A δ^2H offset correction method for quantifying root water uptake of riparian trees

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Abstract

Root water uptake plays an important role in water cycle in Groundwater-Soil-Plant-Atmosphere-Continuum. Stable isotopes (δ^2H and $\delta^{18}O$) are effective tools to quantify the use of different water sources by plant roots. However, the widespread δ^2H offsets of stem water from its potential sources due to δ^2H fractionation during root water uptake result in conflicting interpretations of water utilization using stable isotopes. In this study, a potential water source line (PWL), i.e., a linear regression line between $\delta^{18}O$ and δ^2H data of both soil water at different depths and groundwater, was proposed to correct δ^2H offsets of stem water. The PWL-corrected δ^2H was determined by subtracting the deviation between δ^2H in stem water and PWL from the original value. The MixSIAR model coupled with seven types of input data (i.e. various combinations of single or dual isotopes with uncorrected or corrected δ^2H data by PWL or soil water line (SWL)) were used to determine seasonal variations in water uptake patterns of riparian tree of *Salix babylonica* (L.) along the Jian and Chaobai River in Beijing, China. These methods were evaluated via three criteria including Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC) and root mean square error (RMSE). Results showed that different types of input data led to considerable differences in the contributions of soil water at upper 30 cm (9.9−57.6%) and below 80 cm depths (29.0−76.4%). Seasonal water uptake patterns were significantly different especially when δ^2H offset was pronounced ($p < 0.05$). The dual-isotopes method with uncorrected δ^2H underestimated the contributions of soil water in the 0−30 cm layer (by 30.4%) and groundwater (by 56.3%) compared to that with PWL-corrected δ^2H. The PWL correction method obtained a higher groundwater contribution (mean of 29.5%) than that estimated by the SWL correction method (mean of 24.5%). The MixSIAR model using dual-isotopes with PWL-corrected δ^2H produced the smallest AIC (94.1), BIC (91.9) and RMSE values (4.8%) than other methods (94.9−101.7, 92.6−99.5 and 5.3−12.4%, respectively), which underlined

the best performance of PWL correction method. The present study provides crucial insights into quantifying accurate root water uptake sources even if δ^2H offset exists.

Key words: Root water uptake; δ^2H offset; MixSIAR model; Potential water source line; Riparian tree

1. Introduction

Terrestrial vegetation plays an irreplaceable role in the global water cycle because 65% of precipitation was transported from land surfaces to the atmosphere by means of plant transpiration (Wang et al., 2014; Good et al., 2015; Wei et al., 2017). In recent years, a growing number of studies have focused on the water cycle in Groundwater-Soil-Plant-Atmosphere-Continuum (GSPAC), which is mainly controlled by plant transpiration (Gou and Miller, 2014; Jiao et al., 2019). In particular, root water uptake is one of the most important components in GSPAC by indicating the plants' abilities to take up different water sources and respond to variable hydrological conditions (Ma and Song, 2016; Barbeta et al., 2019). However, the explicit quantification of root water uptake remains challenging due to the complexity and variability of plant water use.

Stable isotope tracing technique, as an efficient tool with minimum damage to plants during sampling, has been widely used in exploring root water uptake by comparing isotopic compositions of stem water and its potential water sources (Dawson and Ehleringer, 1991; Asbjornsen et al., 2007; Yang et al., 2015a; Ma and Song, 2016; Rothfuss and Javaux, 2017; Yang et al., 2018). The quantification of the main plant water sources is usually carried out via the statistically-based multisource mixing models such as the IsoSource model and Bayesian mixing models (e.g., SIAR, MixSIR and MixSIAR) (Rothfuss and Javaux, 2017; Wang et al., 2019a). Specifically, MixSIAR not only accounts for the uncertainties in the root water uptake estimations of isotope ratios of stem water and its corresponding water sources, but also provides an optimal solution rather than a range of feasible solutions (Rothfuss and Javaux, 2017; Wang et al., 2019a). The isotopic tracing method relies on a basic assumption that no isotopic fractionation occurrs during root water uptake (Dawson and Ehleringer, 1991; Ehleringer and Dawson, 1992). Hydrogen (δ^2H) and oxygen (δ^{18}O) isotopes of twig/xylem water represents a weighted mean signature of all water sources used by plants respectively to their contributions (Dawson and Ehleringer, 1993; Ehleringer and Dawson, 1992). Both δ^2H and δ^{18}O isotopes of stem water should match those of source water if the assumption of no isotopic fractionation is true (Lin and Sternberg, 1993; Barbeta et al., 2019).

However, some studies reported that δ^2H fractionation occurred in root water uptake for some halophytes and xerophytes species (Lin and Sternberg, 1993; Ellsworth and Williams, 2007). As a result, the δ^2H of stem water was far less than that of soil water, groundwater, and river water, which were possible sources of the root water uptake. Lin and Sternberg (1993) found that the depletion of δ^2H in stem water ranged from 2−13‰ compared to that of source water both in the field and greenhouse experiments for coastal wetland plants. It was reported that 3−9‰ depletion in δ^2H of stem water in comparison to that of soil water was observed in twelve of sixteen shrubs and tree species from arid and semi-arid regions in greenhouse experiments by Ellsworth and Williams (2007). These δ^2H offsets of stem water from their potential sources due to isotopic fractionation challenged the reliability of isotopic tracing method in identifications of plant water sources (Barbeta et al., 2019). A growing number of studies showed that δ^2H offsets of stem water also existed in non-halophytes and non-xerophytes such as the riparian trees (Brooks et al., 2010; Zhao et al., 2016; Geris et al., 2017; Barbeta et al., 2019) and the laboratory-controlled tree species (Vargas et al., 2017; Barbeta et al., 2020). These δ^2H offsets of stem water mainly resulted from δ^2H fractionation occurring in roots or between stem and root water, which was related to soil water loss, soil type as well as leaf transpiration (Lin and Sternberg, 1993; Vargas et al., 2017; Barbeta et al., 2019). Therefore, the δ^2H offsets caused by hydrogen fractionation should be kept in mind in applications such as quantifying sources of root water uptake.

Previous studies usually did not take the δ^2H offsets of stem water into account and still used single or dual-isotopes with uncorrected δ^2H method to quantify plant water sources. They usually speculated that a missing water source in the sampling process led to the δ^2H offsets (Bowling et al., 2017). Evaristo et al. (2017) indicated that plant water source estimations were less sensitive to δ^2H fractionation when both δ^2H and δ^{18}O were combined within a Bayesian inference approach. On the contrary, some studies confirmed that there were remarkably divergent source water contributions either using single uncorrected δ^2H, single δ^{18}O or both isotopes due to δ^2H offsets (Barbeta et al., 2019; Barbeta et al., 2020). In order to avoid inaccurate results caused by pronounced δ^2H offsets, some studies directly used single δ^{18}O to quantify plant water sources (Asbjornsen et al., 2007; Goebel et al., 2015). Nevertheless, single isotopic tracer is insufficient to identify plant water sources when the isotopic compositon of stem water matches with several water sources (Barbeta et al., 2019; Parnell et al., 2010). Therefore, neither single nor dual-isotopes method using uncorrected isotopes is effective for the identification of plant water sources when δ^2H offsets exist. How to correct δ^2H offsets and make accurate estimations of plant water sources is an urgent need.

A concept of line-condition excess (lc-excess) which was originally used to describe the δ^2H offset of the river water from the local meteoric water line (LMWL) was presented by Landwehr and Coplen (2006). Recently, Barbeta et al. (2019) modified the lc-excess and corrected δ^2H of stem water for riparian trees by subtracting the SW-excess, which represents for the δ^2H offsets of stem water from their corresponding soil water line (SWL). The SWL correction method only considered soil water as potential water sources for plants. However, the potential water sources also include other sources such as groundwater, rock moisture, fog water, and dew water (Evaristo et al., 2015; Wang et al., 2017a; Wang et al., 2019b). In particular, groundwater serves as an important and independent water source for phreatophytes especially during drought periods or in arid and semiarid regions (Contreras et al., 2011; Miguez-Macho and Fan, 2012; Fan, 2015), Mediterranean region (Dawson and Pate, 1996), and even humid region (Vincke and Thiry, 2008). Several tree species could tap into capillary fringe or even water tables to take up groundwater directly to meet transpiration needs (Song et al., 2016; Christina et al., 2018). Groundwater is extracted by trees more efficiently than soil water in the unsaturated zone because a few deep roots can withdraw a large quantities of groundwater (20%) for transpiration (Ferro et al., 2003). Although groundwater is identified as an important water source, it was not considered in the SWL correction method due to its similar isotopic values with deep soil water in Barbeta et al. (2019). However, the isotopic composition of groundwater may vary greatly from that in the deep soil water. Therefore, the δ^2H offset correction should consider the isotopic values of potential water sources such as soil water at different depths and groundwater if the plants have deep roots to acquire groundwater.

In this study, the MixSIAR model accompanied with a develped δ^2H offset correction method was used to quantify root water uptake patterns of riparian trees along the Jian and Chaobai River in Beijing, China. The objectives of this study were to: (1) propose a water source line that can correct the δ^2H offset of stem water from its potential water sources; (2) compare the outputs of MixSIAR model using single or dual-isotopes method with uncorrected or corrected δ^2H input data; (3) evaluate the effects of δ^2H offsets and single or dual-isotopes method on determination of water sources for riparian trees.

2. Materials and methods

2.1. Theoretical consideration

2.1.1. PWL definition

The potential water source line (PWL) was presented to correct the δ^2H offset of stem water from the potential water sources including both soil water at different depths and groundwater. δ^2H values of stem water corrected by PWL can match those of source water. The PWL was proposed on the basis of the concept of lc-excess, which was defined by Landwehr and Coplen (2006) as following:

$$\text{lc-excess} = \delta^2\text{H} - a\delta^{18}\text{O} - b\ , \qquad (1)$$

where a and b represent the slope and intercept of LMWL. δ^2H and δ^{18}O in Eq. (1) are isotopic compositions of river water samples.

Generally, trees cannot take up rainwater or river water directly but rely on soil water. In order to access the δ^2H deviation of stem water from the SWL (i.e., SW-excess), Barbeta et al. (2019) changed the above lc-excess formula into:

$$\text{SW-excess} = \delta^2\text{H} - a_s\delta^{18}\text{O} - b_s\ , \qquad (2)$$

where a_s and b_s represent the slope and intercept of SWL, respectively. δ^2H and δ^{18}O in Eq. (2) are isotopic compositions of stem water. The SW-excess indicates the δ^2H offsets of stem water with respect to their corresponding SWL which limits the plant water sources to only soil water pools. Positive SW-excess value means that the δ^2H in stem water is more enriched than the SWL, while negative value means that δ^2H in stem water is more depleted than SWL. The concept of the SWL correction method is shown in Fig. 1.

Besides soil water, groundwater is a crucial water source especially for phreatophytes growing in areas with shallow water table depth (WTD). Groundwater and deep soil water cannot be merged into one source for the estimations of water uptake patterns, when their isotopic compositions are significantly different. Groundwater will greatly affect the fitting of the correction water line. Therefore, the PWL was proposed by performing a linear regression on all soil water and groundwater isotope data, as shown in Fig. 1. The δ^2H deviation of stem water from the PWL (i.e., PW-excess) was as follows:

$$\text{PW-excess} = \delta^2\text{H} - a_p\delta^{18}\text{O} - b_p\ , \qquad (3)$$

where a_p and b_p are the slope and intercept of the PWL, respectively.

Positive value of PW-excess means that the δ^2H in stem water is more enriched than the PWL. The larger the positive value is, the greater the degree of isotopic enrichment is. On the contrary, negative value of PW-excess represents that δ^2H in stem water is more depleted than that the PWL. The larger the negative value is, the greater the degree of isotopic depletion is. When PW-excess is zero, there is no δ^2H offset between stem water and the PWL. The δ^2H value of stem water is corrected by subtracting the corresponding PW-excess from the original value.

<Figure 1>

2.1.2. MixSIAR model and different types of input data

The MixSIAR model (v3.1) incorporating with stable isotopes (δ^2H and δ^{18}O) was used to calculate contributions of potential water sources to plant stem water. The isotopic values of stem water were referred as the mixture data, whereas those of soil water at different depths and groundwater were set as the source data. The Markov chain Monte Carlo (MCMC) parameter run length in the MixSIAR model was selected as "very long" for convergence. The model errors were evaluated via the process and residual errors. The calculated 50% percentile of the posterior contribution was referred as the main proportional contribution of each water source to stem water in this study (Stock and Semmens, 2013). More details about MixSIAR model (v3.1) could be found in Stock and Semmens (2013).

In order to evaluate the effects of δ^2H offset in stem water and single or dual-isotopes method on quantifying root water uptake, we compared the performance of MixSIAR model input with seven types of isotopic data for stem water including (1) uncorrected δ^2H and δ^{18}O, (2) single uncorrected δ^2H, (3) single δ^{18}O, (4) dual isotopes with δ^2H corrected by the SWL (subtracting the SW-excess from the δ^2H values) and δ^{18}O, (5) single δ^2H corrected by the

SWL, (6) dual isotopes with δ^2H corrected by the PWL (subtracting the PW-excess from the δ^2H values) and $\delta^{18}O$, and (7) single δ^2H corrected by the PWL.

To assess the effectiveness of the developed δ^2H offset correction method in identifying root water uptake sources, two types of evaluation methods were used to evaluate the results of seven types of input data. The first method was based on the correlations between plant water source estimations and environment variables. Previous studies showed that δ^2H offsets and root water uptake patterns were affected by different environmental variables such as vapor pressure deficit (VPD), precipitation, soil sand content (SSC), WTD and soil water content (SWC) (Qian et al., 2017; Vargas et al., 2017; Wang et al., 2017b; Barbeta et al., 2019). For example, precipitation, the fluctuation of WTD and SWC could affect water availabilities of potential water sources for trees (Qian et al., 2017). Geris et al. (2017) concluded that soil type might have a strong effect on water uptake patterns. This could be explained by the fact that soil types affected both precipitation infiltration and groundwater capillary rise through changing soil moisture and root distribution (Vereecken et al., 2015; Zipper et al., 2015). The VPD could impact the transpiration rate of plants, which was the driving force of root water uptake. A significant relationship was found between the VPD and water source contributions (Barbeta et al., 2019). Therefore, the correlations between plant water source estimations and these multiple environment variables could be considered to evaluate the performances of MixSIAR model with seven types of input data. The stronger the correlation was, the water source contributions calculated by MixSIAR model were closer to actual values. The correlation analysis was conducted using general linear mixed models (GLMM) in the SPSS software (22.0 version) to avoid the influence of random errors (e.g., different sites and sampling campaigns). The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values (Rascher et al., 2004) were used to compare the correlations of plant water source estimations with different environmental variables among the seven types of input data. The input data with the lower values of AIC and BIC were the preferred type.

Secondly, the deviation of water source contributions estimated with each type of input data from the average values of all seven types of input data was assessed. It could reflect the uncertainties of MixSIAR estimations with different input data by the root mean square error (RMSE):

$$\mathrm{RMSE} = \sqrt{\left[\frac{1}{n}\sum_{i=1}^{n}\left(p_i - \overline{p}\right)^2\right]}\ , \qquad (4)$$

where n indicates the number of all water sources including soil water at different depths and groundwater at all sites and dates, p_i is the proportional contribution of the ith water source estimated by MixSIAR model with one certain type of input data, and $\overline{p}$ is the average contribution of the ith water source calculated through seven types of input data. The smaller the RMSE value is, the smaller the uncertainties of plant water source estimations are. The best type of input data for quantification of plant water source contributions using the MixSIAR model was then selected through the smallest AIC, BIC and RMSE values.

2.2. Field observations

2.2.1. Study area and field measurements

In order to test the correction method of stem water δ^2H offset by PWL for determining plant water sources, experiments for riparian trees of *S. babylonica* were conducted during April to November in 2019 along the reaches of the Jian and Chaobai River in Shunyi district, Beijing, China (40°07′30″N, 116°40′37″E) (Fig. 2). The study area has a temperate continental sub-humid monsoon climate. The annual average temperature is 11.5 ^{o}C and annual average evaporation is 1175 mm. The annual average precipitation is 610 mm, with 80% of which occurring in the wet season from June to August. The water depth in river is mean of 1.4 m in the reach of Jian River with a width of 50−90 m, and remains approximately 0.7 m in the reach of the Chaobai River with a width of about 200 m. *S. babylonica* is one of the most widely distributed riparian trees with growing season starting from late April to early November. With a rooting system suitable for waterlogging (approximately 4 m deep), *S. babylonica* can survive being below the water tables (Markus-Michalczyk et al., 2019; Martorello et al., 2020).

<Figure 2>

Three representative sites in the riparian zone alongside the Jian River (site A) and Chaobai River (sites B and C) with different soil textures and WTDs were selected in this study area (Fig. 2). The soil textures within 0−3 m depth were mainly clay loam, sandy loam, and sand for sites A, B, and C, respectively (Table 1). There was extremely significant difference in the SSC ($p < 0.001$) among sites A (33.4%), B (80.6%) and C (90.8%). The annual mean WTD was significantly different among sites A (21.1 m), B (2.3 m) and C (1.6 m). Both soil water and groundwater can be taken up by *S. babylonica* easily at sites B and C due to shallow WTD. They were used to compare the performances of MixSIAR model with δ^2H corrected by the PWL and SWL. The site A was selected as a comparison where the potential water sources for *S. babylonica* were only confined to the soil water sources at different depths under the deep WTD, and the PWL was the same as SWL. These three sites with various environmental conditions were adequate to qualitatively evaluate the significance of the PWL correction method for quantifying root water uptake sources of riparian trees and evaluate the performance of MixSIAR model with seven types of input data.

<Table 1>

Daily meteorological data including temperature, radiation and relative humidity was collected from the meteorological observation station (ET007, Insentec instrument, Hangzhou, China) in this study area (Fig. 2). Daily VPD was estimated through relative humidity and temperature. The daily precipitation data was recorded via a tilting rain gauge (SL3-1, Shanghai meteorological instrument, Shanghai, China) installed on the opposite side of site C.

The WTD was measured once a month from the groundwater monitoring wells constructed at each site.

2.2.2. Water sampling and isotope analysis

Water samples of precipitation, river, groundwater, stem, and soil were collected for δ^2H and $\delta^{18}O$ analysis. Precipitation greater than 1.5 mm was collected during the observation period in 2019. The polyethylene bottle coupled with a funnel and plastic ball was used to avoid evaporation (Yang et al., 2015b). Water samples of river, groundwater, stem, and soil were collected on the same day with six campaigns on May 5, June 14, July 26, August 15, September 26, and November 5 in 2019. River water was sampled at a depth of 0.3 m below the water surface using the organic glass hydrophore. Groundwater was sampled from the monitoring well at each site by a water pump.

S. babylonica trees in three plots with distances of 5, 10, and 20 m away from the river bank at each site were selected for stem water isotope analysis (Fig. 2). The mean diameter at breast height and average height of the studied trees were 66.5 cm and 8.0 m, respectively. Three non-green and suberized stems approximately 10 mm in diameter were taken from twigs of each tree and combined to represent a single stem sample. They were removed the bark and phloem tissue, immediately placed into air-tight glass vials and sealed with parafilm.

Soil samples were collected within 1 m of each tree using a power auger with the petrol engine-driven post driver (CHPD78, Christie Engineering Company, Sydney, Australia). Soil was sampled at depths of 5, 10, 15, 20, 30, 40, 60, 80, 100, 150, 200, 250, and 300 cm. The roots were removed, and then soil samples were placed into air-tight glass vials and sealed with parafilm. The soil samples were also used for gravimetric SWC measurements by oven-dry method and soil texture measurements by a laser particle size analyzer (Mastersize-2000, Malven Instruments Ltd., UK).

All soil and stem samples were kept frozen in a refrigerator until water extraction. The water contained in the stem and soil samples were collected using an automatic cryogenic vacuum distillation system (LI-2100, LICA, Beijing, China). The extraction progress was described in detail by Wu et al. (2019a). All the water extractions were completed, which had been checked by oven drying samples at 105 ºC for 12 h and reweighing them, to ensure complete extraction (Yang et al., 2015b).

The isotopic compositions of rainwater, soil water, groundwater, and river water were measured by an isotopic ratio infrared spectroscopy (IRIS) system (DLT-100, Los Gatos Research, mountain view, USA). The measurement precision of the IRIS system was ±1‰ for δ^2H and ± 0.1‰ for δ^{18}O (Wang et al., 2009). Because organic contaminants in the water cryogenically extracted from the tree stems would affect the isotopic measurements by the IRIS method (Zhao et al., 2011), we used an Isotope Ratio Mass Spectrometry (IRMS) system (MAT253, Thermo Fisher Scientific, Bremen, Germany) to measure the δ^2H and δ^{18}O in stem water. The precision of the IRMS system was ± 1‰ for δ^2H and ± 0.1‰ for δ^{18}O, respectively. The measured isotopic compositions for different waters were calibrated and normalized against the Vienna Standard Mean Ocean Water (VSMOW). No significant difference in δ^2H (p = 0.98) and δ^{18}O (p = 0.89) measurements for groundwater, rainwater and soil water was observed between the IRIS and IRMS methods.

There was no significant difference in water isotopes among the trees in the three plots at each site, and they were considered as three replicates to analyze the water sources of riparian trees. Four soil layers (0−30, 30−80, 80−150, 150−300 cm) were divided based on seasonal variations in SWC and soil water isotopic composition at different depths. The isotopic ratios of stem water and soil water in each layer were input into MixSIAR model to quantify the water source contributions for riparian trees in each plot, and then the estimated results of three plots were averaged to determine the root water uptake patterns at each site.

2.3. Statistical analysis

One-way analysis of variance (ANOVA) with Kolmogorov-Smirnov, levene's and post-hoc Tukey's tests ($p < 0.05$) were used to examine differences in the isotopic compositions of different water sources as well as differences in the δ^2H offsets among three sites. Two-way ANOVA was performed to detect the significant effects of both sampling sites and dates on the δ^2H offsets and the differences of proportional contributions of water sources among seven types of input data. The above statistical analysis was performed in the SPSS software (22.0, Inc., Chicago, IL, USA).

3. Results

3.1. Environmental variables

The total precipitation was 399 mm during the observation period in 2019 (Fig. 3). There were pronounced differences in seasonal variations of precipitation ($p < 0.01$). The accumulated monthly precipitation during April to November was 18.4, 25.8, 19.5, 133.7, 89.1, 79.1, 32.9 and 0.6 mm, respectively. Monthly mean VPD was 0.9, 1.4, 1.4, 1.2, 1.0, 0.8, 0.5 and 0.3 kPa from April to November, respectively, with mean of 1.0 kPa and standard deviation (SD) of 0.5 kPa (Fig. 3). The WTD was significantly different among sites A (20.5 ± 0.5 m), B (1.9 ± 0.3 m), and C (1.5 ± 0.1 m) ($p < 0.05$) (Fig. 3). The increase of WTD was observed at sites A (from 20.0 to 21.2 m) and B (from 1.7 to 2.5 m) during the wet season, whereas WTD was relatively stable at site C.

The depth distribution and seasonal variation in SWC exhibited significant differences among the three sites ($p < 0.05$). The average SWC in the 0−30 cm layer was larger at site A (mean of 0.16 g g^{-1} and SD of 0.03 g g^{-1}) than that at site B (mean of 0.09 g g^{-1} and SD of 0.02 g g^{-1}) and site C (mean of 0.09 g g^{-1} and SD of 0.03 g g^{-1}) (Fig. 4). However, the SWC in the 80−300 cm layer was largest (mean of 0.25 g g^{-1}) at site C, following by that at site B (mean of

0.21 g g^{-1}) and smallest at site A (mean of 0.20 g g^{-1}) (Fig. 4). There was an evident decline of SWC in the 0−150 cm layer during May to August at sites A and B, but not at site C.

<Figure 3>

<Figure 4>

3.2. Isotopic compositions of different water bodies

The isotopic values of precipitation ranged from −68.3 to −26.0‰ for δ^2H and −13.9 to −6.3‰ for δ^{18}O (Fig. 5). The LMWL fitted by the isotopic compositions of precipitation was established as: $\delta^2H = 5.5\delta^{18}O - 7.9$ ($R^2 = 0.81$) during the observation period in 2019. Groundwater gradually enriched from site A (mean of −71.1‰ for δ^2H and −10.2‰ for δ^{18}O) to site B (mean of −55.7‰ for δ^2H and −6.9‰ for δ^{18}O) and site C (mean of −51.1‰ for δ^2H and −6.4‰ for δ^{18}O) (Fig. 5). The isotopic compositions of groundwater were more depleted than those of river water at site A ($p < 0.001$) (Fig. 5). Nevertheless, no significant difference was found in seasonal variations of isotopic values between groundwater and river water at sites B and C during the observation period ($p > 0.05$).

Soil water isotopes at different depths ranged from −86.6 to −45.6‰ for δ^2H and from −14.1 to −3.2‰ for δ^{18}O at the three sites (Fig. 5). They were enriched in the 0−30 cm soil layer but depleted with depth within the 0−300 cm profile at site A. It was evident that soil water isotopes in the 150−300 cm layer at sites B and C were evidently affected by groundwater, being more enriched than those in the 80−150 cm layer (Fig. 5).

The δ^2H in stem water was more depleted than that of potential water sources and fell to the lower right of the PWL at sites B and C in the dual-isotopes plots (Fig. 5). Nevertheless, the δ^{18}O in stem water was always within the range of that in groundwater and soil water, suggesting that groundwater was an important water source for riparian trees at sites B and C. As river water and groundwater interacted closely and had similar isotopic characteristics, they could be pooled together as one potential water source for riparian trees at these two sites. On the contrary, the $\delta^{18}O$ in stem water (mean of −7.4‰) was remarkably enriched than that of groundwater (mean of −10.2‰) and more depleted than that of river water (mean of −6.9‰) at site A. Trees could not take up groundwater under the deep WTD (mean of 20.5 m). Therefore, neither groundwater nor river water was considered as water sources for riparian trees at site A.

<Figure 5>

3.3. δ^2H offsets of stem water

The PWL and SWL for sites A (PWL was the same as SWL), B and C during the observation period were fitted with $R^2 > 0.66$ ($p < 0.001$) in Fig. 5. The slope of SWL and PWL indicated the evaporation degree of soil water sources and potential water sources, respectively. On average, the SWL had a slope of 6.4, 4.2, and 4.8 at site A, B, and C, respectively. In comparison, the slopes of PWL at site B (mean of 4.5) and site C (mean of 5.3) were larger than those of SWL, which indicated that the evaporation degree of potential water sources was smaller than that of soil water sources. Additionally, evaporation of both soil water and potential sources were strongest at site B among the three sites.

The δ^2H offset of stem water from its potential water sources was calculated by the PW-excess and SW-excess (Fig. 6). The mean SW-excess value during the observation period was −4.7, −5.1 and −8.0‰ for site A, B, and C, respectively. The PW-excess values (mean of −8.5‰) were significantly lower than SW-excess values (mean of −6.5‰) over the observation period at sites B and C ($p < 0.05$). There were pronounced seasonal differences in the δ^2H offset characteristics among the three sites ($p < 0.001$) (Fig. 6). The average value of PW-excess (same as SW-excess) for site A remained stable with SD of 0.8‰ during the observation period. The average value of PW-excess varied greatly, ranging from −13.7‰ to −1.7‰ among the six sampling campaigns during the observation period at sites B and C (Fig. 6). Extremely significant δ^2H offset of stem water occurred on May 5, June 14, and July 26 ($p < 0.01$).

<Figure 6>

3.4. Comparison of water use patterns determined by different input data

The proportional contributions of different potential water sources to riparian trees estimated by MixSIAR model with seven types of input data were shown in Fig. 7 and Table 2. When using dual-isotopes method with δ^2H in stem water corrected by PWL, the average contributions of soil water in the 0−30, 30−80, 80−150, 150−300 cm layers and groundwater were 22.4, 18.3, 14.1, 16.7 and 28.5%, respectively (Table 2). There were significant differences in proportional contributions of soil water sources below 80 cm (29.0−76.4%) among seven types of input data ($p < 0.05$), especially when δ^2H offset was pronounced. For example, those average contributions estimated using single uncorrected δ^2H (mean of 41.4%) and dual-isotopes method with uncorrected δ^2H (mean of 36.9%) were lower than those estimated by single δ^{18}O (mean of 62.2%), dual-isotopes method with SWL-corrected δ^2H (mean of 62.7%), and dual-isotopes method with PWL-corrected δ^2H (mean of 63.6%). The differences were also observed in the contribution of groundwater among seven types of input data during the whole growing season ($p < 0.05$). For instance, groundwater contributed a little to trees estimated using single uncorrected δ^2H (mean of 12.9%) and dual-isotopes method with uncorrected δ^2H and δ^{18}O (mean of 12.9%), whereas it contributed more using single δ^{18}O (mean of 27.4%), single δ^2H corrected by PWL (mean of 30.6%), and dual-isotopes with δ^{18}O and PWL-corrected δ^2H (mean of 29.5%) (Table 2). Additionally, the PWL correction method estimated a higher contribution of groundwater (mean of 29.5%) than that (mean of 24.5%) estimated by the SWL correction method (Table 2).

<Table 2>

There were significant differences in seasonal water uptake patterns for riparian trees among different types of input data ($p < 0.05$) (Fig. 7 and Table 2). The results calculated by dual-isotopes method with PWL-corrected δ^2H showed that riparian trees mainly used water from soils below 150 cm on May 5, June 14, July 26, and August 15 with contributions greater than 54.6%. Then the main water uptake depth changed to the 0−150 cm layer on September 26 and November 5 with the contributions more than 60.5%. However, the main water uptake depth estimated by single and dual-isotopes method with uncorrected δ^2H was in the 0−150 cm layer during the entire observation period, with average contribution of 72.3% (Fig. 7 and Table 2). The proportional contribution of soil water in the 0−30 cm layer to stem water of trees during wet season (June to August) differed greatly among seven types of input data. It contributed more estimated using dual-isotopes method with PWL-corrected δ^2H (with mean of 25.8%), whereas the average contributions were 18.4, 20.2 and 19.6% calculated by single uncorrected δ^2H, single δ^2H corrected by SWL and PWL, respectively. The absolute (from -8.6% to 10.6%) and relative (from -29.9% to 64.7%) differences in the contributions of tree water sources were evident on several sampling campaigns especially at sites B and C between the single δ^{18}O and dual-isotopes with PWL-corrected δ^2H methods (Fig. 7 and Table S1). For example, the single δ^{18}O method overestimated the contributions of soil water in the 30−80 cm layer by 64.2% on Aug 15, while it underestimated groundwater contributions by 26.1% on September 26 at site B relative to the dual-isotopes with PWL-corrected δ^2H method.

<Figure 7>

3.5. Best input isotope data for identifying riparian tree water sources

The AIC and BIC values that reflected the relationship between source contributions to stem water and environmental variables for selecting the preferred input data were shown in Table 3. Without consideration of the δ^2H offset, both single δ^2H and dual-isotopes methods displayed the largest AIC (101.7) and BIC (101.7) (Table 3). It was worth noting that the single δ^{18}O method showed lower AIC (94.9) and BIC values (92.6). On the contrary, when δ^2H in stem water was corrected by PWL, dual-isotopes method produced smaller AIC (94.1) and BIC (91.9) than single PWL-corrected δ^2H (AIC of 98.0 and BIC of 95.8) and single δ^{18}O (AIC of

94.9 and BIC of 92.6). The estimations of plant water sources with corrected isotopes displayed significantly smaller AIC and BIC values than those with uncorrected isotopes ($p < 0.05$). For instance, the average single corrected δ^2H produced a lower AIC (97.1) and BIC (94.9) than single uncorrected δ^2H (AIC of 101.7 and BIC of 99.5). Moreover, the dual-isotopes method with SWL-corrected δ^2H figured out larger AIC (97.6) and BIC (95.4) values than that with PWL-corrected δ^2H. This suggested that dual-isotopes method with PWL-corrected δ^2H had better performance than that with SWL-corrected δ^2H.

The RMSE values for explaining the deviation of the source contributions estimated by one type of input data from the average source contributions of different input data were shown in Table 3. RMSE value was remarkably smaller when using dual-isotopes than that using single isotope ($p < 0.05$) (Table 3), whether δ^2H offset was corrected or not. For example, RMSE value was 12.4% when using single uncorrected δ^2H, whereas it was 9.5% when using dual-isotopes method with uncorrected δ^2H. The water source contribution estimations with corrected isotopes displayed significantly smaller RMSE values (mean of 5.1%) than those with uncorrected isotopes (mean of 9.6%) ($p < 0.05$). Furthermore, the dual-isotopes method with SWL-corrected δ^2H had significant higher RMSE values than the dual-isotopes method with PWL-corrected δ^2H ($p < 0.05$). Overall, our results suggested that the dual-isotopes method with PWL-corrected δ^2H performed best in identifying water uptake patterns.

<Table 3>

4. Discussion

4.1. Possible reasons for isotopic offsets of stem water

Spatial and seasonal disparities of PW-excess values suggested that δ^2H offsets of stem water differed greatly during the observation period among the three sites (Fig. 6). A δ^2H offset could be atrributed to methodological issues reporetd by Orlowski et al. (2018). However, water extraction of soil and stem samples via automatic cryogenic vacuum distillation system was well conducted and yielded a collection rate more than 98% in this study. Contamination of extracted water by organic compounds was also routinely dealt with custom and post-measurment corrections. These techniques extremely avoided the fractionation processes occuring during water extraction. Another possibility for explaining the δ^2H offset is the isotopic heterogeneity in plant water pools aroused by discrimination during water trasnport and redistribution within the plant (Zhao et al., 2016; Barbeta et al., 2020). The δ^2H offset would be decreased or even reversed under drier conditions as a result of evaporative enrichment (Barbeta et al., 2020). These studies indicated that there were no δ^2H fractionation and offset occuring during root water uptake. However, δ^2H offsets were more noticeable under drier conditions in our study (e.g. much lower PW-excess values occurring on May 5 at sites B and C). It was impossible to be completely ascribed to the evaporative enrichment in plant water pools.

The δ^2H offset of stem water probably occurred in the soil-root interfaces by root water uptake (Allison et al., 1983; Vargas et al., 2017). It was found that large δ^2H offset was synchronized to low SWC in the 0−150 cm layer and the decline of water table from May to June (Fig. 4). More interestingly, δ^2H offset progressively decreased as SWC in the 0−150 cm layer increased with increasing precipitation amount and rising water table. This might be due to that pore spaces between soil grains and roots increased with the soil water loss under the increase of WTD, which resulted in stronger δ^2H fractionation during root water uptake (Barnes and Allison, 1983; Vargas et al., 2017). Moreover, the δ^2H offsets at high-SSC sites (mean SSC of 80.7% for site B and 90.8% for site C) were significantly larger than those at low-SSC site (mean SSC of 33.4% for site A) (Table 1 and Fig. 6). It has been reported that δ^2H fractionation was controlled by variable diffusive resistance of soil vapors, which was indicated by air filled porosity and the tortuosity of the soil (Barnes and Allison, 1988). Therefore, the high SSC could increase the pore spaces (Barnes and Allison, 1983; Vargas et al., 2017) and possibilities of roots contacting with air during root water uptake, which could lead to δ^2H offset (Evaristo et al., 2017; Geris et al., 2017).

Previous studies found that soil clay content and/or carbonate content could result in $\delta^{18}O$ fractionation of water added to soil particularly under low soil water content, leading to conflicting results in quantification of root water uptake (Meiβner et al., 2014; Yang et al., 2015). The bias of $\delta^{18}O$ might be caused by oxygen isotope exchanges between soil water and carbonates during the water extraction process. The adsorbed cation isotope effects in mineral–water interface were also examined in greenhouse experiments by Oerter et al. (2014). However, if soil water with depleted $\delta^{18}O$ values was taken up by roots, stem water should be depleted in both isotopes but not only in δ^2H (Barbeta et al., 2019). The stem $\delta^{18}O$ matched those of source water during the growing season of riparian trees and no $\delta^{18}O$ offset was observed in our study (Fig.5). Lin and Sternberg (1993) and Ellsworth and Williams (2007) reported that passage of water through symplastc pathway led to δ^2H fractionation in soil-root interface, but no $\delta^{18}O$ fractionation was observed during root water uptake, transfer and transport within the plant (Zhao et al., 2016). And a few laboratory experiments confirmed this finding (Vargas et al., 2017; Barbeta et al., 2020). Quite a few studies presented notable isotopic offsets for δ^2H rather than for $\delta^{18}O$ (Zhao et al., 2016; Evaristo et al., 2017; Barbeta et al., 2020). It is mainly due to that the reversible diffusion of water through the ultrafiltration membrance from the external medium to the root xylem discriminates against ^2H about 10 times more than ^{18}O during water uptake (Lin and Sternberg, 1993; Vargas et al., 2017). Nevertheless, the bias of $\delta^{18}O$ and corresponding reasons need further investigations.

4.2. Correction of δ^2H offset for identifications of plant water sources

By means of comparing AIC, BIC and RMSE during the observation period at the three sites, the MixSIAR model outputs with uncorrected δ^2H displayed higher AIC, BIC and RMSE values than those with corrected δ^{2}H (Figs. 6 and 7). This indicated that δ^{2}H offsets in stem water greatly affected plant water source contributions estimated using either single or dual-isotopes method. Generally, δ^{2}H offsets lead to underestimation of proportional contributions of deep water sources using uncorrected δ^{2}H (Evaristo et al., 2017; Barbeta et al., 2019). Barbeta et al. (2019) found that dual-isotopes approach with SWL-corrected δ^{2}H estimated 1.5 times of the groundwater contribution to stem water than dual-isotopes method with uncorrected δ^{2}H. Our study showed that dual-isotopes method with uncorrected δ^{2}H underestimated groundwater contribution by 56.3% at shallow WTD sites compared to dual-isotopes method with corrected δ^{2}H (Fig. 7). Moreover, soil water contribution in the 0–30 cm layer was underestimated by 30.4% at deep WTD site where groundwater could not be used by plants (Fig. 7). It was evident that the effects of δ^{2}H offsets on quantifying plant water sources were remarkably different among the three sites with various WTDs. Identifying plant water sources should primarily check δ^{2}H offsets especially under the conditions of high SSC and variable WTD fluctuations.

The MixSIAR model outputs using single δ^{18}O displayed lower AIC, BIC and RMSE values than those using dual-isotopes with uncorrected δ^{2}H (Table 3). This suggested that single δ^{18}O performed better than dual-isotopes method with uncorrected δ^{2}H in the attribution of plant water sources when there were notable δ^{2}H offsets of stem water from its potential sources (Goebel et al., 2015; Evaristo et al., 2017; Vargas et al., 2017; Barbeta et al., 2019). However, the MixSIAR model outputs estimated using single δ^{18}O were greatly different with those estimated using dual-isotopes with PWL-corrected δ^{2}H method on several sampling campaigns especially at sites B and C (Fig. 7 and Table S1). The differences would be enlarged with the increase of δ^{2}H offsets as indicated by Barbeta et al.(2019). It was evident that the single δ^{18}O method showed larger uncertainties (RMSE of 7.0%) for plant source water identifications over the observation period than the dual-isotopes with PWL-corrected δ^{2}H method (RMSE of 4.8%). Moreover, the single $\delta^{18}O$ method could lead to erroneous interpretations when root water uptake took place simultaneously from several zones, while dual-isotopes method might provide information that was not apparent in the single isotope method (Evaristo et al., 2017).

Furthermore, the source contributions estimated using dual-isotopes with PWL-corrected $\delta^{2}H$ method had closer correlations with the environmental variables indicating by lower AIC and BIC values (Table 3). That is, when the isotopic offsets were corrected and the isotopes in stem water did not deviated from their corresponding water sources, the MixSIAR model with dual isotopes was more accurate to identify water sources than that with single $\delta^{18}O$ isotope. Parnell et al. (2010) also reported that increasing the number of isotopes without $\delta^{2}H$ offsets could improve the predictive accuracy of the Bayesian model, when the number of sources (e.g., five water sources for trees in this study) were more than that of tracer isotopes. Therefore, it is essential to propose a correction method to correct the $\delta^{2}H$ offsets rather than just use $\delta^{18}O$ for plant water source identifications.

The MixSIAR model outputs estimated using dual-isotopes with PWL-corrected $\delta^{2}H$ method displayed lower AIC, BIC, and RMSE values than those using dual-isotopes with SWL-corrected $\delta^{2}H$ method (Table 3). It suggested that dual-isotopes method with PWL-corrected $\delta^{2}H$ performed better in plant water source estimations than that with SWL-corrected $\delta^{2}H$. The reason was probably due to that groundwater was a crucial and independent water source for *S. babylonica* growing in areas with shallow WTD. Low precipitation and shallow groundwater with abundant dissolved oxygen and nutrients during the growing season of *S. babylonica* could stimulate deep roots to tap into capillary fringe or even water tables to take up groundwater directly to meet the water requirement (Yu et al., 2017). Therefore, both groundwater and soil water should be in consideration of correcting stem water $\delta^{2}H$ offsets especially for phreatophytes in shallow WTD areas. The PWL correction method was more accurate and avoided an underestimation of groundwater contribution (mean of 5.0 %) in comparison to the SWL correction method.

In summary of previous and our results, we propose four distinct types of δ^2H offsets and the corresponding correction methods based on different WTDs and groundwater recharge sources for riparian trees (Fig. 8). There is one thing in common among these four types: the contributions of plant water sources estimated using δ^2H are not in agreement with those estimated using δ^{18}O due to stem water δ^2H offsets (Barbeta et al., 2020). On the one hand, when groundwater recharge mainly comes from precipitation, the isotopic composition of groundwater is generally more depleted than that of soil water at different layers (Figs. 8a and 8b). δ^2H offset characteristics depends on whether δ^{18}O in stem water is within the range of that in groundwater or not. For instance, when groundwater cannot be taken up by plants under deep WTD conditions, δ^{18}O in stem water is not within the range of that in groundwater as observed in previous studies (Brooks et al., 2010; Evaristo et al., 2017) and at site A in this study (Fig. 8a). Consequently, groundwater will not be considered to correct δ^2H offset. In case that groundwater serves as an important water source for riparian trees in shallow WTD areas (Oerter and Bowen, 2019), both groundwater and soil water should be taken into consideration to correct δ^2H offset (i.e., PWL correction method) (Fig. 8b). On the other hand, groundwater is principally recharged by seepage of surface water, which may lead to more enriched isotopic composition of groundwater compared to the depleted soil water in deep layers (Figs. 8c and 8d). If δ^{18}O in stem water is within the range of that in groundwater such as at sites B and C in our study and in other field studies (Bowling et al., 2017; Barbeta et al., 2019), groundwater should be considered to correct δ^2H offset (Fig. 8d). Otherwise, when δ^{18}O in stem water is not within the range of that in groundwater (Fig. 8c), groundwater is not included in one of the water sources to correct δ^2H offset. Therefore, the proposed PWL correction method in this study considers all potential water sources, and can be applied to quantify root water uptake under different types of δ^2H offsets of stem water.

<Figure 8>

4.3. Implications

Riparian trees perennially or seasonally depended on groundwater in the arid and semi-arid climate regions (Fan, 2015; Contreras et al., 2011; Miguez-Macho and Fan, 2012) or Mediterranean climate region (Dawson and Pate, 1996). There could be an underestimation of groundwater contributions when using uncorrected δ^2H due to δ^2H offset, which could be resolved by the developed PWL correction method in this study. When groundwater served as a crucial water source, the PWL correction method performed better than both the SWL correction method and non-correction method in identifications of plant water sources. It was evident that MixSIAR model using dual isotopes with PWL-corrected δ^2H estimated more accurate proportional contributions of groundwater.

In this study, only possible reasons for δ^2H offsets of stem water from its potential sources was deducted by indirect evidences. The mechanisms of δ^2H offsets requires further investigation by collecting different plant water pools from roots, xylem sap as well as stem tissues under various soil texture and water table conditions. The potential water sources might not be confined to soil water and groundwater in some regions. They also included other sources such as rock moisture, fog water, and dew water (Wang et al., 2017a; Wang et al., 2019b). Only when all potential water sources were considered to fit the correction line, the MixSIAR model with PWL-corrected input data could obtain more accurate estimations of plant water sources contributions. The PWL correction method was evaluated for determining riparian tree water sources only considering soil water and groundwater sources in this study. It requires further validation using more cases in consideration of other water sources including rock moisture, fog water and dew water. The PWL correction method provides insights into determining accurate root water uptake patterns even if δ^2H offset exists. It further contributes to understanding the relationship between plants and water such as partitioning evapotranspiration fluxes into transpiration and evaporation (Wang et al., 2010), water competition among different plant species (Wang et al., 2017b), species' abilities to respond to variable hydrological conditions (Wu et al., 2019b), or even the parameterization of ecohydrological models at both plot and catchment scales (Miller et al., 2012; Beyer et al., 2016; Sprenger et al., 2018).

5. Conclusions

In this study, the PWL correction method was proposed to correct the δ^2H offsets of stem water from its potential water sources. The MixSIAR model coupled with dual stable isotopes (δ^2H and $\delta^{18}O$) were used to determine seasonal variations in water uptake patterns of riparian trees (*S. babylonica*) at three sites in 2019 along the Jian and Chaobai River in Beijing, China. When using dual-isotopes method with δ^2H in stem water corrected by the PWL, the average contributions of soil water in the 0−30, 30−80, 80−150, 150−300 cm layers and groundwater were 22.4%, 18.3%, 14.1%, 16.7% and 28.5%, respectively. Riparian trees mainly used soil water below 150 cm depth on May 5, June 14, July 26, and August 15 with contributions greater than 54.6%, then the main root water uptake depth returned to the 0−150 cm layer on September 26 and November 5 with contributions more than 60.5%. Different types of input data led to considerable differences in the contributions of soil water in the 0−30 cm layer (9.9−57.6%) and water sources below the depth of 80 cm (29.0−76.4%) especially when δ^2H offset was pronounced. The MixSIAR model with dual-isotopes method was more accurate to identify plant water sources than that with single-isotope method. The best performance of PWL correction method was underlined compared to SWL correction and non-correction methods when groundwater was accessible for plants. Furthermore, four distinct types of δ^2H offsets in riparian zone and their correspondingly suitable correction methods have been summarized. This study provides crucial insights into exploring accurate root water uptake patterns to account for δ^2H offset of stem water.

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Figure captions

Fig. 1. The illustration for δ^2H offsets of the stem water from its potential water sources that derived from soil water line (SWL) and potential water source line (PWL). The δ^2H offsets of the stem water enclosed by a yellow square are corrected by SW-excess (Y1−Y2) and PW-excess (Y1−Y3), respectively.

Fig. 2. Schematic diagram for the the study area and the three sampling sites (A, B, and C) , and the pictures of experimental plots at site C.

Fig. 3. Changes of (a) daily precipitation and daily vapor pressure deficit (VPD) in the study area, (b) water table depth (WTD) at sites A, B, and C during the observation period in 2019.

Fig. 4. The SWC in different soil layers at sites (a) A, (b) B, and (c) C during the observation period in 2019. The box lines represent mean and standard deviation values (SD), whiskers indicate maximum and minimum values, and black diamonds are outliers.

Fig. 5. Dual-isotopes (δ^2H and δ^{18}O) plots of stem water of the riparian trees and their potential water sources (soil water in different layers, precipitation, groundwater, and river water) at sites (a) A, (b) B, and (c) C on six sampling campaigns during the observation period. The significant levels of all SWL and PWL are less than 0.001 ($p < 0.001$).

Fig. 6. Seasonal variations in (a) the PW-excess and (b) SW-excess of riparian trees at sites A, B, and C in 2019. The PW-excess value is as the same as the SW-excess value at site A. The box lines represent means and standard deviations (SD), whiskers indicate maximum and minimum values, and black diamonds are outliers.

Fig. 7. Seasonal water uptake patterns for riparian trees at three representative sites A, B, and C estimated via the MixSIAR model incorporating with (a) uncorrected δ^2H and δ^{18}O, (b) uncorrected δ^2H, (c) δ^{18}O, (d) δ^2H corrected by SWL and δ^{18}O, (e) δ^2H corrected

by SWL, (f) δ^2H corrected by PWL and $\delta^{18}O$, and (g) δ^2H corrected by PWL. The MixSIAR model outputs using PWL correction method is same with those using SWL correction method at site A.

Fig. 8. Different types of δ^2H offset between stem water and its potential water sources shown in dual-isotopes (δ^2H and $\delta^{18}O$) plots. The potential water sources in the shaded area represent main water sources of the enclosed stem water sample by the red square. The red star represents the δ^2H-corrected stem water which derives from the enclosed stem water by the red square.

Table
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Table 1. Soil particle size and soil texture at different depths at the three sites.

Site	Depth (cm)	Soil particle size (%)			Soil texture
		Clay	Silt	Sand	
Site A	0–30	5.8	46.8	47.4	Clay loam
	30–80	8.5	70.3	21.2	Clay loam
	80–150	7.5	62.0	30.5	Clay loam
	150–300	6.8	56.5	34.5	Clay loam
Site B	0–30	1.3	17.3	81.4	Sandy loam
	30–80	1.2	17.8	81.0	Sandy loam
	80–150	1.6	21.1	77.4	Sandy loam
	150–300	0.9	16.2	82.9	Sandy loam
Site C	0–30	0.6	14.9	84.5	Sand
	30–80	0.1	7.9	92.0	Sand
	80–150	0.1	6.9	93.0	Sand
	150–300	0.1	6.1	93.8	Sand

Table 2. Proportions of potential water source contributions to riparian trees estimated by MixSIAR model incorporating with seven types of isotope data.

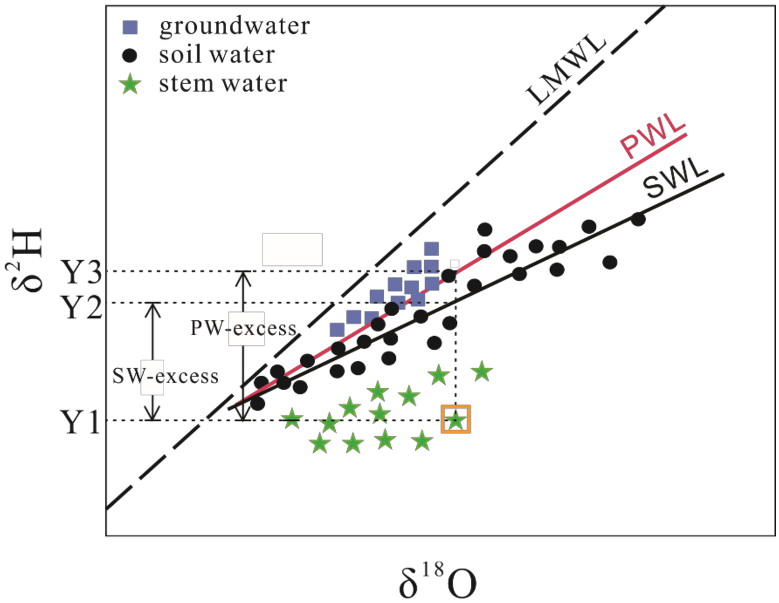
Input data modes	Proportional contributions (%)									
	0-30 cm		30-80 cm		80-150 cm		150-300 cm		Groundwater	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
$\delta^2H + \delta^{18}O$	27.6	13.2	30.3	9.2	16.7	2.8	12.6	2.8	12.9	4.6
δ^2H	16.7	8.9	31.1	13.6	22.4	7.1	17.0	5.5	12.9	4.1
$\delta^{18}O$	22.3	4.9	20.2	7.2	13.7	5.5	16.4	4.5	27.4	7.7
δ^2H (corrected by SWL) + $\delta^{18}O$	21.4	6.8	19.7	4.4	16.5	7.5	17.9	5.5	24.5	7.5
δ^2H (corrected by SWL)	17.4	7.5	18.8	1.8	18.9	6.2	21.1	4.8	23.7	3.1
δ^2H (corrected by PWL) + $\delta^{18}O$	22.4	5.0	18.3	6.1	14.1	6.5	15.7	5.1	29.5	7.4
δ^2H (corrected by PWL）	19.3	9.0	15.5	4.2	14.9	4.4	19.7	6.0	30.6	6.6

Table 3. Performances of the seven types of isotope data to estimate water source contributions of riparian trees by the MixSIAR model.

Input data modes	AIC	BIC	RMSE (%)
$\delta^2H + \delta^{18}O$	101.7	99.5	9.5
δ^2H	101.7	99.5	12.4
$\delta^{18}O$	94.9	92.6	7.0
δ^2H (corrected by SWL) + $\delta^{18}O$	97.6	95.4	5.3
δ^2H (corrected by SWL)	96.2	94.0	5.5
δ^2H (corrected by PWL) + $\delta^{18}O$	94.1	91.9	4.8
δ^2H (corrected by PWL）	98.0	95.8	8.1

Note: The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values represent the correlation between water source contributions to stem water and environment variables. The Root Mean Square Error (RMSE) values represent the deviations of the source contributions estimated by one certain input data from the average values of all types of input data.

Figure



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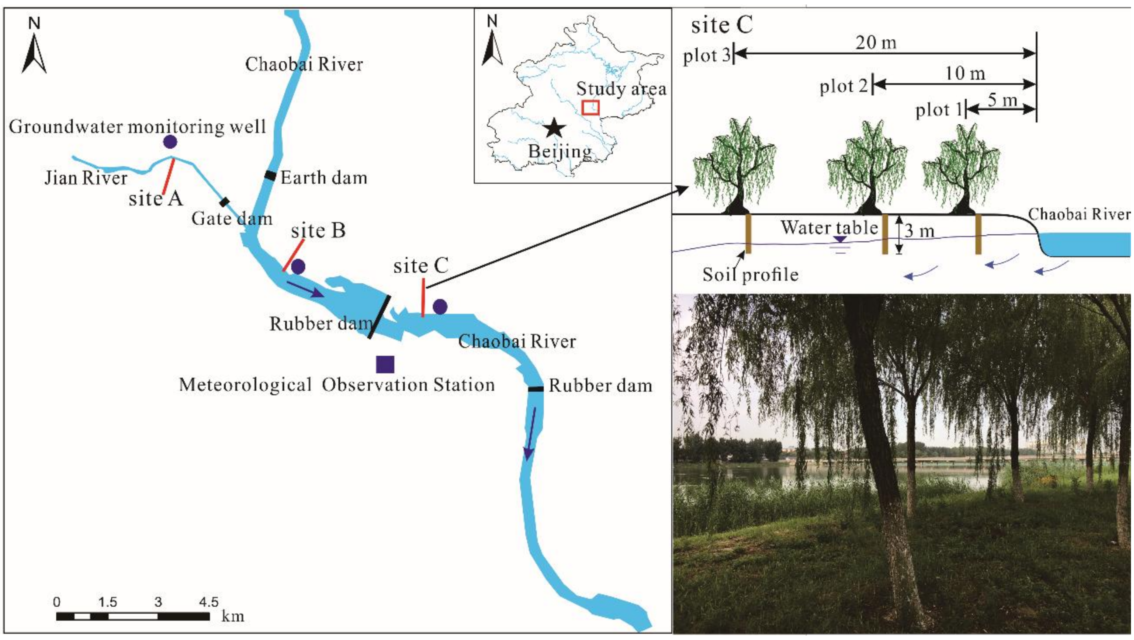

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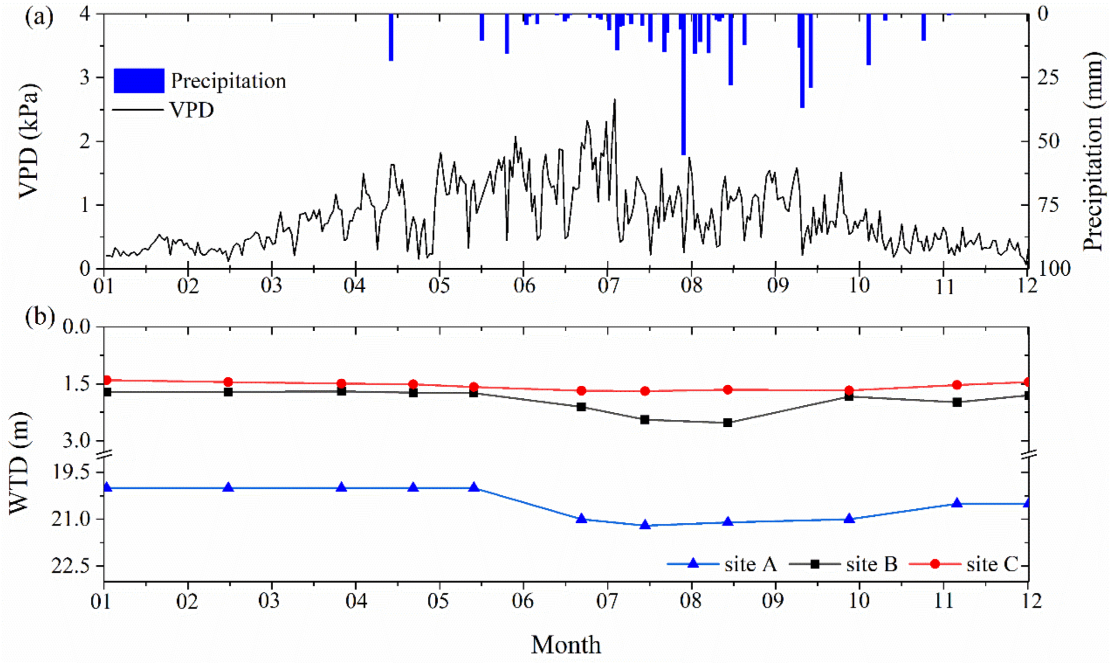

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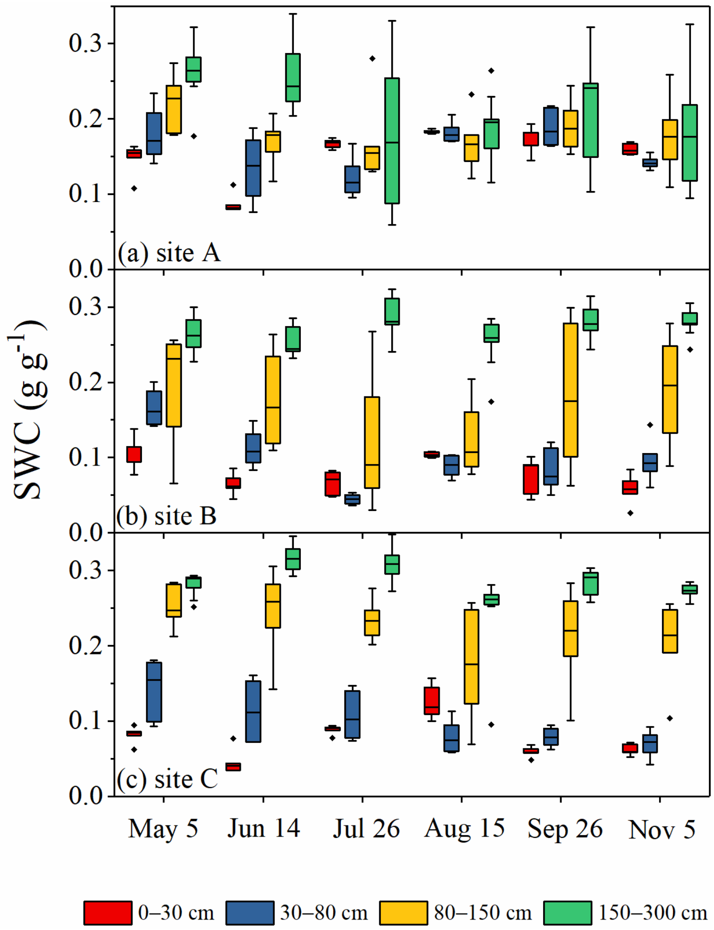

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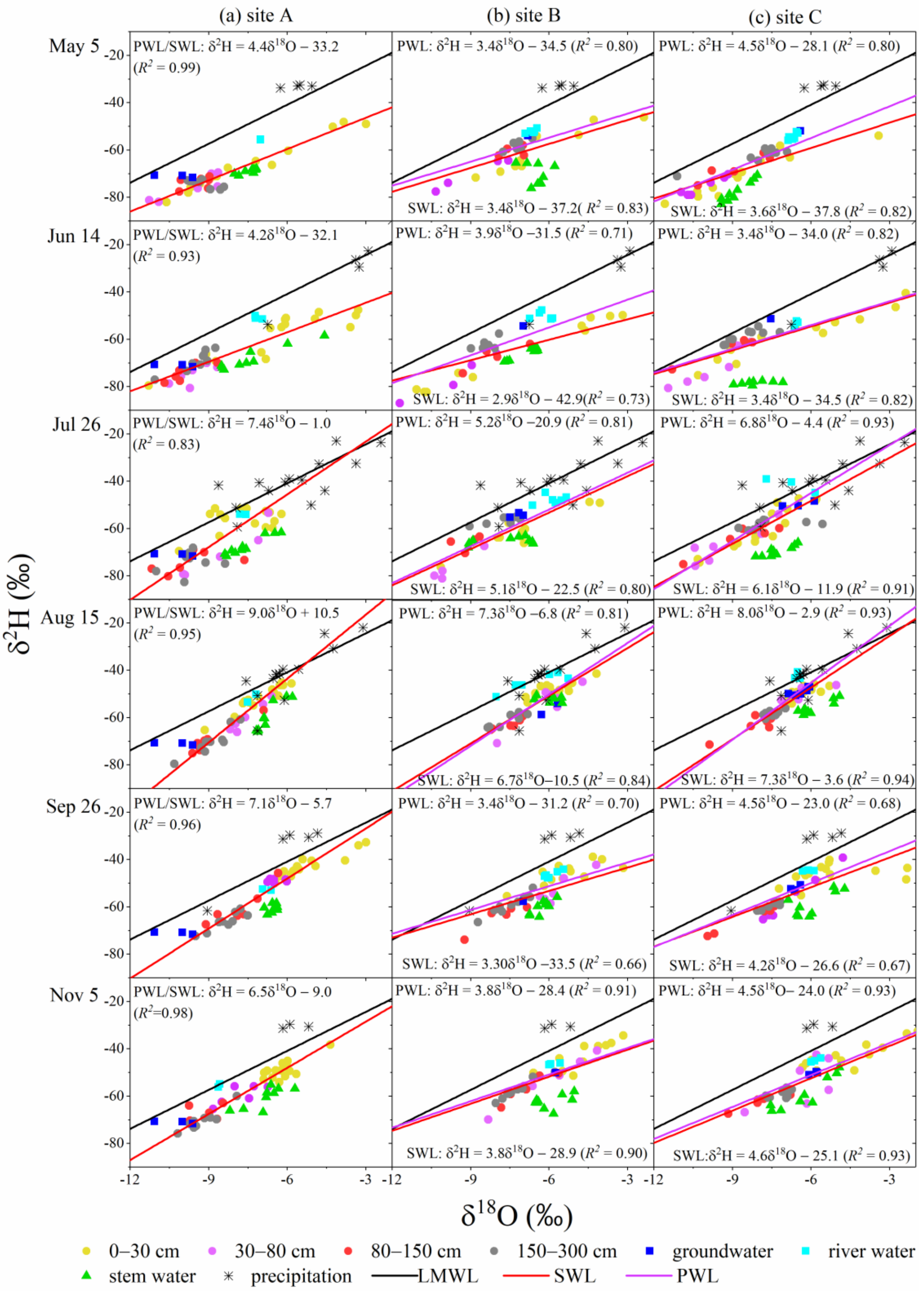

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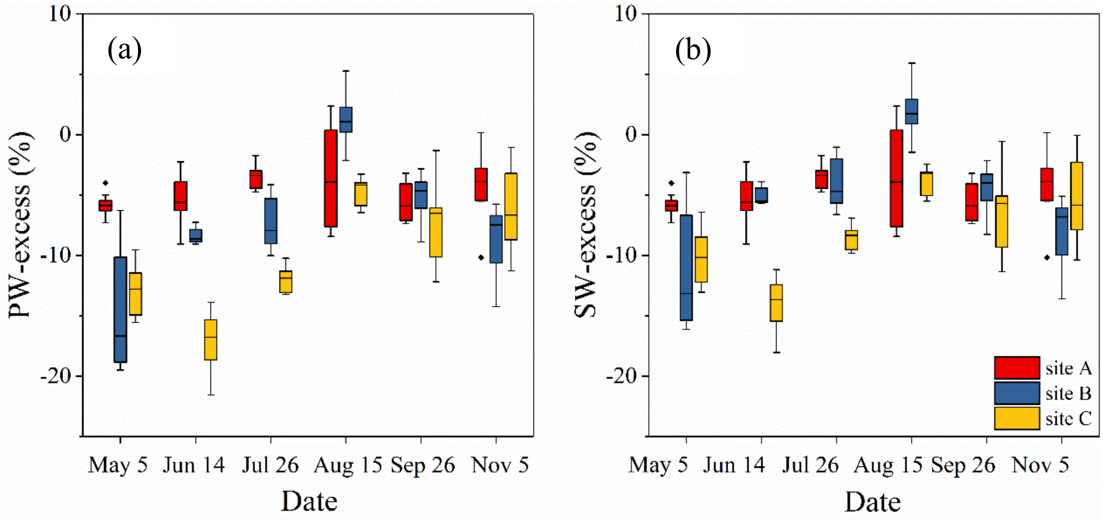

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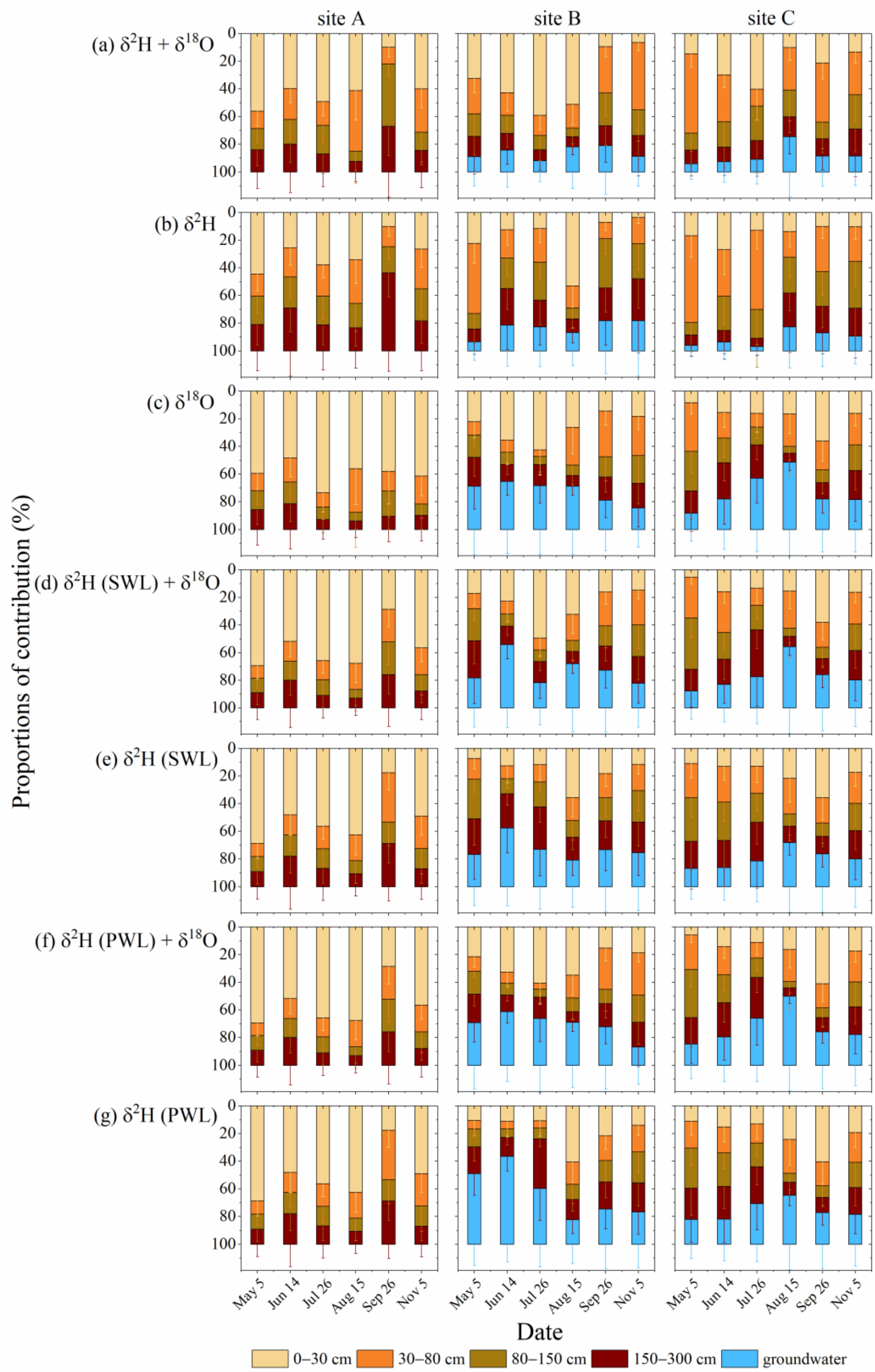

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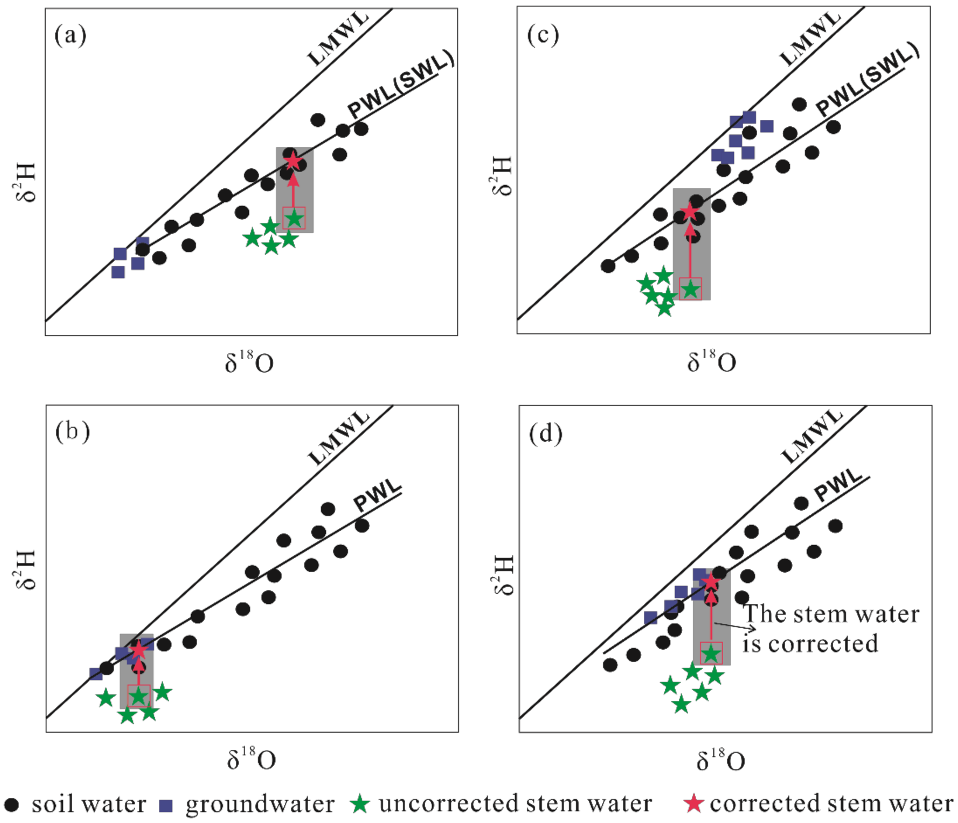

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