https://doi.org/10.5194/hess-2021-289
Preprint. Discussion started: 6 July 2021

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Controls of seasonality and altitude on generation of leaf water isotopes

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https://doi.org/10.5194/hess-2021-289
Preprint. Discussion started: 6 July 2021

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Abstract

Stable oxygen and hydrogen isotopes ($\delta^{18}O$ and $\delta^{2}H$) of leaf water which bridges between hydrological processes and plant-derived organic materials vary spatially and temporally. It is critical to study what controls the $\delta^{18}O$ and $\delta^{2}H$ values of leaf water for a wide range of applications. Here, we repeatedly sampled soil water, stem water, and leaf water along an elevation transect across seasons on the Chinese Loess Plateau and analyzed the variations in the $\delta^{18}O$ and $\delta^{2}H$ values from precipitation, soil water, stem water, and leaf water. We found consistency in the $\delta^{18}O$ and $\delta^{2}H$ values in precipitation, soil water, stem water, and leaf water across seasons, indicating that leaf water can record the isotopic signals of precipitation well. Importantly, leaf water isotope lines were generated by the first-order control of source water (soil water and precipitation) associated with seasonality and altitude, as well as the secondary control of hydroclimate and biochemical factors resulting in weak correlations of the $\delta^{18}O$ and $\delta^{2}H$ values in leaf water. This study improves our understanding of the generation of leaf water isotopes.

Short Summary

Why do leaf water isotopes can generate to be an isotopic line in a dual-isotope plot? This isotopic water line is as important as the local meteoric water line (LMWL) in the isotope ecohydrology field. We analyzed the variations of oxygen and hydrogen isotopes in soil water, stem water, and leaf water along an elevation transect across seasons. We found that both seasonality and altitude affecting source water are likely

https://doi.org/10.5194/hess-2021-289
Preprint. Discussion started: 6 July 2021

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to result in the generation of an isotopic water line in leaf water.

Keywords: Leaf water, stable isotope, controls, seasonality, altitude

1 Introduction

The stable isotope compositions of water ($\delta^{18}O$ and $\delta^{2}H$) are increasingly used as powerful tracers to follow the movement of water from its input as precipitation, movement through the soil, and ultimately to its release as soil evaporation and leaf transpiration (Mook, 2001; Penna and Meerveld, 2019). Leaf water transpiration plays a key role in regulating the water balance at scales ranging from catchments to the globe. Terrestrial plants can enrich heavier isotopes (^{2}H and ^{18}O) in leaf water due to evapotranspiration (Helliker and Ehleinger, 2000; Liu et al., 2015; Cernusak et al., 2016), which is highly dependent on atmospheric conditions (e.g., temperature and relative humidity) and biophysiological processes (Farquhar et al., 2007; Kahmen et al., 2011; Cernusak et al., 2016). Subsequently, the isotope signals of leaf water are integrated into plant organic materials, such as cellulose (e.g., Barbour, 2007; Lehman et al., 2017) and leaf wax (Liu et al., 2016, 2021) as powerful proxies used for paleoclimate reconstruction (Pagani et al., 2006; Schefuβ et al., 2011; Hepp et al., 2020). Therefore, leaf water $\delta^{18}O$ and $\delta^{2}H$ values ($\delta^{18}O_{lw}$ and $\delta^{2}H_{lw}$) are the fundamental parameters required for an in-depth understanding of these plant organic biomarkers in paleoclimate contexts.

$\delta^{18}O_{lw}$ and $\delta^{2}H_{lw}$ values are influenced first by the plant's source water (mainly water taken up by roots from the soil; Munksgaard et al., 2016; Cernusak et al., 2016). Soil water for terrestrial plants generally originates from local precipitation, which serves as a critical component of the water cycle. Precipitation isotopes vary spatially and temporally, being subject to controls by the temperature, altitude, latitude, distance from the coast, and amount of precipitation (Bowen, 2010; Bowen and Good, 2015; Cernusak et al., 2016). Soil water isotopes are determined by a mixture of individual precipitation events with distinct isotope signals and are also affected by evaporation, both of which lead to isotopic gradients of soil water with depth (Allison et al., 1983; Liu et al., 2015). A number of studies have shown that the $\delta^{18}O$ and $\delta^{2}H$ values of root/xylem water can be used to characterize the water sources used by plants (Jia et al., 2013; Rothfuss and Javaux, 2017; Wu et al., 2018; Wang et al., 2019; Amin et al., 2020; Zhao et al., 2020; Liu et al., 2021a), and these studies rested on an assumption that no isotope fractionations of $\delta^{18}O$ and $\delta^{2}H$ values occurred during water uptake by plant roots (Dawson and Ehleringer, 1991; Ehleringer and Dawson, 1992; Chen et al., 2020), except in saline or xeric environments (Lin and Sternberg, 1993; Ellsworth and Williams, 2007). Some recent studies showed, however, that the occurrence of isotopic fractionation during root water uptake was likely more common, especially regarding the $\delta^{2}H$ values (Zhao et al., 2016; Wang et al., 2017; Barbeta et al., 2019; Poca et al., 2019; Liu et al., 2021a). Therefore, studying the isotopic variations in the water continuum from precipitation, soil water, stem water, to leaf water will help provide substantial insight into understanding the spatiotemporal variations in leaf water

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isotopes.

In addition to being influenced by plant source water, $\delta^{18}O_{lw}$ and $\delta^{2}H_{lw}$ values are influenced by the evaporative process of transpiration and the isotopic composition of the vapour in the atmosphere surrounding the leaf, the influences of which can be predicted using the Craig-Gordon model (Craig and Gordon, 1965), which has been modified for leaves under steady-state conditions (Dongmann et al., 1974; Farquhar et al.,1989; Farquhar and Cernusak, 2005):

$$\Delta_e = \varepsilon^+ + \varepsilon_k + (\Delta_v - \varepsilon_k)\frac{e_a}{e_i}$$

where Δ_e is the enrichment of evaporative site water above source water, ε^+ is the equilibrium fractionation between liquid water and vapour, ε_k is the kinetic fractionation during the diffusion of vapour through the stomata and the boundary layer, Δ_v is the isotopic enrichment of vapour compared to source water, and $(\frac{e_a}{e_i})$ is the ratio of the water vapour pressure fraction in the air relative to that in the intercellular spaces, which is equal to the relative humidity in the air. However, the model fails to explain the intra-leaf heterogeneity of $\delta^{18}O_{lw}$ and $\delta^{2}H_{lw}$ (Cernusak et al., 2016; Liu et al., 2021b), which is currently explained by a two-pool model (Leaney et al., 1985; Song et al., 2015a) and/or an advection-diffusion model, as the *Péclet* effect (Farquhar and Lloyd, 1993; Farquhar and Gan, 2003). Subsequently, more complicated models under non-steady-state conditions have been developed (Cuntz et al., 2007; Ogée et al., 2007). These models emphasize on a mechanistic understanding of leaf water isotopic fractionation, but under natural conditions, the relevant parameters cannot be strictly

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constrained or precisely monitored which hinders the uses of these models (Plavcová et al., 2018). Thus, the relationships between $\delta^{18}O_{lw}$ and/or $\delta^{2}H_{lw}$ and geo-climate factors critically need to be resolved.

In this study, we measured the $\delta^{18}O_{lw}$ and $\delta^{2}H_{lw}$ values of precipitation, soil water, stem water, and leaf water along an elevation transect across different seasons (i.e., spring, summer, autumn). The objectives of our study were to better understand the seasonal patterns of the leaf water $\delta^{18}O_{lw}$ and $\delta^{2}H_{lw}$ values, and the controls of altitude and seasonality on the $\delta^{18}O_{lw}$ and $\delta^{2}H_{lw}$ values of leaf water generation. The results can help to qualitatively and quantitatively evaluate the leaf water-based transpiration flux in ecohydrological processes and the accuracy of plant organic biomarkers in natural archives since they provide an insight into potential controls on leaf water isotopic generation.

2 Materials and Methods

2.1 Study area

The Qinling Mountains form the dividing line between northern and southern China and mark the boundary between the watersheds of the Yellow River and Yangtze River valleys. Mt. Taibai (Fig. 1; 33. 96◦ N, 107.77◦ E; 3767 m asl) is the peak of the Qinling Mountains, with a warm temperate ecosystem characterized by a rich and colourful flora and fauna. The mean annual temperature at the bottom of Mt. Taibai is 12.9°C, and the mean annual precipitation is 609.5 mm (Zhang and Liu, 2010). The climate,

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soil, and vegetation vary significantly along the slope transect, exhibiting vertical geo-ecological zonation (Fig. 1), which includes a variety of climate zones: warm temperate (< 1300 m), temperate (1300 ~ 2600 m), cool temperate (2600 ~ 3350 m), and alpine (> 3350 m). The soil background covers yellow loess soil at low elevations, spectacular rocky outcrops at middle elevations, and glacial remnants at high elevations; and the vegetation consists mainly of coniferous and broadleaf forests, and alpine and subalpine vegetation along the transect.

2.2 Sampling strategy

Plant and soil samples were performed in May, July and September 2020, and the samples were collected from ten plots (3 × 3 m) along the northern slope of Mt. Taibai extending from 608 m to 3533 m asl (Fig. 1). One or two plant species were simultaneously collected; plant species were chose if they had a high abundance in the community and/or were widely distributed for each plot. For plants, three stem and leaf samples were collected for each species. Intact leaves with minimal damage were collected from fully sunlit canopy branches considering the likely isotopic gradients within a leaf (Liu et al., 2016). Suberized twigs were cut into 3-4 cm segments as a sample, and these small plant segments were immediately placed into capped glass vials. For soils, three surface soil samples (less than 10 cm) around the sampling plants were taken using a small metal scoop. All sampled plots were located on slopes far away from rivers and surface water bodies, which guaranteed that the soil water in each plot was derived exclusively from precipitation. Although the surface soil layers were only collected in this study, these samples provided a comparative reference for soil water

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that originated from surface water instead of deep water, which is supported by a prior study conducted at the same elevation transect (Zhang and Liu, 2010). The soil samples were tightly sealed in a polyethylene zipper bag on site. All plant and soil samples were frozen in a cooler (~ 4 °C) in the field and immediately transported to the laboratory. The altitude of each plot was determined using a handheld GPS unit with an error of ± 5 m.

2.3 Isotopic analyses

Water in plant and soil samples was extracted using an automatic cryogenic vacuum extraction system (LI-2100 Pro, LICA United Technology Limited, Beijing, China). The auto-extraction process was set for 3 hours, and the extraction rate of water from samples was more than 98%. The isotopic composition of soil water was measured using a Picarro L2130-I isotope water analyzer (Sunnyvale, CA, USA) at the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Science. The analytical accuracies were ± 0.1‰ for $\delta^{18}O$ and ± 1‰ for δ^2H. The isotopic measurements of root and leaf waters were conducted using an isotope ratio mass spectrometer coupled with a high-temperature conversion elemental analyzer (HT2000 EA-IRMS, Delta V Advantage; Thermo Fisher Scientific, Inc. USA) in Huake Precision Stable Isotope Laboratory at the campus of Tsinghua University Shenzhen International Graduation School. The measurement precisions were ± 0.2‰ and ± 1‰ for $\delta^{18}O$ and δ^2H, respectively. The isotopic composition of $\delta^{18}O$ and δ^2H is expressed as an isotope ratio:

$$\delta_{sample}(‰) = (\frac{R_{sample} - R_{standard}}{R_{standard}}) \times 1000 \qquad (1)$$

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where δ_{sample} represents $\delta^{18}O$ or $\delta^{2}H$, and R_{sample} and $R_{standard}$ indicate the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ of the sample and standard, respectively. The $\delta^{18}O$ and $\delta^{2}H$ values are reported relative to the Vienna mean standard ocean water (VSMOW). The $\delta^{18}O$ and $\delta^{2}H$ values of precipitation were determined by the Online Isotope in Precipitation Calculator (Bowen and Revenaugh, 2003).

2.4 Data analysis

Statistical analyses (e.g., mean, max., min., and s.d.) for isotopes of precipitation, soil, stem and leaf waters were performed to show the range and distribution of $\delta^{18}O$ and $\delta^{2}H$. Pearson correlation was conducted to describe the various correlations between $\delta^{18}O$ and $\delta^{2}H$ among the different water types (e.g., precipitation, soil water, stem water, and leaf water) because the isotopic data were normally distributed according to the Kolmogorov-Smirnov (K-S) test. One-way ANOVA combined with a post hoc Tukey's least significant difference (LSD) test was performed to identify the significant differences in isotopic compositions of precipitation, soil, stem, and leaf waters across months. Comparisons of the relationships of $\delta^{18}O$ and $\delta^{2}H$ for soil water and leaf water were performed by using analysis of covariance (ANCOVA) to compare slopes across months. The significance level for all statistical tests was set to the 95% confidence interval. Moreover, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2003) was used to perform air mass back-trajectory calculations for a central site (34.13°N, 107.83°E, 2270 m asl) of the study area. Trajectories were initiated four times daily (at 00:00, 06:00, 12:00, and 18:00 UTC) and their air parcel was released at 2300 m asl for May, July and September 2020 and

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moved backward by winds for 120 h (5 days).

3 Results

3.1 Seasonal variations

The $\delta^{18}O$ and $\delta^{2}H$ values in precipitation, soil water, stem water, and leaf water varied significantly among them across months (Fig. 2). The $\delta^{18}O$ values of precipitation, soil water, stem water, and leaf water were -7.7 ± 2.0‰, -3.8 ± 3.4‰, 1.9 ± 4.2‰, and 4.7 ± 3.0‰ in May, -9.1 ± 1.4‰, -11.5 ± 1.3‰, 3.4 ± 2.6‰, and 1.4 ± 4.1‰ in July, and -9.5 ± 1.5‰, -11.6 ± 1.3‰, 7.5 ± 6.7‰, and 9.7 ± 5.6‰ in September, respectively. Likewise, the $\delta^{2}H$ values of precipitation, soil water, stem water, and leaf water were -50.7 ± 13.9‰, -47.1 ± 10.5‰, -31.6 ± 20.3‰, and -18.2 ± 14.5‰ in May, -63.0 ± 9.7‰, -92.1 ± 9.9‰, -69.9 ± 15.2‰, and -54.4 ± 12.8‰ in July, and -66.4 ± 10.6‰, -87.7 ± 11.9‰, -84.5 ± 25.2‰, and -97.0 ± 28.0‰ in September, respectively. Both the $\delta^{18}O$ and $\delta^{2}H$ values for all four water types (i.e., precipitation, soil water, stem water, and leaf water) were significantly different ($p < 0.05$), exhibiting relatively heavier values in May, intermediate values in July, and lower values in September, except for the $\delta^{18}O$ values in soil water (Fig. 2).

3.2 Correlations of $\delta^{18}O$ and $\delta^{2}H$ values

Significant correlations of the $\delta^{18}O$ and $\delta^{2}H$ values in different water types were observed across months (Fig. 3). The local meteoric water lines (LMWLs) were obtained from the $\delta^{18}O$ and $\delta^{2}H$ values of precipitation, in which of the slopes and intercepts varied slightly across months (7.04, 6.79 and 6.85 for slopes and 3.26, -1.12

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and -1.42 for intercepts in May, July and September, respectively). Similarly, the regression lines of the $\delta^{18}O$ and δ^2H values from soil water, stem water, and leaf water were observed (Fig. 3), suggesting that leaf water isotopes could well inherit the isotopic signals of source waters that originated from stem water, soil water, and ultimately precipitation. However, the slopes and coefficients of determination (R^2) of the $\delta^{18}O$ and δ^2H values showed consistent decreasing trends from precipitation, soil water, stem water and leaf water in all three months, except for soil water in May (Fig. 3). The ANCOVA tests showed no significant differences for the regression lines for precipitation (df = 0.47, $F = 2.49$, $p = 0.11 > 0.05$), stem water (df = 53.2, $F = 0.42$, $p = 0.66 > 0.05$), and leaf water (df = 437.3, $F = 2.78$, $p = 0.08 > 0.05$) across months, but a significant difference for soil water across months (df = 308.8, $F = 10.9$, $p < 0.05$). The difference in soil water regression lines across months was probably due to the mixture of various precipitation events and evaporation in the upper soil layers (Yang and Fu, 2017).

3.3 Altitude effects

Both the $\delta^{18}O$ and δ^2H values in precipitation and soil water decreased significantly with an increase of altitude (Fig. 4; all for $R^2 > 0.37$, $p < 0.05$). Stem water and leaf water showed decreasing trends for δ^2H in July ($R^2 = 0.82$ and 0.43) and for $\delta^{18}O$ ($R^2 = 0.61$ and 0.44) and δ^2H values ($R^2 = 0.84$ and 0.90) in September; in contrast, there were nonsignificant correlations between isotopes in stem water and leaf water and altitude for $\delta^{18}O$ values in July and for both $\delta^{18}O$ and δ^2H values in September (Fig. 4).

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4 Discussion

4.1 Consistent variations among water types

We found a seasonal consistency in the $\delta^{18}O$ and $\delta^{2}H$ values from precipitation to soil water, stem water, and ultimately leaf water (Fig. 2). This finding of temporal consistency among water types (i.e., precipitation, soil water, stem water, leaf water) has been observed in a number of studies (Phillips and Ehleringer, 1995; Cernusak et al., 2005; Sprenger et al., 2016; Berry et al., 2017; Liu et al., 2021a). The isotopic inheritance from precipitation to leaf water indicated that seasonal variations in the precipitation $\delta^{18}O$ and $\delta^{2}H$ values could exert the first order of control on the temporal patterns of leaf water. The spatiotemporal variability of the precipitation $\delta^{18}O$ and $\delta^{2}H$ values could be explained by a combination of effects such as temperature, altitude, latitude, continent, and amount, which are associated with orographic conditions, sub-cloud evaporation, moisture recycling, and differences in the vapor source at the regional and continental scales (Dansgaard, 1964; McGuire and McDonnell, 2007; Li et al., 2016; Penna and Meerveld, 2019; Wu et al.,2019). Our recent study, conducted approximately 200 km away from the observed transect on the Chinese Loess Plateau, demonstrated that the temperature effect (i.e., altitude effect), but not the precipitation amount effect, was the dominant control on the precipitation $\delta^{18}O$ and $\delta^{2}H$ values (Liu et al., 2021a). The underlying mechanism of the temperature effect in monsoon regions is very complicated because three typical processes coexist: 1) the evaporation condition over the vapour source area affects the initial isotopic ratio of atmospheric moisture; 2) the transportation process of the water vapour affects the extent of rainout

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of the air mass during the course of transportation; and 3) the extent of condensation of the vapour is influenced by the condensation temperature (Pang et al., 2006; Li et al., 2019).

The $\delta^{18}O$ and δ^2H values from soil water, stem water and leaf water were isotopically heavier in May, intermediate in July, and lowest in September, responding well to the decreasing trends of precipitation $\delta^{18}O$ and δ^2H values (Fig. 2). The monthly variations in precipitation $\delta^{18}O$ and δ^2H values from the Global Network for Isotopes in Precipitation (GNIP, http://www.iaea.org/) at Xi'an station (1985-1992 AD), ca. 100 km away from our study transect, were ^{18}O- and ^2H-enriched in May relative to July and September (Fig. 5a, b). The cluster mean of moisture transport routes using HYSPLIT (Draxler and Rolph, 2003) and climatological 850 hPa wind vectors showed that the main moisture was from western China and central Asia in May, from the China-India Peninsula and the Bay of Bangle, and from the local moisture recycling and convection (Fig. 5c, d, e). The seasonal variation of precipitation $\delta^{18}O$ and δ^2H values is consistently related to the onset, advancement and retreat of the Asian summer monsoon and associated large-scale monsoon circulation change (e.g., Cheng et al., 2009; Zhang et al., 2020, 2021). As the summer monsoon starts in mid-May, the rainfall season starts in southern China, however, the study area is mainly controlled by the moisture from westerlies (Chiang et al., 2015) with relatively higher vapour/precipitation $\delta^{18}O$ and δ^2H values (Fig. 5c, a, b). In July, the summer monsoon reaches its strongest phase, the rainfall belt shifts to central and northern China, and the southerly wind brings plenty of moisture from the China-India Peninsula and the Bay of Bangle with lower vapour/precipitation $\delta^{18}O$ and δ^2H values (Fig. 5d, a, b). When the summer monsoon withdraws in September, the study area is mainly controlled by moisture from local moisture recycling and convection (Fig. 5e). Soil water stores June-August monsoon rainfall with lower $\delta^{18}O$ and δ^2H values, resulting in further lower precipitation $\delta^{18}O$ and δ^2H values in September than those in July (Fig. 5a, b), and thus resulting in significantly lower $\delta^{18}O_{lw}$ and δ^2H_{lw} values (Fig. 6).

4.2 Generation of leaf water isotope line

The LMWL, generated by the precipitation $\delta^{18}O$ and δ^2H values at the observed locations (Fig. 2), is an important reference line for ecohydrological process and acts as a benchmark for comparison among different water types. The LMWLs in May (spring), July (summer) and September (autumn) were slightly smaller than the global meteoric water line (GMWL: $\delta^2H = 8.17 \times \delta^{18}O + 10.35$; Rozanski et al., 2013), suggesting different water vapour sources in the local circulation system and strong evaporative fractionation under arid conditions. Across months, July precipitation tended to have an isotopically lower slope value (6.79) than that of both May (7.04) and September precipitation (6.85), but the difference across months was not significant ($p = 0.11 > 0.05$). The slopes of the LMWLs from different months indicated that the water vapour of precipitation across seasons came from the same source but suffered from different intensities of evaporation due to temperature (Wu et al., 2019; Li et al., 2019). Likewise, the regression lines of the $\delta^{18}O$ and δ^2H values in soil water, stem water, and leaf water were observed across months (Fig. 3). The slopes in other water types (i.e, soil water, stem water, and leaf water) were relatively lower than the LMWLs, in which the slopes for soil water and stem water were intermediates; however, they were lowest for leaf water across seasons, except for soil water in May (Fig. 3). These observations were supported by a variety of studies (Brooks et al., 2010; Evaristo et al., 2015; Sprenger et al., 2016, 2017; Wang et al., 2017; Benettin et al., 2018; Barbeta et al., 2019; Penna and Meerveld, 2019; Liu et al., 2021a) due to the occurrence of secondary evaporation in other water types. Moreover, the R^2 values of dual-isotope space ($\delta^{18}O$ and δ^2H) decrease significantly from precipitation, soil water, stem water and leaf water in all seasons (Fig. 3), suggesting that besides physically evaporative fractionation, other factors likely affect the $\delta^{18}O$ and δ^2H values in leaf water. Although the abovementioned Craig-Gordon model has been used to explain the variation in $\delta^{18}O$ and δ^2H values in leaf water, the factors that control the leaf water $\delta^{18}O$ and δ^2H values under non-steady-state conditions and the *Péclet* effect remain to be further studied (Song et al., 2015b; Cernusak et al., 2016; Barbour et al., 2017).

In a dual-isotope space in leaf water, a significantly distributed pattern across months was observed: isotopically depleted in September, intermediate in July, and enriched in May (Fig. 6). When focusing on each month, we found relatively higher isotopic values occurring at low elevations but lower isotopic values at high elevations despite no or weak correlations between altitude and $\delta^{18}O/\delta^2H$ values (Fig. 4). Combining these two effects (i.e., seasonality and altitude), the $\delta^{18}O$ and δ^2H values in leaf water yield a remarkable isotopic line in the dual-isotope plot (Fig. 3), which typically lies at the right

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of the LMWLs. This result is supported by a recent study that conducted consecutive measurements of $\delta^{18}O$ and $\delta^{2}H$ values in xylem/leaf water in Switzerland and indicated that leaf water provides great potential to determine source water of plants (Benettin et al., 2021). A schematic of effects of seasonality and altitude on leaf water $\delta^{18}O$ and $\delta^{2}H$ values is shown in Fig. 7, which involves many of hydroclimatic and biochemical factors that control the leaf water $\delta^{18}O$ and $\delta^{2}H$ values. Significant isotopic fractionation occurred mainly at two key locations across vertical soil profiles and leaf architectures from precipitation to leaf water, but both seasonality and altitude, in essence, affected the precipitation $\delta^{18}O$ and $\delta^{2}H$ values (Fig. 7). An isotopic gradient across the vertical soil profile appeared because of evaporation at the surface soil layers (Ehleringer et al., 1992; Goldsmith et al., 2012; Evaristo et al., 2015), which led to a linear enrichment trajectory in the soil water dual-isotope plot (Goldsmith et al., 2012; Jia et al., 2013; Rothfuss and Javaux, 2017; Wu et al., 2018; Wang et al., 2019; Amin et al., 2020; Zhao et al., 2020; Liu et al., 2021a). The soil water isotope line provides a water source for leaf water isotope line generation. However, biochemical factors also exert an effect on leaf water $\delta^{18}O$ and $\delta^{2}H$ values, as supported by different $\delta^{2}H$ enrichments in leaf water between dicots and monocots, associated with leaf veinal structures (Liu et al., 2021b). This result is consistent with the weaker correlations of $\delta^{18}O$ and $\delta^{2}H$ values in leaf water than in soil water (Fig. 3). Collectively, the leaf water isotope line is generated by the first-order control of spatiotemporal variation in the precipitation $\delta^{18}O$ and $\delta^{2}H$ values (associated with seasonality and altitude) and secondarily affected by biochemical factors within a leaf.

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4.3 Insights and implications

The ecohydrological cycle over continents primarily involves the input from precipitation and the output to the atmosphere through evapotranspiration. Among them, leaf water transpiration is a key component of water cycle in terrestrial ecosystems. Stable isotope technique of leaf water has been used to estimate transpiration through leaf surface, contributing up to 50 to 90% of ecosystem evapotranspiration (Jasechko et al., 2013; Schlesinger and Jasechko, 2014). Moreover, the $\delta^{18}O$ values of leaf water partly influences the oxygen isotope values of atmospheric CO_2 (Farquhar et al., 1993), which can be helpful to constrain global carbon cycle. All of these various applications rest on a firm understanding of the mechanisms that control leaf water $\delta^{18}O$ and $\delta^{2}H$ values (Cernusak et al., 2016).

However, there were great variabilities in leaf water $\delta^{18}O$ and $\delta^{2}H$ values over diurnal and seasonal cycle. For example, leaf water $\delta^{18}O$ and $\delta^{2}H$ values generally showed a maximum in the early afternoon and a minimum in the early morning (Cernusak et al., 2016). Our results showed a seasonal variation in leaf water $\delta^{18}O$ and $\delta^{2}H$ values, which followed the isotopic patterns in other waters such as stem water, soil water and precipitation. The seasonal variability in leaf water $\delta^{18}O$ and $\delta^{2}H$ values has also been observed in tropical monsoon condition (Hartsough et al., 2008). The diurnal and seasonal variations in leaf water $\delta^{18}O$ and $\delta^{2}H$ values indicate the leaf water isotopic line would vary with time. Moreover, as we all known, the LMWL varys significantly

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over space, with the slopes ranging between 5 and 6.5 in middle latitudes and between 2 and 5 in arid climates (Gibson et al., 2008; Sprenger et al., 2016). Collectively, the leaf water isotope line will vary temporally and spatially. Thus, it needs to be widely explored for the spatio-temporal variations of leaf water isotope line in the future studies.

5 Conclusion

Along the elevation transect, precipitation, soil water, stem water, and leaf water were repeatedly sampled to analyze for $\delta^{18}O$ and $\delta^{2}H$ values associated with season and altitude. There was a seasonal consistency of $\delta^{18}O$ and $\delta^{2}H$ values from precipitation, soil water, stem water, and ultimate leaf water, suggesting that leaf water recorded well the isotopic signals of precipitation, which was primarily affected by the water vapour source in our studied transect. Moreover, both $\delta^{18}O$ and $\delta^{2}H$ values of precipitation and soil water were significantly correlated with altitude, but no or weak correlations occurred between $\delta^{18}O$ and $\delta^{2}H$ values of stem/leaf water and altitude, which indicated that besides source water (i.e., precipitation, soil water), biochemical factors likely exerted a secondary control on leaf water $\delta^{18}O$ and $\delta^{2}H$ values. Therefore, leaf water isotopes were controlled by combined effects of source water and leaf water transpiration surrounding the leaf surface, in which seasonality and altitude acted as a trigger to form a leaf water isotopic line.

Data availability statement

https://doi.org/10.5194/hess-2021-289
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Data related to this article can be found in Electric Annex and Mendeley Data (https://data.mendeley.com/drafts/t44wybgpr3).

Author contribution

J.L. conceived the idea of research. J.L. and H.W. performed the data analysis and wrote the manuscript. H.W. and H.Z. edited the paper. C.J. and J.H. performed the lab work. All authors contributed to discuss the results.

Competing interests

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.

Acknowledgement

We would like to thank X. Cao and M. Xing for their help with laboratory assistance and Y. Cheng for helps in the field. We thank Prof. J. J. McDonnell for pre-discussing the framework of the paper. This work was supported by the Chinese Academy of Sciences (XAB2019B02; ZDBS-LY-DQC033) and National Natural Science Foundation of China (42073017), and by the open fund from State Key Laboratory of Loess and Quaternary Geology (SKLLQG1926).

References

https://doi.org/10.5194/hess-2021-289
Preprint. Discussion started: 6 July 2021

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Discussions

Amin, A., Zuecco, G., Geris, J., Schwendenmann, L., McDonnell, J.J., Borga, M., Penna, D., 2020. Depth distribution of soil water sourced by plants at the global scale: a new direct inference approach. Ecohydrology 13, e2177.

Allison, G., Barnes, C., and Hughes, M., 1983. The distribution of deuterium and ^{18}O in dry soils 2. Experimental, J. Hydrol. 64, 377–397.

Barbeta A, Jones SP, Clavé L, Gimeno TE, Fréjaville B, Wohl S, Ogée J, 2019. Unexplained hydrogen isotope offsets complicate the identification and quantification of tree water sources in a riparian forest. Hydrol Earth Syst Sci 23, 2129-2146.

Barbour, M.M., 2007. Stable oxygen isotope composition of plant tissue: a review. Funct. Plant Biol. 34, 83–94.

Barbour MM, Farquhar GD, Buckley TN, 2017. Leaf water stable isotopes and water transport outside the xylem. Plant Cell and Environment 40, 914-920.

Benettin P, Nehemy MF, Cernusak LA, Kahmen A, McDonnell JJ, 2021. On the use of leaf water to determine plant water source: A proof of concept. Hydrological Processes DOI: 10.1002/hyp.14073

Benettin P., Volkmann THM, von Freyberg J, Frentress J, Penna D, Dawson TE, Kirchner JW, 2018. Effects of climatic seasonality on the isotopic composition of evaporating soil waters. Hydrol. Earth Syst. Sci. 22, 2881-2890.

Berry, Z.C., Evaristo, J., Moore, G., Poca, M., Steppe, K., Verrot, L., Asbjornsen, H., Borma, L.S., Bretfeld, M., Herve-Fernandez, P., Seyfried, M., Schwendenmann, L., Sinacore, K., Wispelaere, L.D., McDonnell, J., 2017. The two water worlds hypothesis: addressing multiple working hypotheses and proposing a way forward. Ecohydrology, e1843.

Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Ziese, M., 2011. GPCC full data reanalysis version 6.0 at 1.0: monthly land-surface precipitation from rain-gauges built on GTS-based and historic data. Global Precipitation Climatology Centre (GPCC): Berlin, Germany.

Bowen, G.J., Revenaugh, J., 2003. Interpolating the isotopic composition of modern meteoric precipitation. Water Resour. Res. 39, 1299.

Bowen, G. J. (2010). Isoscapes: Spatial pattern in isotopic biogeochemistry. Annual Review of Earth and Planetary Sciences, 2010, 161–187.

Bowen GJ, Good SP, 2015. Incorporating water isoscapes in hydrological and water resource investigations. Wiley Interdiscip. Rev. Water 2, 107–119.

Brooks JR, Barnard HR, Coulombe R, McDonnell JJ, 2010. Ecohydrologic separation of water between trees and streams in a Mediterranean climate. Nature Geoscience 3, 100-104.

Cernusak, L.A., Farquhar, G.D., Pate, J.S., 2005. Environmental and physiological controls over oxygen and carbon isotope composition of Tasmanian blue gum, *Eucalyptus globulus*. Tree Physiol. 25, 129–146.

Cernusak LA, Barbour MM, Arndt SK, Cheesman AW, English NB, Feild TS, Helliker BR, Holloway-Phillips MM, Holtum JAM, Kahmen A, McInerney FA, Munksgaard NC, Simonin KA, Song X, Stuart-Williams H, West JB, Farquhar GD, 2016. Stable isotopes in leaf water of terrestrial plants. Plant Cell Environment 39, 1087-1102.

Chen Y, Helliker BR, Tang X, Li F, Zhou Y, Song X, 2020. Stem water cryogenic

https://doi.org/10.5194/hess-2021-289
Preprint. Discussion started: 6 July 2021

extraction biases estimation in deuterium isotope composition of plant source water. Proceedings of the National Academy of the Sciences USA 117, 33345-33350.

Cheng, H., Sinha, A., Wang, X., Cruz, F.W., Edwards, R.L., 2012. The Global Paleomonsoon as seen through speleothem records from Asia and the Americas. Climate Dynamics 39, 1045-1062.

Chiang, J.C., Fung, I.Y., Wu, C.-H., Cai, Y., Edman, J.P., Liu, Y., Day, J.A., Bhattacharya, T., Mondal, Y., Labrousse, C.A., 2015. Role of seasonal transitions and westerly jets in East Asian paleoclimate. Quaternary Science Reviews 108, 111-129.

Craig, H., Gordon, L.I., 1965. Deuterium and oxygen-18 variations in the ocean and the marine atmosphere. In 'Proceedings of a conference on stable isotopes in oceanographic studies and paleotemperatures'. pp. 9–130.

Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16, 436–468.

Dawson, T. E. and Ehleringer, J. R., 1991. Streamside trees that do not use stream water, Nature, 350, 335–337.

Dongmann G, Nurnberg HE, Forstel H, Wagener K (1974) On the enrichment of $H_2^{18}O$ in the leaves of transpiring plants. Radiation and Environmental Biophysics **11**, 41–52.

Draxler, R.R., Rolph, G.D., 2003. HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) Model Access via NOAA ARLREADY. htmlNOAA Air Resources Laboratory. Website. http://www.arl.noaa.gov/ready/hysplit4.

Ehleringer, J. R. & Dawson, T. E. (1992) Water uptake by plants: perspectives from stable isotope composition. *Plant Cell Environ.* **15**, 1073–1082.

Ehleringer, J. R. and Dawson, T. E., 1992. Water uptake by plants: perspectives from

https://doi.org/10.5194/hess-2021-289
Preprint. Discussion started: 6 July 2021

stable isotope composition, Plant Cell Environ., 15, 1073–1082,

Ellsowrth, P.Z., Williams, D.G., 2007. Hydrogen isotope fractionation during water uptake by woody xerophytes. Plant Soil 291, 93–107.

Evaristo J., Jasechko S., McDonnell J.J. 2015. Global separation of plant transpiration from groundwater and streamflow. *Nature* **525** : 91-94.

Farquhar, G.D., Cernusak, L.A., Barnes, B., 2007. Heavy water fractionation during transpiration. Plant Physiol. 143, 11–18.

Farquhar GD, Cernusak LA (2005) On the isotopic composition of leaf water in the non- steady state. Functional Plant Biology **32**, 293–303.

Farquhar G.D., Gan K.S. (2003) On the progressive enrichment of the oxygen isotopic composition of water along leaves. Plant, Cell and Environment 26, 801–819.

Farquhar G.D., Lloyd J. (1993) Carbon and oxygen isotope effects in the exchange of carbon dioxide between terrestrial plants and the atmosphere. In Stable Isotopes and Plant Carbon–Water Relations (eds J.R. Ehleringer, A.E. Hall, & G.D. Farquhar), pp. 47–70. Academic Press, San Diego.

Gibson JJ, Birks SJ, Edwards TWD, 2008. Global prediction of δA and δ^2H-$\delta^{18}O$ evaporation slopes for lakes and soil water accounting for seasonality. Global Biogeochem. Cycles, 22, GB2031

Goldsmith, G.R., Munoz-Villers, L.E., Holwerda, F., McDonnell, J.J., Asbjornsen, H., Dawson, T.E., 2012. Stable isotopes reveal linkages among ecohydrological processes in a seasonally dry tropical montane cloud forest. Ecohydrology 5, 779–790.

Hartsough P, Poulson SR, Biondi F, Estrada IG, 2008. Stable isotope characterization

https://doi.org/10.5194/hess-2021-289
Preprint. Discussion started: 6 July 2021

of the ecohydrological cycle at a tropical treeline site. Arctic, Antarctic, and Alpine Research 40, 343-354.

Helliker, B.R., Ehleringer, J.R., 2000. Establishing a grassland signature in veins: ^{18}O in the leaf water of C_3 and C_4 grasses. Proc. Natl. Acad. Sci. U.S.A. 97, 7894–7898.

Hepp J, Schäfer IK, Lanny V, Franke J, Blidtner M, Rozanski K, Glaser B, Zech M, Eglinton TI, Zech R, 2020. Evaluation of bacterial glycerol dialkyl glycerol tetraether and ^{2}H-^{18}O biomarker proxies along a central European topsoil transect. Biogeosciences 17, 741-756.

Jasechko S, Sharp ZD, Gibson JJ, Birks SJ, Yi Y, Fawcett PJ, 2013. Terrestrial water fluxes dominated by transpiration. Nature 496, 347-350.

Jia, X., Wang, Y., Shao, M., Luo, Y., Zhang, C., 2017. Estimating regional losses of soil water due to the conversion of agricultural land to forest in China's Loess Plateau. Ecohydrology 10, e1851.

Kahmen A., Sachse D., Arndt S.K., Tu K.P., Farrington H., Vitousek P.M. & Dawson T.E. (2011) Cellulose $\delta^{18}O$ is an index of leaf-to-air vapor pressure difference (VPD) in tropical plants. Proceedings of the National Academy of Sciences of the United States of America, 108, 1981-1986.

Leaney F., Osmond C., Allison G. & Ziegler H. (1985) Hydrogen-isotope composition of leaf water in C_3 and C_4 plants: its relationship to the hydrogen-isotope composition of dry matter. Planta 164, 215–220.

Lehmann, M. M., Gamarra, B., Kahmen, A., Siegwolf, R. T. W., & Saurer, M. (2017). Oxygen isotope fractionations across individual leaf carbohydrates in grass and tree

https://doi.org/10.5194/hess-2021-289
Preprint. Discussion started: 6 July 2021

species. *Plant, Cell & Environment 40*, 1658–1670.

Li Z, Feng Q, Wang Q, Kong Y, Cheng A, Yong S, Li Y, Li J, Guo X, 2016. Contributions of local terrestrial evaporation and transpiration to precipitation using $\delta^{18}O$ and D-excess as a proxy in Shiyang inland river basin in China. Global and Planetary Change 146, 140-151.

Li Z, Li Z, Yu H, Song L, Ma J, 2019. Environmental significance and zonal characteristics of stable isotope of atmospheric precipitation in arid Central Asia. Atmospheric Research 227, 24-40.

Lin, G.H., Sternberg, L.S.L., 1993. Hydrogen isotopic fractionation by plant roots during water uptake in coastal wetland plants. Stable Isotopic and Plant Carbon/Water Relations. Academic Press, New York, pp. 497–510.

Liu, J., Liu, W., An, Z., 2015. Insight into the reasons of leaf wax $\delta D_{\text{n-alkane}}$ values between grasses and woods. Sci. Bull. 60, 549–555.

Liu, J., Liu, W., An, Z., Yang, H., 2016. Different hydrogen isotope fractionations during lipid formation in higher plants: Implications for paleohydrology. Sci. Report 6, 19711.

Liu J, Wu H, Cheng Y, Jin Z, Hu J, 2021a. Stable isotope analysis of soil and plant water in a pair of natural grassland and understory of planted forestland on the Chinese Loess Plateau. Agricultural Water Management 249, 106800.

Liu J, An Z, Lin G, 2021b. Intra-leaf heterogeneities of hydrogen isotope compositions in leaf water and leaf wax of monocots and dicots. Science of the Total Environment 770, 145258.

https://doi.org/10.5194/hess-2021-289
Preprint. Discussion started: 6 July 2021

McGuire, K., and J. McDonnell (2007), Stable isotope tracers in watershed hydrology, in Stable Isotopes in Ecology and Environmental Science, Ecological Methods and Concepts Series, pp. 334–374.

Munksgaard NC, Cheesman AW, English NB, Zwart C, Kahmen A, Cernusak LA, 2016. Identifying drivers of leaf water and cellulose stable isotope enrichment in Eucalyptus in northern Australia. Oecologia 183, 31-43.

Pang, H., He, Y., Lu, A., Zhao, J., Ning, B., Yuan, L., Song, B., 2006. Synoptic-scale variation of $\delta^{18}O$ in summer monsoon rainfall at Lijiang, China. Chin. Sci. Bull. 51, 2897–2904.

Pagani M, Pedentchouk N, Huber M, Sluijs A, Schouten S, Brinkhuis H, Damsté J S S. Dichens GR, 2006. Arctic hydrology during global warming at the Palaeocene/Eocene thermal maximum. Nature 442, 671–675.

Penna D, van Meerveld HJ, 2019. Spatial variability in the isotopic composition of water in small catchments and its effect on hydrograph separation. WIREs Water, e1367.

Phillips, S.L., Ehleringer, J.R., 1995. Limited uptake of summer precipitation by big tooth maple (*Acer grandidentatum* Nutt) and Gambels oak (*Quercus gambelii* Nutt). Trees 9, 214–219.

Plavcová L, Hronková M, Šimková M, Květoň J, Vráblová M, Kubásek J, Šantrůček J, 2018. Seasonal variation of $\delta^{18}O$ and $\delta^{2}H$ in leaf water of *Fagus sylvatica* L. and related water compartments. Journal of Plant Physiology 227, 56-65.

Poca M, Coomans O, Urcelay C, Zeballos SR, Bodé S, Boecks P, 2019. Isotope fractionation during root water uptake by *Acacia caven* is enhanced by arbuscular

https://doi.org/10.5194/hess-2021-289
Preprint. Discussion started: 6 July 2021

Hydrology and Earth System Sciences
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Discussions

mycorrhizas. Plant and Soil, 3.

Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.-K., 2011. MERRA: NASA's modern-era retrospective analysis for research and applications. Journal of Climate 24, 3624-3648.

Rothfuss, Y., Javaux, M., 2017. Reviews and syntheses: isotopic approaches to quantify root water uptake: a review and comparison of methods. Biogeosciences 14, 2199–2224.

Rozanski, K., Araguas-Araguas, L., Gonfiantini, R., 2013. Isotopic patterns in modern global precipitation. Geophys. Monogr. Ser. 1–36.

Song X., Loucos K.E., Simonin K.A., Farquhar G.D., Barbour M.M., 2015a. Measurements of transpiration isotopologues and leaf water to assess enrichment models in cotton. New Phytologist 206, 637–646.

Song X, Simonin KA, Loucos KE, Barbour MM, 2015b. Modelling non-steady-state isotope enrichment of leaf water in a gas-exchange cuvette environment. Plant, Cell and Environment 38, 2618-2628.

Schefuβ, E., Kuhlmann, H., Mollenhauer, G., Prange, M., Pätzold, J., 2011. Forcing of wet phases in Southeast Africa over the past 17,000 year. Nature 480, 22–29.

Schleinger WH, Jasechko S, 2014. Transpiration in the global water cycle. Agr. Forest Meterol. 189-190, 115-117.

Sprenger M, Leistert H, Gimbel K, Weiler M, 2016. Illuminating hydrological processes at the soil-vegetation-atmosphere interface with water stable isotopes. Rev. Geophys. 54, 674-704.

Sprenger M, Tetzlaff D., Soulsby S., 2017. Soil water stable isotopes reveal evaporation dynamics at the soil-plant-atmosphere interface of the critical zone. Hydrol. Earth Syst. Sci. 21, 3839-3858.

Wang J, Fu B, Lu N, Zhang L, 2017. Seasonal variation in water uptake patterns of three plant species based on stable isotopes in the semi-arid Loess Plateau. Science of the Total Environment 609, 27-37.

Wang, J., Lu, N., Fu, B., 2019b. Inter-comparison of stable isotope mixing models for determining plant water source partitioning. Sci. Total Environ. 666, 685–693.

Wu, H., Li, J., Li, X., He, B., Liu, J., Jiang, Z., Zhang, C., 2018. Contrasting response of coexisting plant's water-use patterns to experimental precipitation manipulation in an alpine grassland community of Qinghai Lake watershed, China. PLoS One 13, e0194242.

Wu H, Wu J, Sakiev K, Liu J, Li J, He B, Liu Y, Shen B, 2019. Spatial and temporal variability of stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) in surface waters of arid, mountainous Central Asia. Hydrological Processes 33, 1658-1669.

Yang, Y.G., Fu, B.J., 2017. Soil water migration in the unsaturated zone of semiarid region in China from isotope evidence. Hydrol. Earth Syst. Sci. 21, 1–24.

Zhang P, Liu W, 2010. Effect of plant life form on relationship between δD values of leaf wax n-alkanes and altitude along Mount Taibai, China. Organic Geochemistry 42, 100-107.

Zhao L, Wang L, Cernusak LA, Liu X, Xiao H, Zhou M, Zhang S, 2016. Significant difference in hydrogen isotope composition between xylem and tissue water in *Populus*

https://doi.org/10.5194/hess-2021-289
Preprint. Discussion started: 6 July 2021

Euphratica. Plant Cell Environ 39, 1848-1857.

Zhao, Y., Wang, Y., He, M., Tong, Y., Zhou, J., Guo, X., Liu, J., Zhang, X., 2020. Transference of *Robinia pseudoacacia* water-use patterns from deep to shallow soil layers during the transition period between the dry and rainy seasons in a waterlimited region. For. Ecol. Manag. 457, 117727.

Zhang, H., Cheng, H., Cai, Y., Spötl, C., Sinha, A., Kathayat, G., Li, H., 2020. Effect of precipitation seasonality on annual oxygen isotopic composition in the area of spring persistent rain in southeastern China and its paleoclimatic implication. Climate of the Past 16, 211-225.

Zhang, H., Zhang, X., Cai, Y., Sinha, A., Spötl, C., Baker, J., Kathayat, G., Liu, Z., Tian, Y., Lu, J., 2021. A data-model comparison pinpoints Holocene spatiotemporal pattern of East Asian summer monsoon. Quaternary Science Reviews 261, 106911.

Figure captions

Fig. 1 Sample sites (black dots) and vertical disrtibution of vegetation across the Mt. Taibai transect (originating from Liu, 2021).

Fig. 2 Boxplots of precipitation, soil water, stem water, and leaf water for $\delta^{18}O$ values (a-d) and $\delta^{2}H$ values (e-h). Box plots show the median (red line), interquartile range (IQR) with the upper (75%) and lower (25%) quartiles, lowest whisker still within 1.5 IQR of th elower quartile, and highest whisker still within 1.5 IQR of the upper quartile; dots mark outliers.

Fig. 3 Dual isotope plots of precipitation, soil water, stem water, and leaf water in May (a), July (b), and September (c).

Fig. 4 Relationships between altitude and $\delta^{18}O$ (a-c) and $\delta^{2}H$ values (d-f) from different water types across months.

Fig. 5 Variation of monthly mean precipitation $\delta^{18}O$ (a) and $\delta^{2}H$ (b) values at Xi'an station from Global Network of Isotopes in Precipitation (GNIP) and cluster mean of moisture transport routes using HYSPLIT model in May (c), July (d) and September (e), 2020. Background in (c-e) is the average precipitation (mm/day) and 850 hPa wind vectors (arrows, m/s) in May (c), July (d) and September (e) in 1979-2016 AD based on the database of the Global Precipitation Climatology

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Center (GPCC) (Becker et al., 2011) and the Modern-Era Retrospective analysis for Research and Applications (Rienecker et al., 2011).

Fig. 6 Dual isotope plots for leaf water across month and altitude.

Fig. 7 Isotopic schematics of the flow diagram from precipitation to leaf water. Overview of the processes through multiple isotopic fractionations associated with various hydroclimate and physio-biological factors in terrestrial plants (Modified from Sachse et al., 2012 and Liu et al., 2016).

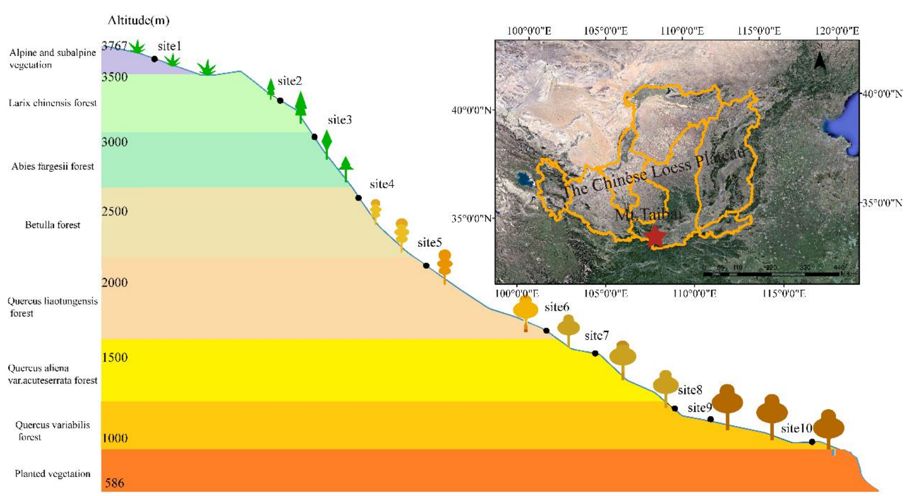

Figure-1

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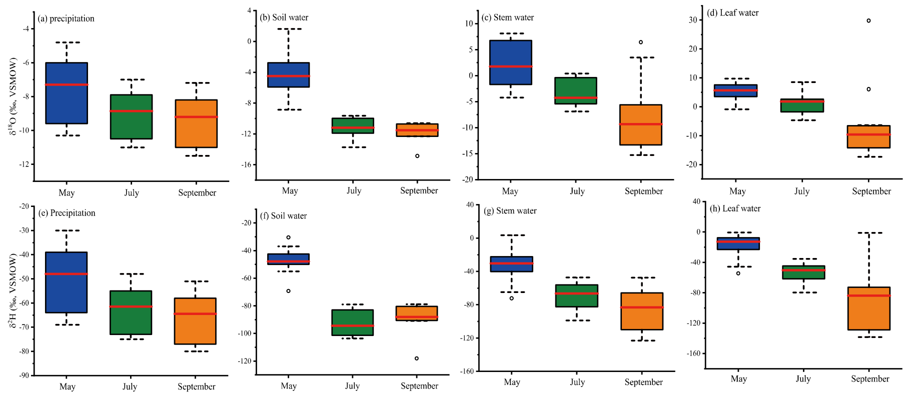

Figure-2

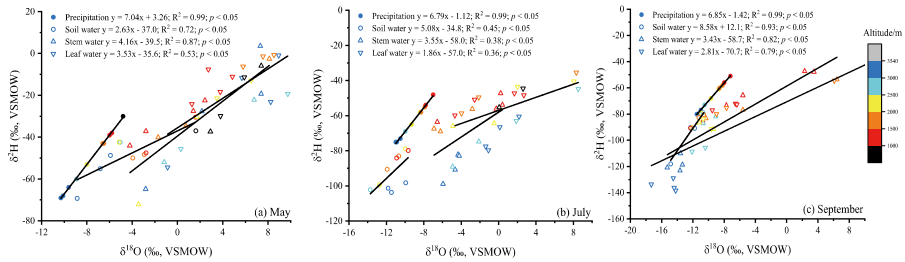

Figure-3

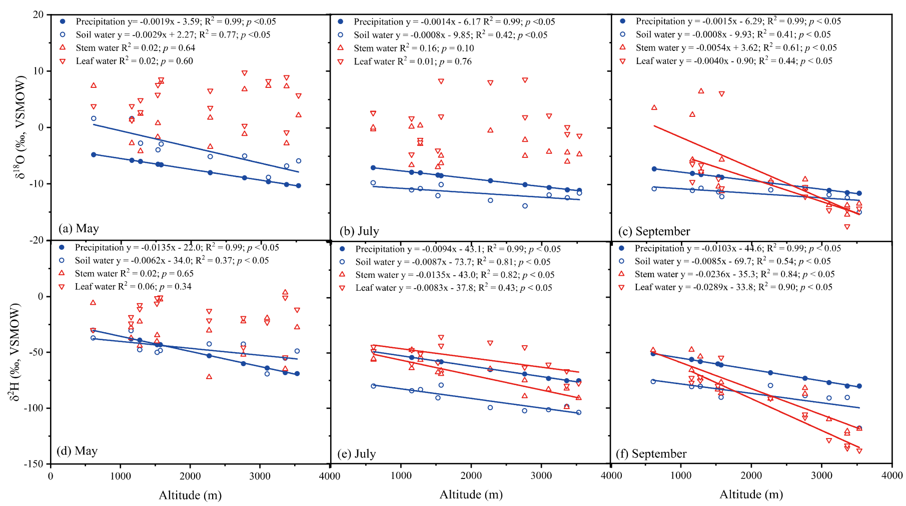

Figure-4

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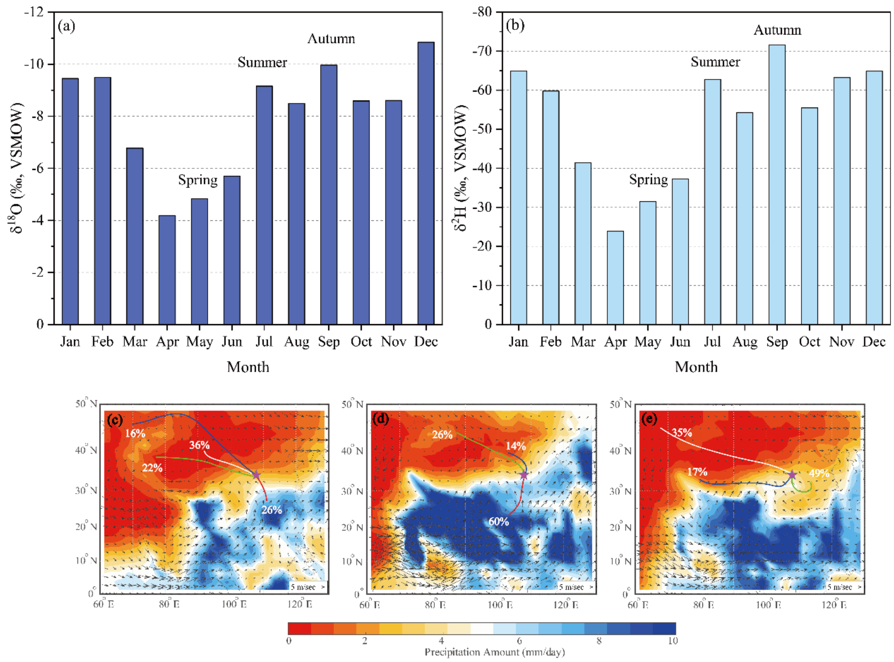


Figure-5

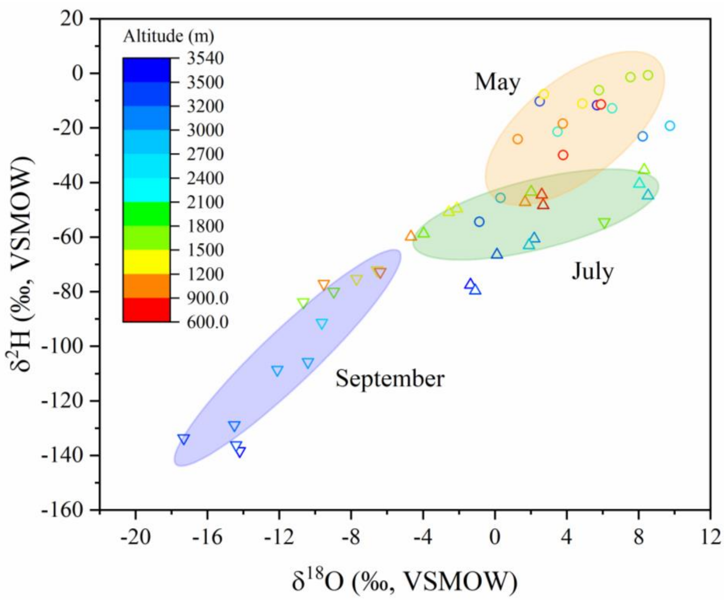
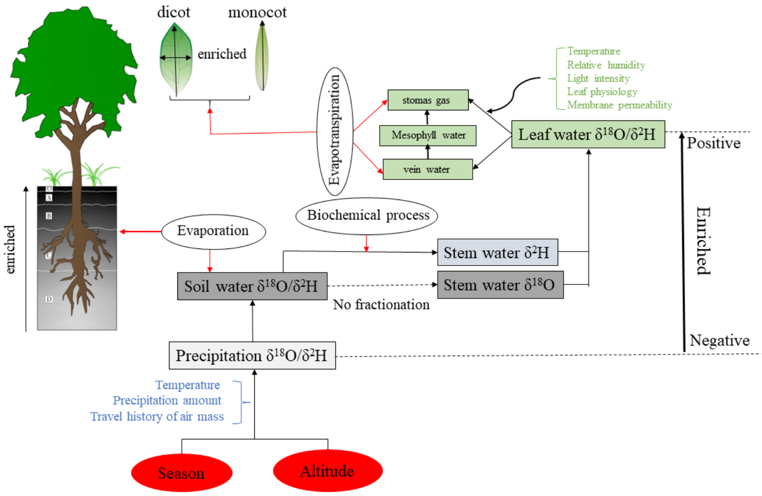


Figure-6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Temperature
Relative humidity
Light intensity
Leaf physiology
Membrane permeability
stomas gas
Mesophyll water
vein water
Evapotranspiration
Leaf water δ18O/δ2H
Positive
Enriched
Negative
enriched
Evaporation
Biochemical process
Stem water δ2H
Stem water δ18O
Soil water δ18O/δ2H
No fractionation
Precipitation δ18O/δ2H
Temperature
Precipitation amount
Travel history of air mass
Season
Altitude

Figure-7