in Figure 5. Generally, the temporal variation in isotopic compositions of groundwater in Figure 5 was in a narrow range. Compared with groundwater, the soil water exhibited remarkable changing patterns. The changing patterns of soil water and stem water were similar somehow. However, further correlation analysis showed that there were only three significant correlations: tree δD and fissure δD in forest ($R = 0.653$, $p = 0.041$); tree $\delta^{18}O$ and groundwater $\delta^{18}O$ in orchard ($R = -0.647$, $p = 0.043$);

and tree $\delta^{18}O$ and groundwater $\delta^{18}O$ in forest ($R = 0.639$, $p = 0.047$). Basically, tree $\delta^{18}O$ has significant relationships with groundwater $\delta^{18}O$, and the relationships differ in land uses, positive in forest and negative in orchard. However, the correlation had limited interpretation of the stem water changing patterns.

The distinct isotopic signatures of source waters (soil water, fissure water, and groundwater) allowed separation of the specific source component from the other components that contributed to the plant water uptake. According to the overlapping area between stem water isotopic composition in Figure 4 and source water isotopic composition in Figure 5, the stem water in forest sites may derive mainly from fissure water while the

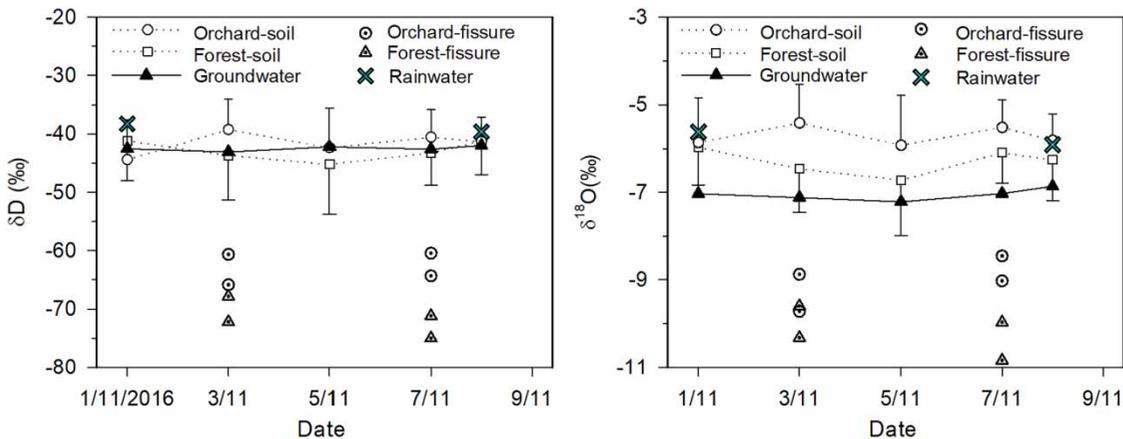


Figure 5 | Time series of isotopic compositions of rainwater, soil water, fissure water, and spring water (groundwater). Only soil water has error bars. The error bar of rainwater is quite small and thus is removed.

stem water in orchard sites may derive primarily from soil water.

Relationships between δD and $\delta^{18}O$

The isotopic values of stem water were located between the isotopic ratios of soil water and fissure water, and were similar to the isotopic ratios of spring water (Figure 6, Table 2). No obvious deviation from the local meteoric water line suggested a limited isotopic fractionation of soil water due to the relatively high air humidity.

The distribution of the isotopic compositions of trees in the orchards was close to that of the soil water, particularly for 7th November, indicating that trees in the orchards primarily obtained water from the soil profile on that day. In contrast, the distribution of the isotopic compositions of trees in the forests was close to that of the fissure water. The results showed the possible different changing patterns of tree water uptake.

Variations in the proportion of tree water uptake

The water uptake (five sampling time-averaged) fraction of the forests was $34.5 \pm 19.9\%$ for the soil layer, $46.3 \pm 22.7\%$ for the fissures and $19.2 \pm 13.3\%$ for the shallow groundwater, while that for the orchards was $33.3 \pm 15.3\%$ for the soil layer, $46.0 \pm 18.6\%$ for the fissures and $20.7 \pm 13.6\%$ for the shallow groundwater during the sampling period (Figure 7). On average, the water uptake fraction of all the trees was $33.9 \pm 17.7\%$ for the soil layer, $46.1 \pm 20.8\%$ for the fissures and $20.0 \pm 13.5\%$ for the shallow groundwater.

On days with a rain event (first and fifth sampling campaigns), the water of the forest trees was derived mainly from the soil layer (44.7%) compared to the fissure (37.1%) and shallow groundwater (18.2%), while the water of the orchards was derived mainly from the fissures (66.3%) compared to the soil layer (19.1%) and shallow groundwater (14.6%). On days without a rain event (second, third and fourth sampling campaigns), the water of the forest trees was derived mainly from the fissures (52.4%) compared to the soil layer (27.7%) and shallow groundwater (19.9%), while the water of the orchards was

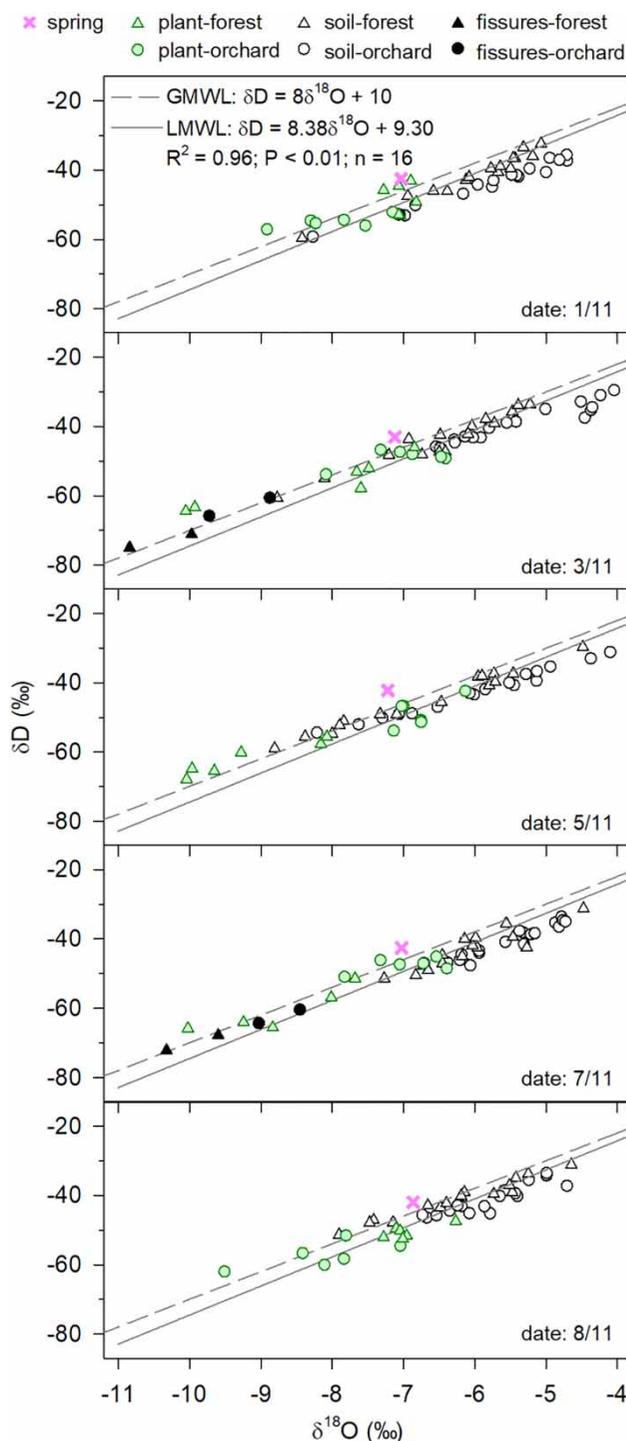


Figure 6 | Relationship between δD and $\delta^{18}O$ in soil water, fissure water, spring water (shallow groundwater) and tree water. GMWL is the global meteoric water line. LMWL is the local meteoric water line. GMWL and LMWL are plotted in each panel for reference.

derived mainly from the soil layer (42.8%) compared to the fissure (32.4%) and shallow groundwater (24.8%).

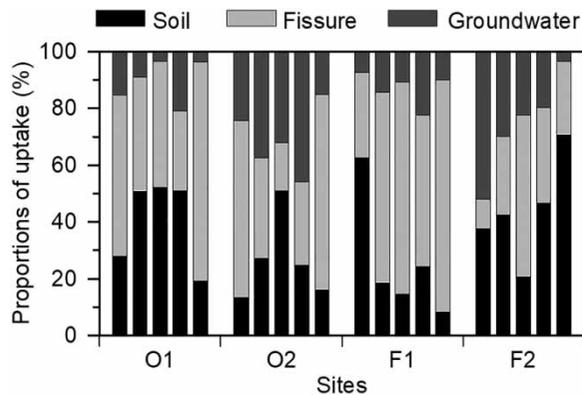


Figure 7 | Variations in proportion of water uptake from soil profile, rock fissures and shallow groundwater for the four sites during the study period based on mixing model (IsoSource).

DISCUSSION

Differences in changing patterns of stem water isotopes

Similar heights in the upper half of the boxes in Figure 3 indicate a similar upper boundary of the absorbed water or a similar upper boundary of soil depth for water sources (Williams & Ehleringer 2000; West *et al.* 2007). The camphor trees exhibited greater variability in stem water isotopic compositions than the tea and peach trees (Figure 3) which indicated that the forest trees had a wide scope of water uptake sources. Given the lower isotopic compositions in fissure water than that in soil water, the deeper locations in the lower boundary of the boxes in Figure 3 implied possible deeper sources of stem water. The large range of isotopic compositions of source water also implies that the camphor trees exhibited better potential or random drought adaptation than the trees in the orchards because they could uptake a wide range of source water and maintain normal activities.

The different patterns of stem water isotopic compositions also indicate different water use strategies in response to source water variations (Wang *et al.* 2017). It is reported that tree water isotope ratios shifted significantly after the intervening rain events (Schwinning 2008). Nie *et al.* (2012) found the water source shift for woody plants growing on dolomite outcrops and nearby soils during dry seasons in karst region on monthly timescales. Strong

seasonal shifts in the isotope ratios were also found in desert areas where water is a limiting factor for plant growth (Ehleringer *et al.* 1991). Ehleringer *et al.* (1991) also emphasized the significant effect of water depletion in autumn on the water source shift (changing from one main water source to another). The isotopic shift seems to be independent on timescale but depends on the water status, such as the water input in water deficit was expected to meet a significant shift in plant water isotopic compositions. This difference in main water source shift indicated the different water use strategy of trees in forests and orchards.

Sources of stem water

Generally, the fissure contributed most of the tree water uptake ($46.1 \pm 20.8\%$) compared to the soil and shallow groundwater. A possible reason is that the shallow soil had a limited capacity of water storage, even in the humid climate conditions with frequent rainfall, thus the trees usually obtained water from fissures under the random drought. Fissure water was stable and had low mobility and was the easily accessible source for tree roots (Brooks *et al.* 2010; Gaines *et al.* 2016; Hasenmueller *et al.* 2017). Similar to the areas with shallow soil under semi-arid climate conditions, trees under humid climate conditions used a considerable amount of water from the bedrock as well.

The large standard deviation suggests that the proportional contribution of soil water varied considerably over the sampling times. The difference in main water source on days with and without rain even implies that the orchards may rely on the water in the shallow soils when they suffered from potential or random drought. The camphor trees use soil water just after rainfall and then switch to the fissure water. Stem water isotope ratios shifted significantly after the intervening rain events (Schwinning 2008). Schwinning (2008) found that stem water isotope ratios also shifted after the summer-drought-ending rain event, and species effects were again non-significant. Nie *et al.* (2012) found the water source shift for woody plants growing on dolomite outcrops and nearby soils during dry seasons in the karst region on a monthly timescale. This study proved that the water source shift occurred on daily timescales and differed from plant species. Given the fact that there

is greater variability in the stem water isotopic compositions of camphor trees than the tea and peach trees, this indicates a large range of source water (e.g. deeper fissure water) and perhaps, good potential drought adaptability.

This study was conducted in a typical shallow-soil catchment in eastern China where beneath the soils are thick rocks with developed fissures. Similar to the areas with shallow soil under semi-arid climate conditions, trees under humid climate conditions used a considerable amount (more than 46% on average) of fissure water as well. This study emphasizes the importance of characterizing the changing patterns of stem water isotopic composition over short timescales, and also provides the evidence that the water stable isotopic composition can be used to reveal the variations in plant water sources on such a short timescale. Further studies conducted under different meteorological conditions and timescales are suggested to gain insight into the changing patterns of tree water uptake in shallow soil–rock profiles.

CONCLUSIONS

Trees in the forest lands had a larger variability in stem water isotopic composition than trees in the orchards, indicating a large range of source water. Significantly different changing patterns of stem water isotopic compositions were found between the orchards and the forest lands. On days with a rain event, the water of the forest trees was derived mainly from the soil layer (44.7%), while the water of the orchards was derived mainly from the fissures (66.3%). On days without a rain event, the water of the forest trees was derived mainly from the fissures (52.4%), while the water of the orchards was derived mainly from the soil layer (42.8%). On average, the fissure contributed most of the tree water uptake ($46.1 \pm 20.8\%$) compared to the soil and shallow groundwater. Main water sources for the trees in this study shifted at daily timescales in the soil–rock profile under humid climate conditions. Compared to orchards, forest trees had a relatively large range of source water (e.g. deeper fissure water) and a good water use strategy in the shallow soil–rock profile in consideration of random drought even under humid climate conditions. This study emphasizes the importance of

characterization of the changing patterns of stem water isotopic composition over short timescales.

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