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The patterns and implications of diurnal variations in the d-excess of plant water, shallow soil water and air moisture

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Abstract. Deuterium excess (d-excess) of air moisture is traditionally considered a conservative tracer of oceanic evaporation conditions. Recent studies challenge this view and emphasize the importance of vegetation activity in controlling the dynamics of air moisture d-excess. However, direct field observations supporting the role of vegetation in d-excess variations are not well documented. In this study, we quantified the d-excess of air moisture, shallow soil water (5 and 10 cm) and plant water (leaf, root and xylem) of multiple dominant species at hourly intervals during three extensive field campaigns at two climatically different locations within the Heihe River basin, northwestern China. The ecosystems at the two locations range from forest to desert. The results showed that with the increase in temperature (T) and the decrease in relative humidity (RH), the δD–δ^{18}O regression lines of leaf water, xylem water and shallow soil water deviated gradually from their corresponding local meteoric water line. There were significant differences in d-excess values between different water pools at all the study sites. The most positive d-excess values were found in air moisture (9.3 ‰) and the most negative d-excess values were found in leaf water (−85.6 ‰). The d-excess values of air moisture (d_{moisture}) and leaf water (d_{leaf}) during the sunny days, and shallow soil water (d_{soil}) during the first sunny day after a rain event, showed strong diurnal patterns. There were significantly positive relationships between d_{leaf} and RH and negative relationships between d_{moisture} and RH. The correlations of d_{leaf} and d_{moisture} with T were opposite to their relationships with RH. In addition, we found opposite diurnal variations for d_{leaf} and d_{moisture} during the sunny days, and for d_{soil} and d_{moisture} during the first sunny day after the rain event. The steady-state Craig–Gordon model captured the diurnal variations in d_{leaf}, with small discrepancies in the magnitude. Overall, this study provides a comprehensive and high-resolution data set of d-excess of air moisture, leaf, root, xylem and soil water. Our results provide direct evidence that d_{moisture} of the surface air at continental locations can be significantly altered by local processes, especially plant transpiration during sunny days. The influence of shallow soil water on d_{moisture} is generally much smaller compared with that of plant transpiration, but the influence could be large on a sunny day right after rainfall events.

1 Introduction

Measurements of water isotopic compositions (e.g., δD, δ^{18}O) provide insights into the study of hydrologic cycles, ecological processes, and palaeoclimates across multiple temporal and spatial scales (e.g., Brunel et al., 1992; Gat, 1996; Dawson et al., 2002; Newman et al., 2010; Wang et al., 2010, 2013, 2014; Zhang et al., 2011; Good et al., 2012). Plant uptake does not fractionate source water (White et al., 1985), δD or δ^{18}O, and therefore can be used to track a plant water source (Ehleringer and Dawson, 1992), to investigate relative rooting depth (Jackson et al., 1999), and to identify hydraulic redistribution (Dawson, 1993). Water isotopes can also be used to trace catchment water movements (Brooks et al., 2010), the geographic origin of water vapor (Clark and Fritz, 1997), basin-level water recycling (Salati et al., 1979), and to reconstruct past environmental parameters such as ambient temperature (T) and relative humidity (RH) (e.g., Helliker and Richter, 2008). The isotopic compositions of water from different areas are affected by specific meteorological processes, which provide a characteristic fingerprint of their origin (Clark and Fritz, 1997). Much work has focused on isotopic compositions of surface water (Zhao et al., 2011b), groundwater (Zhao et al., 2012) and precipitation (Dalai et al., 2002; Karim and Veizer, 2002; Zhao et al., 2011b; Soderberg et al., 2013). However, fewer investigations were conducted to measure simultaneously δD and δ^{18}O of leaf water, xylem water, shallow soil water and air moisture, especially on the diurnal variations in these pools at ecosystem scale.

Deuterium excess (d-excess) is defined as d-excess $= \delta$D–$8.0 \times \delta^{18}$O (Dansgaard, 1964). Points that fall on the global meteoric water line (GMWL) have a constant d-excess of 10.0 ‰. This is because rainout isotopic fractionation is considered an equilibrium process, which affects the position of the data points on the GMWL, but which does not affect the intercept – d-excess. Since the effect of equilibrium Rayleigh condensation processes roughly follows the GMWL slope of 8, variations in d-excess can provide information about the environmental conditions (e.g., RH and T) during non-equilibrium processes in oceanic moisture source regions. In other words, d-excess is considered a conservative tracer of oceanic evaporation conditions, assuming there are no contributions from surface evapotranspiration as the air mass travels over land (Welp et al., 2012). Therefore, d-excess is used to identify the location of a moisture source when there are no contributions from surface evapotranspiration (Uemura et al., 2008). Transpiration does not change source water d-excess, since transpiration does not fractionate source water. Evaporation, however, usually results in a higher d-excess value (Gat et al., 1994). d-excess has been used to estimate evaporation in previous studies. For example, d-excess was used to quantify sub-cloud evaporation in Alpine regions (Froehlich et al., 2008) and to estimate the contribution of evaporation from the Great Lakes to the continental atmosphere (Gat et al., 1994).

By using a meta-analysis approach to synthesize d-excess measurements from multiple sites, Welp et al. (2012) showed that the d-excess value of surface atmospheric vapor can be significantly altered by local processes and that it is not a conserved tracer of humidity from the marine moisture source region, as previously assumed. In addition, modeling simulations also showed that plant transpiration plays an important role in diurnal d-excess variations (Welp et al., 2012), which contradicts the conventional understanding. Based on isotopic observations from a US Pacific Northwest temperate forest and a modeling exercise, Lai and Ehleringer (2011) concluded that atmospheric entrainment appears to drive the isotopic variation in water vapor in the early morning when the convective boundary layer develops rapidly, while evapotranspiration becomes more important in mid-afternoon as a primary moisture source of water vapor in the studied forest. These authors therefore also cast some doubts on whether continental water vapor d-excess can be used as a conserved tracer of environmental conditions during evaporation at the moisture source. Despite this new understanding of biological and environmental controls on d-excess variations, field observations of the role of the direct vegetation effect on diurnal d-excess variations are not readily seen in the literature. In addition, Merlivat and Jouzel (1979), one of the few who theoretically calculated the quantitative relationship between the d-excess of evaporating vapor with T and RH, predicted that d-excess is affected by both T and RH, and the d-excess of evaporating vapor increases with T (0.35 ‰ °C^{-1}), but decreases with RH (-0.43 ‰ %$^{-1}$) (Merlivat and Jouzel, 1979). Field testing of such a theoretical relationship is lacking. The quantitative relationship will enhance our prediction of climatic and environmental change impact (e.g., changes in T, RH, rainfall and location) on water cycles. Furthermore, it is unclear whether a consistent d-excess–RH relationship, similar to the d-excess–RH relationship of ocean evaporation, exists in evapotranspiration. Evapotranspiration from the earth's surface is a key process in the hydrological cycle connecting the earth's surface and the atmosphere. Therefore, it is essential to study the evapotranspiration process and its link to the atmospheric circulation in order to understand the feedbacks between the earth's surface and the atmosphere better (Aemisegger et al., 2013).

In this study, we quantified the d-excess dynamics of air moisture, shallow soil water (5 and 10 cm), and leaf and xylem water of multiple dominant species at hourly intervals during three extensive field campaigns at two climatically different locations in the Heihe River basin, China. We aim to provide a field-based fine-resolution d-excess record and to explore the underlying mechanisms. The questions we addressed in this study are the following: (1) what are the diurnal patterns of d-excess in air moisture, leaves, roots, xylem and shallow soil water under different climatic and meteorological conditions? (2) What are the mechanisms of the observed patterns and their controlling factors? (3) How well do the widely used steady-state models capture the leaf d-excess dynamics?

2 Materials and methods

2.1 Sampling sites

The field sampling took place at two locations (Dayekou and Ejin) with distinct climatic conditions within the Heihe River basin (HRB), northwestern China (Fig. 1). The temperature is lowest in January, and is highest in July in both Dayekou (Zhao et al., 2011a) and Ejin. Dayekou is located

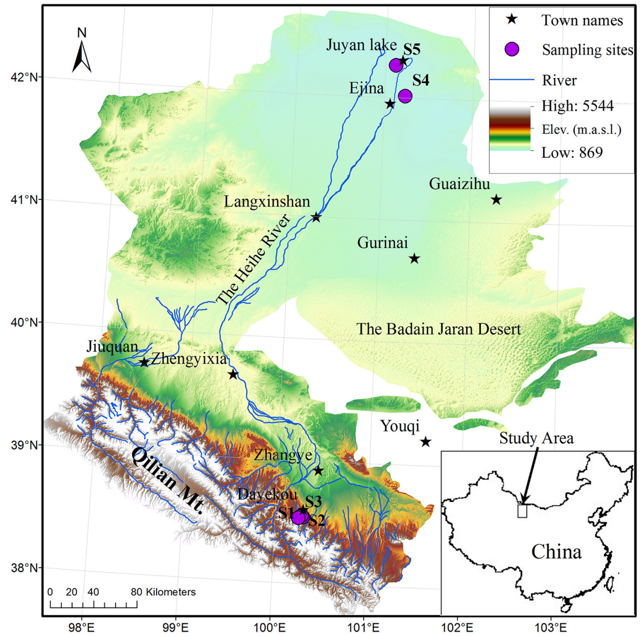

Figure 1. Locations of the sampling sites in the Heihe River basin. Note: the information about sampling locations, altitude, period of sampling and climatic conditions is listed in Table 1.

in the upper reaches (Fig. 1). The mean annual temperature of Dayekou is about 0.7 °C, with a mean January temperature of −12.9 °C and a mean July temperature of 12.2 °C. The mean annual precipitation is 369.2 mm, with over 71 % of the rainfall occurring between June and September, and the rainfall in July is the highest. Ejin is located in the lower reaches (Fig. 1). The mean annual temperature of Ejin is 8.8 °C, with a mean January temperature of −11.3 °C and a mean July temperature of 26.8 °C. The mean annual precipitation from 1960 to 2007 was 35.0 mm year^{-1}, with 75 % of the rainfall occurring between June and September. With a strong potential evapotranspiration of 3700 mm (Gong et al., 2002), Ejin is considered one of the driest regions in China. At Dayekou, three sites were selected, with two sites (S1-Sep/S1-Jun and S2-Jun) in the Pailugou valley and the other (S3-Aug) in the Guantan valley. The site names were assigned based on a combination of location and sampling time. S1 (100°18′ E, 38°33′ N, 2900 m) was dominated by tree species: Qinghai spruce (Q.S.), shrub species *Potentilla fruticosa* (P.F.), and grass species *Polygonum viviparum* (P.V.). S2 (100°17′ E, 38°33′ N, 2700 m) was dominated by tree species Q.S. and grass species *Stipa capillata* (S.C.). S3 (100°15′ E, 38°32′ N, 2800 m) was dominated by tree species Q.S. Two sites were selected at Ejin: one is in the riparian forest (S4-Aug: 101°14′ E, 42°01′ N, 930 m) with the dominant tree species *Populus euphratica* (P.E.) and the shrub species *Sophora alopecuroides* (S.A.); the other is in the Gobi (S5-Aug: 101°07′ E, 42°16′ N, 906 m), with the main shrub species *Reaumuria soongorica* (R.S.) (Table 1).

2.2 Plant and soil sample collections

Three extensive field samplings were conducted in August 2009 and in June and September 2011 in the upper and lower reaches of the HRB (Table 1). In the upper reaches, at S1-Jun, samples were taken from 06:00 LT (unless otherwise stated, all times hereafter are in local time), 23 June to 18:00, 25 June 2011 at 1-hour intervals for leaves and stems of Q.S., 5 and 10 cm soil as well as atmospheric vapor near the ground (about 20 cm above the ground) and at the canopy. Leaves and stems of P.F. as well as leaves and roots of P.V. were taken from the same period at 2-hour intervals. All these samples were referred to as S1-Jun. At S1-Sep, samples were taken from 08:00, 6 September to 17:00, 8 September 2011 at 1-hour intervals for leaves and stems of Q.S., 5 and 10 cm soil and atmospheric vapor near the ground and at the canopy. Leaves and stems of P.F. as well as leaves and roots of P.V. were taken from the same period at 2-hour intervals. At S2-Jun, leaves and stems of Q.S., 5 and 10 cm soil and atmospheric vapor near the ground and at the canopy were sampled from 06:00, 27 June to 18:00, 28 June 2011 at 1-hour intervals, while leaves and roots of S.C. were taken from 06:00, 27 June to 18:00, 28 June 2011 at 2-hour intervals. At S3-Aug, it rained twice during the sampling period (from 17:00, 31 July to 04:00, 1 August and from 10:40 to 20:00, 2 August 2009). Leaves and stems of Q.S. as well as 5 and 10 cm soil samples were taken from 06:00, 1 August to 18:00, 2 August and from 06:00 to 18:00, 3 August 2009 at 2-hour intervals. The atmospheric vapor at the canopy was collected from 06:00, 2 August to 18:00, 3 August 2009 at 2-hour intervals (Table 1).

In the lower reaches of the HRB, at S4-Aug, a leaf and stem of P.E. and a leaf of S.A., 10 cm soil and atmospheric vapor at the canopy were taken from 06:00, 6 August to 22:00, 9 August 2009 at 2-hour intervals. At S5-Aug, a leaf and stem of R.S., 10 cm soil and atmospheric vapor at the canopy were taken from 18:00, 10 August to 18:00, 12 August 2009 at 2-hour intervals. When samples were taken during rainy days and mornings, napkins were used to wipe off water from the leaf and stem surfaces (Table 1).

For the soil, leaf and stem samples, samples from two 8 mL bottles were used to extract water and measure δD and δ^{18}O. All samples were frozen in the Linze and Ejin field stations right after sampling and then transferred back to the laboratory for water extraction. Water samples were extracted from leaves, stems, roots and soil by a cryogenic vacuum distillation line (Zhao et al., 2011b). The extracted water was frozen in a collection tube.

2.3 Air moisture collection

We used a method similar to Wang and Yakir (2000) for short-term sampling of ambient air moisture at different locations, such as Qinghai spruce forest (S1-Sep, S1-Jun, S2-Jun and S3-Aug) in the upper reaches, and riparian forest

Table 1. The vegetation types, sampling dates and time, and sampling types at the sampling sites in the Heihe River basin.

Study region	Ecosystem type	Altitude (m)	Location ID	Sampling time and interval	Meteorological conditions	Sampling types
The upper reaches	Forest	2900 m	S1-Sep: Pailugou	6–8 September 2011 1 h interval	The cloudy day: 6 September 2011 The sunny day: 7 and 8 September 2011	Qinghai spruce – leaf and stem 5 cm soil water 10 cm soil water Atmospheric vapor near the ground Atmospheric vapor at the canopy
				6–8 September 2011 2 h interval		*Potentilla fruticosa* – leaf and stem *Polygonum viviparum* – leaf and root
	Forest	2900 m	S1-Jun: Pailugou	23–25 June 2011 1 h interval	The sunny day: 23 June 2011 The drizzly day: from 09:00 to 20:00 on 24 June 2011 The cloudy day: 25 June 2011	Qinghai spruce – leaf and stem 5 cm soil water 10 cm soil water Atmospheric vapor near the ground Atmospheric vapor at the canopy
				23–25 June 2011 2 h interval		*Potentilla fruticosa* – leaf and stem *Polygonum viviparum* – leaf and root
	Forest	2700 m	S2-Jun: Pailugou	27–28 June 011 1 h interval 27–28 June 2011 2 h interval	The sunny day: 27 June 2011 The cloudy day: 28 June 2011	Qinghai spruce – leaf and stem 5 cm soil water 10 cm soil water Atmospheric vapor near the ground Atmospheric vapor at the canopy *Stipa capillata* – leaf and root
	Forest	2800 m	S3-Aug: Guantan	31 July, 1–2 August 2009 2 h interval	Rain time: From 17:00, 31 July to 04:00, 1 August From 10:40 to 22:00, 2 August 2009 The sunny day: 1 August	Qinghai spruce – leaf and stem 5 cm soil water 10 cm soil water Atmospheric vapor at the canopy
The lower reaches	Riparian forest	930 m	S4-Aug: Qidaoqiao	6–9 August 2009 2 h interval	The sunny day	*Populus euphratica* – leaf and stem *Sophora alopecuroides* – leaf 10 cm soil water Atmospheric vapor at the canopy
	Gobi	906 m	S5-Aug: Gobi	10–12 August 2009 2 h interval	The sunny day	*Reaumuria soongorica* – leaf and stem 10 cm soil water Atmospheric vapor at the canopy

(S4-Aug) and the Gobi (S5-Aug) in the lower reaches. At S1-Sep, S1-Jun and S2-Jun, the samples of air moisture were collected within a canopy and near the ground (about 20 cm above the ground). At S3-Aug, S4-Aug and S5-Aug, the samples of air moisture were collected within a canopy (Fig. 1 and Table 1). Air was sucked by a small diaphragm pump through low-adsorption plastic tubes and a small cryogenic trap at −80 °C at a rate of about 250 mL min^{-1} for about 50 min. Pump and traps were located on the ground downwind of the sampling site, and all the tubing was flushed with sample air before the actual trapping. After sampling, liquid water was transferred from traps to 2 mL glass bottles and transported to the laboratory for δ^{18}O and δD analysis.

2.4 Isotope analysis

The δ^{18}O and δD values of the water samples were measured using a Euro EA3000 element analyzer coupled to an Isoprime isotope ratio mass spectrometer (Isoprime Ltd, UK) at the Heihe Key Laboratory of Ecohydrology and River Basin Science, Cold and Arid Regions Environmental and Engineering Research Institute. To avoid the memory effect associated with continuous-flow methods, measurements of each sample were repeated five times, and the first values were discarded. The accuracy was better than ±1.0 ‰ for δD and ±0.2 ‰ for δ^{18}O. The δ^{18}O and δD were calibrated using two international standard materials (*V-SMOW* and *GISP* or *SLAP*) and one working standard. The δ^{18}O and δD values are expressed in ‰ on a *V-SMOW–SLAP* scale.

2.5 Meteorological measurements

During each study period, RH, T and photosynthetically available radiation (PAR) were measured due to their significant effects on soil evaporation and transpiration. At S3-Aug, T, RH and PAR were measured every 30 min with a weather station permanently installed at the station (HMP45C for measuring T and RH, LI190SB for measuring PAR) at 2, 10 and 24 m in height. At S1-Sep, S1-Jun, S2-Jun, S4-Aug and S5-Aug, RH, T and PAR were measured every 10 min with a portable weather station (Davis Vantage Pro2 portable weather station) at 2 m. Only 2 m height weather data such as T, RH and PAR were used in this study.

2.6 Modeling leaf water δ^{18}O, δD and d-excess

Leaf water isotope enrichment is conventionally described by the steady-state Craig–Gordon equation (Craig and Gordon, 1965), and non-steady-state forms have also been proposed to account for the less enriched leaf water condition predicted by the steady-state model (e.g., Cuntz et al., 2007; Farquhar et al., 2007). To test whether we could use the current understanding of leaf water enrichment to reproduce the observed d-excess variations in leaf water, we used the steady-state Craig–Gordon model to estimate leaf water δ^{18}O and δD values, and then calculated d-excess values using d-excess = δD–8.0 × δ^{18}O (Dansgaard, 1964). Only leaf water δ^{18}O, δD and d-excess values of P.E. at S5-Aug were modeled for this study, because it was sunny and had the most complete data set through that entire study period. The leaf water enrichment ($\delta_{\mathrm{l,s}}$) is calculated as

$$\delta_{\mathrm{l,s}} \approx \delta_x + \varepsilon_{\mathrm{eq}} + \varepsilon_{\mathrm{k}} + h(\delta_v - \varepsilon_{\mathrm{k}} - \delta_x), \quad (1)$$

where δ_x represents the δ^{18}O or δD values of liquid water at the evaporating front. We estimated δ_x using the isotopic composition of xylem water. δ_v comprises the δ^{18}O or δD values of the background atmospheric water vapor, α^* (> 1) is the temperature-dependent equilibrium fractionation factor between liquid and vapor, $\varepsilon_{\mathrm{eq}}$ equals $1000(1-1/\alpha^*)$, α_{k} is the kinetic fractionation associated with diffusion of water through the soil, and ε_{k} equals $1000(\alpha_{\mathrm{k}}-1)$, 1.0189 (∼ 19 ‰) for oxygen and 1.017 (∼ 17 ‰) for hydrogen in a turbulent boundary layer (Wang and Yakir, 2000). h is relative humidity normalized to the leaf temperature.

3 Results

3.1 Meteorological conditions at each site during the sampling periods

This study was conducted at the sites with dramatically different climatic conditions. The results showed that T, RH and PAR varied significantly with the meteorological conditions and locations (Fig. 2). Low RH, high T and PAR were found during the sunny days, whereas high RH, low T and PAR were found during the cloudy days at each site (Fig. 2). The RH decreased and T increased from the upper reaches to the lower reaches, except at S2-Jun, with the lowest mean RH (42.2 %) (Table 2 and Fig. 2).

3.2 Variations in δ^{18}O and δD in different water pools

Figure 3 shows the measured isotopic compositions of all the water samples in the δD–δ^{18}O plots. In general, the δD and δ^{18}O of xylem and soil water showed relatively small ranges compared to those of leaf water and air moisture (Table 3 and Fig. 3). The δD and δ^{18}O in leaf water varied from −37.6 to 44.0 ‰ and from −6.2 to 32.4 ‰, respectively, for all species. The δD and δ^{18}O of air moisture at the canopy ranged from −188.9 to −25.7 ‰ and from −24.9 to −6.0 ‰, respectively, at all the study sites. The δD and δ^{18}O of air moisture near the ground ranged from −133.0 to −40.6 ‰ and from −19.7 to −7.9 ‰, respectively, in the upper reaches. The δD and δ^{18}O in xylem water (including stem and root) varied from −72.7 to −21.4 ‰ and from −9.0 to 2.9 ‰, respectively. The δD and δ^{18}O in soil water varied from −67.4 to −6.3 ‰ and from −9.9 to 5.1 ‰, respectively (Table 3).

The air moisture had the lowest average δD and δ^{18}O at all study sites that increased with rising altitude (Table 3). The δD–δ^{18}O regression lines were followed closely by the local meteoric water lines (LMWL) (Fig. 3). The average δD and δ^{18}O of air moisture were −101.7 and −14.1 ‰ near the ground, and were −99.1 and −13.3 ‰ at the canopy, respectively, in the upper reaches. In the lower reaches, the average δD and δ^{18}O of air moisture were −116.7 and −16.2 ‰ at S4-Aug and −136.3 and −17.7 ‰ at S5-Aug, respectively.

Leaf water had the highest average δD and δ^{18}O values, leaf δD–δ^{18}O regression lines deviated highly from their corresponding LMWL, and leaf water showed the greatest variation in the observed δ^{18}O values. In addition, leaf water δD and δ^{18}O values increased with the decrease in altitude and the increase in T (Tables 2 and 3). In the upper reaches, the average δD values in the leaf water of Q.S., P.F., P.V. and S.C. were 1.9, −5.6, −2.2 and 10.4 ‰, respectively, and the average δ^{18}O values were 8.3, 3.0, 1.5 and 8.2 ‰, respectively. In the lower reaches, the average δD values in the leaf water of P.E., S.A. and R.S. were 6.2, 10.4 and 7.5 ‰, respectively, and the average δ^{18}O values were 14.6, 15.6 and 27.2 ‰, respectively.

The average δD and δ^{18}O values were −34.9 and −4.2 ‰ in 5 cm of soil water and −43.2 and −5.2 ‰ in 10 cm of soil in the upper reaches, and −34.2 and 1.4 ‰ in 10 cm of water in the lower reaches, respectively. With the increase in T and the decrease in altitude, the δD–δ^{18}O regression lines gradually deviated from their corresponding LMWL, and the variations in δ^{18}O values in xylem and soil water also increased gradually (Tables 2 and 3). There were significant differences in δD and δ^{18}O between xylem water of S.C. and 5 cm of soil water in the upper reaches. Differences were also seen in P.E. and R.S. in the lower reaches (Fig. 3 and Table 3).

3.3 Variations in d-excess in each water pool

3.3.1 The diurnal variations in d-excess in leaf and xylem water during the sunny days

Several sunny days were selected based on the meteorological record (Fig. 2). The selected periods included the following: from 06:00 to 18:00, 7 and 8 September at S1-Sep, from 06:00 to 16:00, 23 June at S1-Jun, from 06:00 to 16:00, 27 June at S2-Jun, from 06:00, 1 August to 16:00, 2 August and from 06:00 to 18:00, 3 August 2009 at S3-Aug. At S4-Aug and S5-Aug, all data were selected. The diurnal

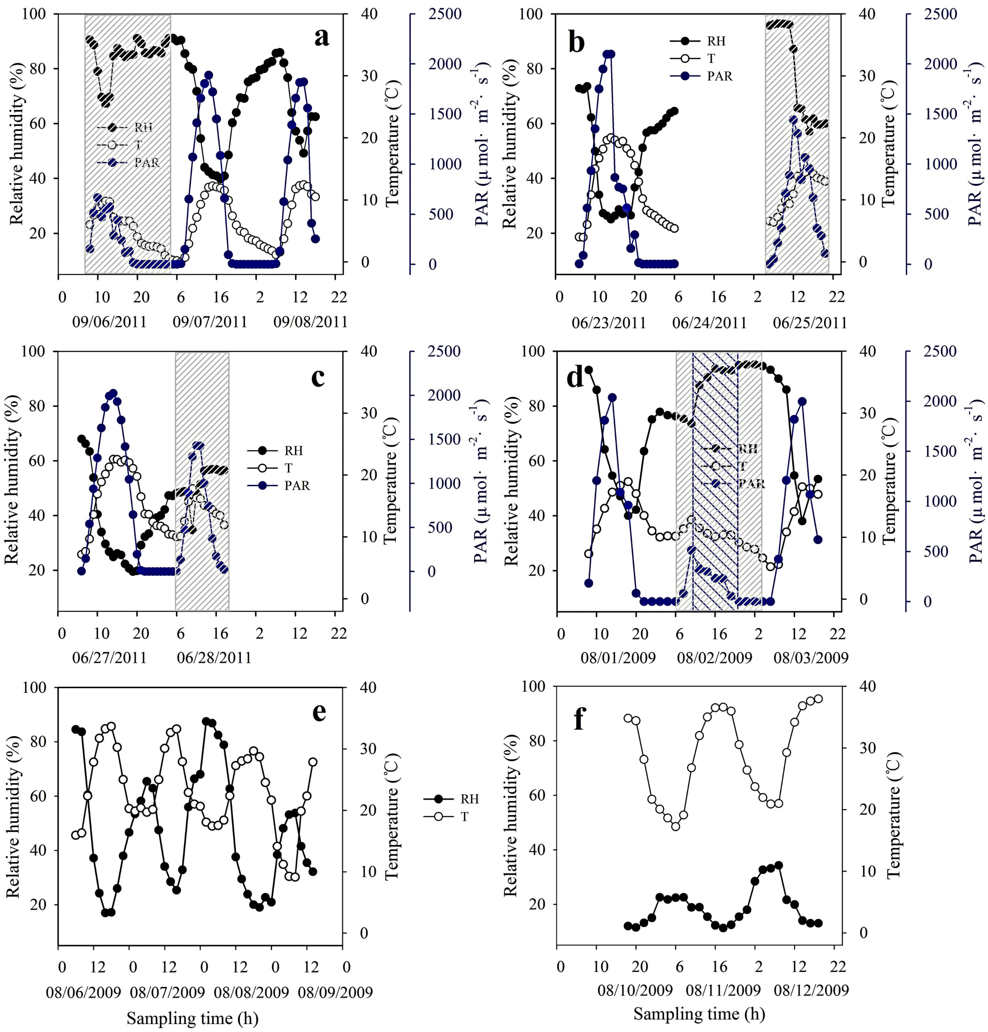

Figure 2. Comparison of hourly average relative humidity (RH), air temperature (T) and photosynthetically active radiation (PAR) during the experimental period. The dark cycles and the white cycles indicate the RH and T at each site. The grey shadow and the blue shadow (the one in panel d) indicate cloudy days and rainy days. Panels **(a)**, **(b)**, **(c)** and **(d)** refer to the Qinghai spruce forest of S1-Sep, S1-Jun, S2-Jun and S3-Aug. Panels **(e)** and **(f)** refer to S4-Aug and S5-Aug.

variations in leaf water d-excess (d_{leaf}) and xylem water d-excess (d_{xylem}) values during the sunny day were shown in Fig. 4. During the sunny days, we found clear and robust diurnal variations in d_{leaf} at all the study sites. The maximum values of d_{leaf} occurred from 06:00 to 10:00, gradually decreasing to a minimum value in the mid-afternoon (from 14:00 to 20:00), and increasing again to a maximum value from 04:00 to 08:00 on the next day (Fig. 4). In the upper reaches, the averaged d_{leaf} values of Q.S. were −64.7 ‰, and varied from 13.4 ‰ (S3-Aug) to −133.8 ‰ (S2-Jun). The d_{leaf} values of P.F. (−29.8 ‰) and P.V. (−14.3 ‰) were higher than that of S.C. (−55.4 ‰). In the lower reaches, the mean d_{leaf} value of P.E. (−110.2 ‰) and S.A. (−114.4 ‰) at S5-Aug were higher than that of R.S. (−210.4 ‰) at S4-Aug (Table 4).

The peak-to-trough amplitudes of d_{leaf} varied greatly. They were 147.2 ‰ in trees (Q.S.), 122.6 ‰ in shrubs (P.F.), and ranged from 143.1 ‰ to 52.6 ‰ in grasses (P.V. and S.C.) in the upper reaches. In the lower reaches, the peak-to-trough amplitudes of d_{leaf} were 124.4 ‰ in P.E. (tree), 96.9 ‰ in S.A. (shrub), and 80.6 ‰ in R.S. (shrub) (Table 4).

Compared to d_{leaf}, the diurnal variations in the d_{xylem} of all species were more stable, and showed no clear diurnal variations (Fig. 4). In the upper reaches, the mean $\mathrm{d}_{\text{xylem}}$ values of Q.S., P.F., P.V. and S.C. were 6.2, 0.8, 7.6 and −18.8 ‰, respectively. The averaged differences between d_{xylem} and d_{leaf} were 70.9, 30.6, 21.9 and 36.6 ‰ in Q.S., P.F., P.V. and S.C. in the upper reaches. In the lower reaches, the mean d_{xylem} values of P.E. and R.S. were −8.2 ‰ (S4-Aug) and −44.8 ‰ (S5-Aug), and the differences between d_{xylem} and

Table 2. Meteorological data at each site during the observation periods. Note: S1-Sep, S1-Jun, S2-Jun and S3-Aug indicate the 2900 m Qinghai spruce forest site in September 2011, the 2900 m site in June 2011, the 2700 m site in June 2011 and the 2800 m site in August 2009 in the upper reaches. S4-Aug and S5-Aug indicate the riparian forest at 930 m and the Gobi site at 906 m in August 2009 in the lower reaches.

	S1-Sep			S1-Jun			S2-Jun		
	RH (%)	*T* (°C)	PAR (μmol m^{-2} s^{-1})	RH (%)	*T* (°C)	PAR (μmol m^{-2} s^{-1})	RH (%)	*T* (°C)	PAR (μmol m^{-2} s^{-1})
Mean	**74.3**	***6.3***	491.7	**58.9**	***11.5***	576.0	**42.2**	***15.2***	687.1
Minimum	39.8	0.0	0.0	25.0	4.0	0.0	19.4	7.2	0.0
Maximum	91.1	12.4	1886.0	96.5	20.0	2097.0	67.9	22.5	2021.0
SD	15.5	3.9	637.6	21.9	5.0	625.9	14.3	4.5	713.1
	S3-Aug			S4-Aug			S5-Aug		
	RH (%)	*T* (°C)	PAR (μmol m^{-2} s^{-1})	RH (%)	*T* (°C)		RH (%)	*T* (°C)	
Mean	**74.8**	***12.0***	541.1	**46.5**	***23.1***		**19.0**	***28.7***	
Minimum	38.0	5.2	0.0	17.0	9.1		11.3	17.2	
Maximum	95.1	18.8	2036.0	87.5	33.7		34.3	38.0	
SD	19.4	4.0	676.5	21.6	6.5		7.0	7.1	

Table 3. Spatial and temporal variations in the δ^{18}O and δD of different water pools in the Heihe River basin. The numbers in parentheses indicate the number of samples. In the upper reaches, Q.S., P.F., P.V. and S.C. refer to Qinghai spruce, *Potentilla fruticosa*, *Polygonum viviparum* and *Stipa capillata* in the forest ecosystem. In the lower reaches, P.E. and S.A. refer to *Populus euphratica* and *Sophora alopecuroides* in the riparian forest ecosystem. R.S. refers to *Reaumuria soongorica* at the Gobi site.

Study sites	S1-Sep, S1-Jun, S2-Jun and S3-Aug								S4-Aug				S5-Aug	
Plant species	Q.S. (*n*=166)		P.F. (*n*=51)		P.V. (*n*=51)		S.C. (*n*=23)		P.E. (*n*=36)		S.A. (*n*=36)		R.S. (*n*=23)	
Leaf water	$\delta^{18}O_{leaf}$	δD_{leaf}	$\delta^{18}O_{leaf}$	δD_{leaf}	$\delta^{18}O_{leaf}$	δD_{leaf}	$\delta^{18}O_{leaf}$	δD_{leaf}	$\delta^{18}O_{leaf}$	δD_{leaf}	$\delta^{18}O_{leaf}$	δD_{leaf}	$\delta^{18}O_{leaf}$	δD_{leaf}
Mean	8.3	1.9	3.0	−5.6	1.5	−2.2	8.2	10.4	14.6	6.2	15.6	10.4	27.2	7.5
Minimum	−4.8	−29.4	−5.0	−37.6	−6.2	−35.0	1.7	−6.1	3.4	−9.7	5.8	−3.8	22.2	−5.0
Maximum	18.5	22.8	17.7	31.6	20.1	44.0	11.4	22.8	21.3	23.4	20.3	19.1	32.4	23.4
SD	6.8	13.3	6.4	17.1	7.0	20.1	2.5	7.9	5.0	8.2	3.9	5.8	2.5	6.6
Xylem water	$\delta^{18}O_{xylem}$	δD_{xylem}	$\delta^{18}O_{xylem}$	δD_{xylem}	$\delta^{18}O_{xylem}$	δD_{xylem}	$\delta^{18}O_{xylem}$	δD_{xylem}	$\delta^{18}O_{xylem}$	δD_{xylem}	$\delta^{18}O_{leaf}$	δD_{leaf}	$\delta^{18}O_{xylem}$	δD_{xylem}
Mean	−6.7	−47.2	−5.0	−39.1	−6.5	−44.6	−1.7	−32.7	−5.2	−48.9	-	-	−2.4	−64.2
Minimum	−9.0	−65.7	−7.5	−60.1	−8.5	−61.5	−5.4	−46.6	−5.6	−51.7	-	-	−4.9	−72.7
Maximum	−2.1	−21.6	−2.9	−23.6	−4.8	−32.7	1.0	−21.4	−4.2	−43.9	-	-	2.9	−50.0
SD	1.6	10.1	1.1	8.8	1.0	7.4	1.6	7.3	0.3	1.7	-	-	1.9	6.1
δ_{xylem}–δ_{leaf}	**−15.0**	**−49.1**	**−8.0**	**−33.5**	**−8.0**	**−42.4**	**−9.9**	**−43.1**	**−19.8**	**−55.1**	**-**	**-**	**−29.6**	**−71.7**
Soil water	5 cm depth ($n=166$)				10 cm depth ($n=166$)				10 cm depth ($n=36$)				10 cm depth ($n=4$)	
	$\delta^{18}O_{soil}$		δD_{soil}		$\delta^{18}O_{soil}$		δD_{soil}		$\delta^{18}O_{soil}$		δD_{soil}		$\delta^{18}O_{soil}$	δD_{soil}
Mean	−4.2		−34.9		−5.2		−43.2		0.0		−31.2		2.7	−37.1
Minimum	−8.9		−62.0		−9.9		−67.4		−2.0		−36.7		1.1	−46.8
Maximum	2.5		−6.3		−0.7		−12.0		2.4		−21.0		5.1	−27.5
SD	2.5		10.7		2.1		10.1		1.1		3.3		1.9	8.3
Air moisture	At the canopy ($n=172$)				Near the ground ($n=172$)				At the canopy ($n=36$)				At the canopy ($n=23$)	
	$\delta^{18}O_{moisture}$		$\delta D_{moisture}$		$\delta^{18}O_{moisture}$		$\delta D_{moisture}$		$\delta^{18}O_{moisture}$		$\delta D_{moisture}$		$\delta^{18}O_{moisture}$	$\delta D_{moisture}$
Mean	−13.3		−99.1		−14.1		−101.7		−16.2		−116.7		−17.7	−136.3
Minimum	−18.5		−135.4		−19.7		−133.0		−23.1		−167.2		−24.9	−188.9
Maximum	−6.0		−25.7		−7.9		−40.6		−11.6		−78.0		−11.7	−96.3
SD	1.8		17.3		2.2		16.6		3.0		22.5		3.3	23.2

d_{leaf} were 102.2 and 165.6 ‰ for S4-Aug and S5-Aug in the lower reaches, respectively (Table 4).

3.3.2 Variations in d-excess in soil water and air moisture during the sunny days

The averaged soil water d-excess values of 5 and 10 cm (d_{soil}) were −0.9 and −1.2 ‰, varying from −37.3 ‰ (S2-Jun) to 14.3 ‰ (S1-Sep), and from −25.7 ‰ (S2-Jun) to 16.6 ‰ (S1-Sep) in the upper reaches, respectively. At S4-Aug and S5-Aug, the averaged d_{soil} values of 10 cm were −31.0 and −59.1 ‰, ranging from −45.5 to −19.8 ‰ and from −75.3 to −48.7 ‰, respectively. The d_{soil} values decreased with the increase in T and the decrease in RH (Tables 2 and 4). Except at S3-Aug, there were no temporal trends in d_{soil} at 5 and 10 cm (Fig. 5). The d_{soil} values of 5 and 10 cm were lowest near 12:00. The highest observed d_{soil} was from 02:00 to 06:00 for site S3-Aug during the first sunny day after the rainy day (Fig. 5d).

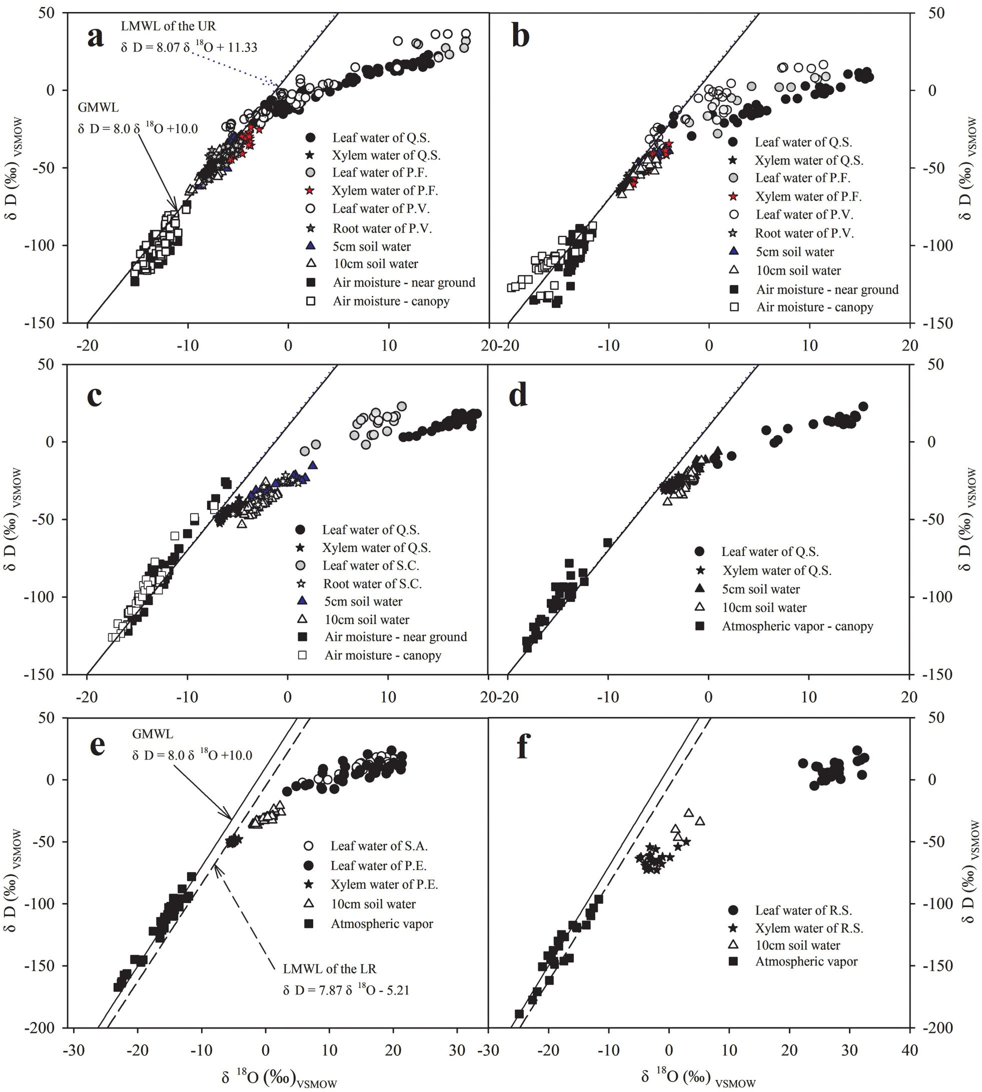

Figure 3. Plot of δD and δ^{18}O of different water pools at each site. The LMWL (cited from He, 2011) is plotted for each site (the dark line is the GMWL (the global meteoric water line); the blue dotted line and the dashed lines are the LMWL of the upper and the lower reaches, respectively). Note: panels **(a)**, **(b)**, **(c)**, **(d)**, **(e)** and **(f)** refer to the same location as in Fig. 2, and the abbreviations of plant Latin names are the same as in Table 3.

Figure 6 shows the diurnal variations in air moisture d-excess (d_{moisture}) from each study site on the sunny days. Although the patterns were similar at all sites, the peak-to-trough amplitudes of d_{moisture} varied greatly. They were 39.9 ‰ near the ground and 36.7 ‰ at the canopy in the upper reaches. In the lower reaches, the peak-to-trough amplitudes of d_{moisture} at the canopy were 17.3 ‰ at S4-Aug and 30.6 ‰ at S5-Aug, respectively (Table 4 and Fig. 6). Except for S2-Jun (Fig. 6c), the d_{moisture} values varied diurnally, showing a clear and robust pattern of maximum d_{moisture} during the mid-day (from about 10:00 to 16:00) (Fig. 6).

3.3.3 Variations in d-excess in leaf water, xylem water, soil water and air moisture water during the cloudy days

In our study, the cloudy days occurred only in the upper reaches (Table 1). The d_{leaf} values during the cloudy days were significantly higher than those of the sunny days, and the d_{leaf} values were significantly lower than the d_{xylem} values (Table 5). During the cloudy days with low PAR in the upper reaches of the HRB, there were no clear diurnal variations for d_{moisture}, d_{leaf} and d_{soil} at 5 and 10 cm in depth, except for d_{moisture} and d_{leaf} at S1-Jun (Figs. 7 and 8). In addition, at S3-Aug, the d_{leaf} increased gradually from 06:00 to 16:00 and showed the opposite diurnal variations compared

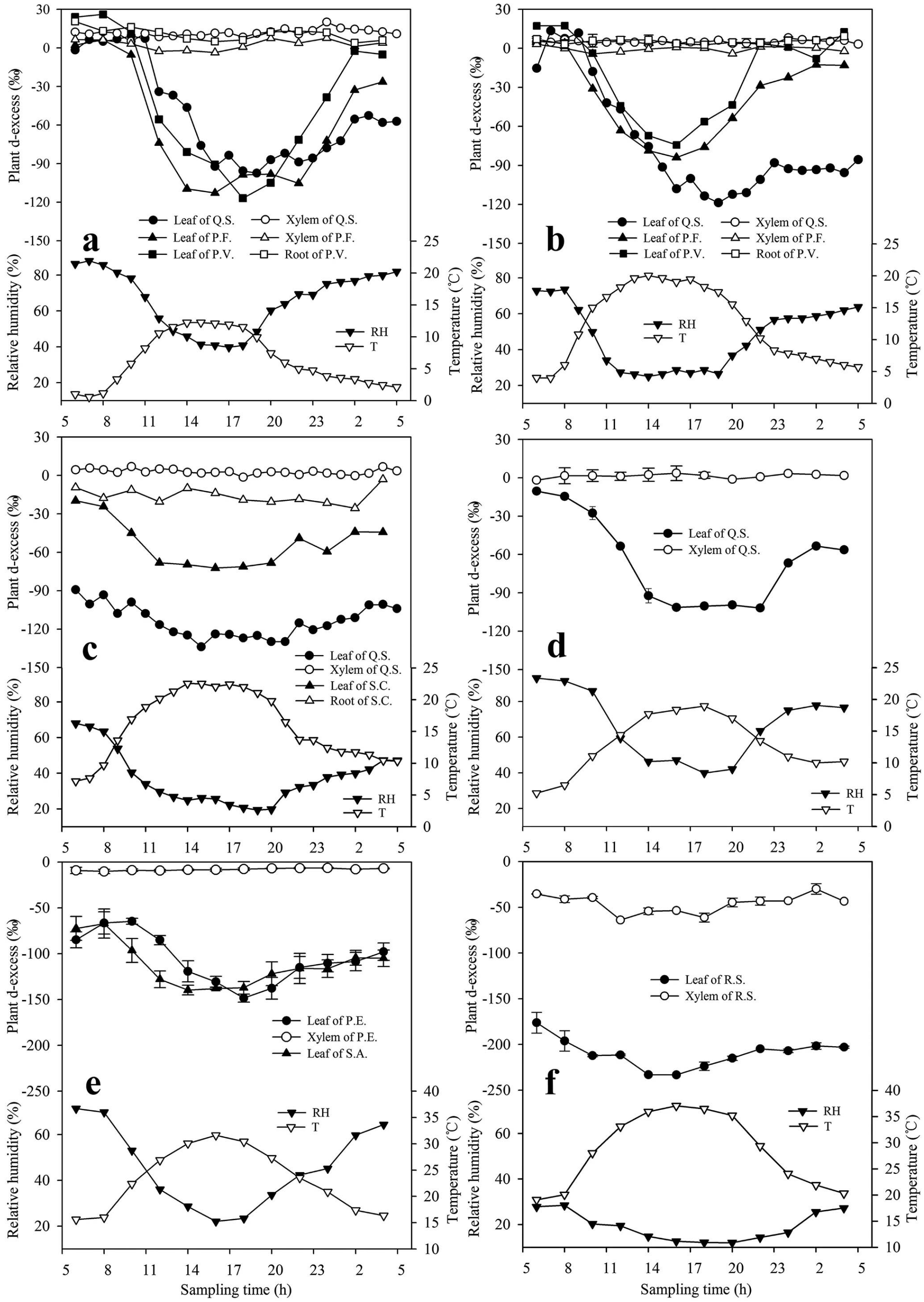

Figure 4. Variations in leaf and xylem water d-excess on the sunny days of the upper reaches and lower reaches of the Heihe River basin. Note: panels **(a)**, **(b)**, **(c)**, **(d)**, **(e)** and **(f)** refer to the same location as in Fig. 2, and the abbreviations of plant Latin names were the same as in Table 3. The following sunny days were selected: S1-Sep: from 06:00 to 18:00, 7 and 8 September; S1-Jun: from 06:00 to 16:00, 23 June; S2-Jun: from 06:00 to 16:00, 27 June; S3-Aug: from 06:00, 1 August to 16:00, 2 August and from 06:00 to 18:00, 3 August 2009. All data at S4-Aug and S5-Aug were selected.

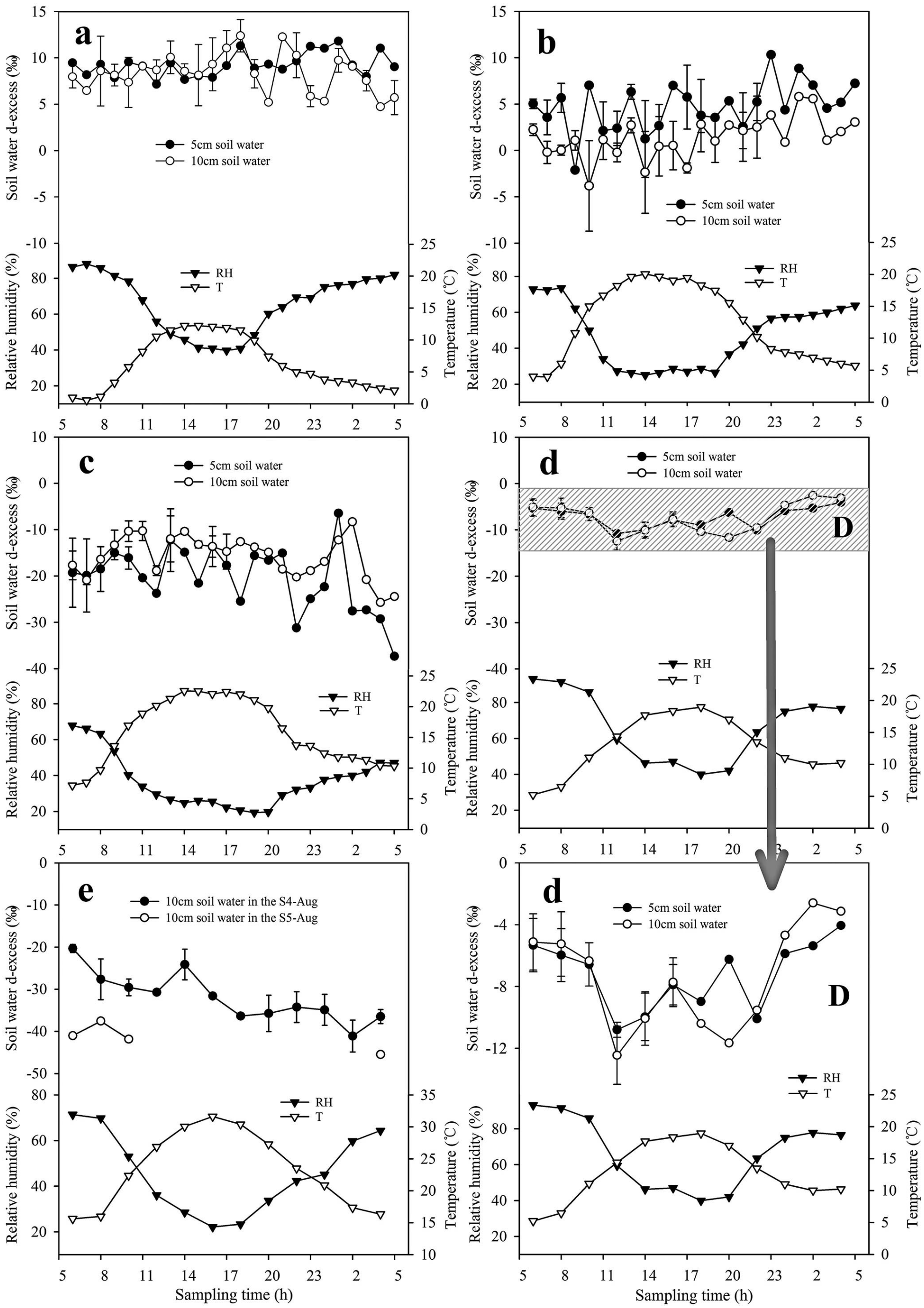

Figure 5. Spatial and temporal variations in soil water d-excess in the Heihe River basin. Note: panels **(a)**, **(b)**, **(c)**, and **(d)** refer to the same locations as in Fig. 2, and panel **(e)** refers to S4-Aug and S5-Aug in the lower reaches.

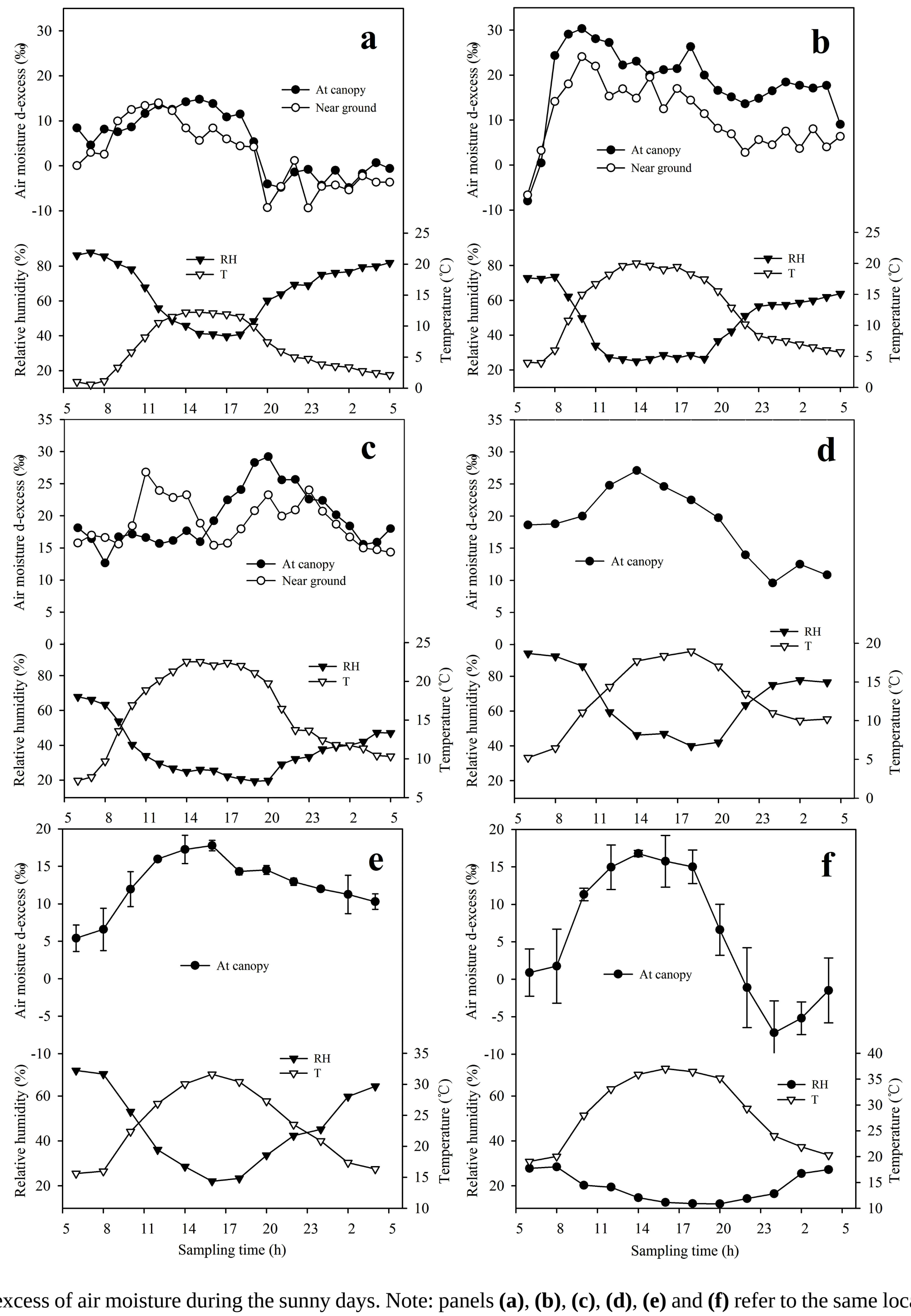

Figure 6. The d-excess of air moisture during the sunny days. Note: panels **(a)**, **(b)**, **(c)**, **(d)**, **(e)** and **(f)** refer to the same locations as in Fig. 2.

Table 4. Spatial and temporal variations in the d-excess (‰) of each water pool in the Heihe River basin. The numbers in parentheses indicate the number of samples. The location ID and the abbreviations of plant Latin names are the same as in Tables 2 and 3.

Study sites	S1-Sep, S1-Jun, S2-Jun and S3-Aug				S4-Aug		S5-Aug
Plant species	Q.S. ($n = 166$)	P.F. ($n = 51$)	P.V. ($n = 51$)	S.C. ($n = 23$)	P.E. ($n = 36$)	S.A. ($n = 36$)	R.S. ($n = 23$)
	Leaf water				Leaf water		Leaf water
Mean	−64.7	−29.8	−14.3	−55.4	−110.2	−114.4	−210.4
Minimum	−133.8	−112.9	−117.0	−72.3	−161.2	−145.4	−245.6
Maximum	13.4	9.7	26.1	−19.7	−36.8	−48.5	−165.0
SD	43.0	35.6	37.0	15.0	34.7	26.0	17.4
The peak-to-trough amplitudes	147.2	122.6	143.1	52.6	124.4	96.9	80.6
	Xylem water				Xylem water		Xylem water
Mean	6.2	0.8	7.6	−18.8	−8.2	-	−44.8
Minimum	−7.2	−7.5	0.3	−34.9	−14.1	–	−73.0
Maximum	15.4	7.5	22.4	−3.1	−3.9	–	−24.2
SD	5.0	3.8	5.2	7.2	2.1	–	12.7
The peak-to-trough amplitudes	22.6	15.0	22.1	31.8	10.2	–	48.8
Mean d_{xylem}–d_{leaf}	70.9	30.6	21.9	36.6	102.0	–	165.6
Soil water	5 cm soil water ($n = 166$)		10 cm soil water ($n = 166$)		10 cm soil water ($n = 36$)		10 cm soil water ($n = 4$)
Mean	−0.9		−1.2		−31.0		−59.1
Minimum	−37.3		−25.7		−45.5		−75.3
Maximum	14.3		16.6		−19.8		−48.7
SD	12.5		10.0		6.2		11.5
The peak-to-trough amplitudes	51.6		42.3		25.7		26.6
Air moisture	At the canopy ($n = 172$)		Near the ground ($n = 172$)		At the canopy ($n = 36$)		At the canopy ($n = 23$)
Mean	7.7		11.2		12.8		5.6
Minimum	−9.9		−7.0		2.6		−11.4
Maximum	26.8		32.9		19.9		19.2
SD	8.5		9.4		4.8		9.1
The peak-to-trough amplitudes	36.7		39.9		17.3		30.6
Mean $d_{moisture}$–d_{soil}	8.6		12.4		43.8		**64.7**

Table 5. Differences between d_{xylem} (‰) and d_{leaf} (‰) on the sunny and the cloudy days. The location ID and the abbreviations of plant Latin names are the same as in Tables 2 and 3.

Study sites	Plant species	The sunny day			The cloudy day			Difference in d_{leaf}	Difference in d_{xylem}
		d_{leaf}	d_{xylem}	d_{xylem}–d_{leaf}	d_{leaf}	d_{xylem}	d_{xylem}–d_{leaf}	d_{cloudy}–d_{sunny}	d_{cloudy}–d_{sunny}
S1-Sep	Q.S.	−51.9	11.8	**63.7**	−6.8	12.0	**18.8**	***45.1***	***0.1***
	P.F.	−60.6	2.7	**63.3**	−4.9	2.7	**7.6**	***55.7***	***0.0***
	P.V.	−42.0	10.6	**52.7**	11.1	8.3	**−2.8**	***53.2***	***−2.3***
S1-Jun	Q.S.	−72.0	5.0	**77.1**	−47.4	5.2	**52.6**	***24.7***	***0.2***
	P.F.	−37.8	−0.6	**37.2**	−15.5	−1.1	**14.4**	***22.3***	***−0.5***
	P.V.	−20.4	5.5	**25.9**	−4.6	6.4	**11.0**	***15.9***	***1.0***
S2-Jun	Q.S.	−114.0	2.9	**116.9**	−116.9	−0.2	**116.7**	***−2.9***	***−3.1***
	S.C.	−52.9	−15.9	**37.0**	−59.5	−23.7	**35.8**	***−6.6***	***−7.8***
S3-Aug	Q.S.	−64.9	1.4	**66.3**	−52.8	4.0	**56.8**	***12.0***	***2.5***
Mean		−57.4	2.6	**60.0**	−33.0	1.5	**34.5**	***24.4***	***−1.1***

to those of the sunny days. The likely reason is the leaf absorption of precipitation with high d-excess (e.g., 11.8 ‰ as in Zhao et al., 2011b) during the rainy conditions (precipitation occurred from 10:40 to 22:00 on 2 August).

During the sunny days, a large difference between d_{xylem} and d_{leaf} was found, and the d_{xylem}–d_{leaf} values varied from 25.9 to 116.9 ‰, with a mean value of 60.0 ‰. Except at S2-Jun, the mean difference between d_{xylem} and d_{leaf} during the cloudy days was 22.6 ‰, and this value was lower than that of the sunny days. A large difference in d_{leaf} between the sunny and cloudy days was found, with a mean of 32.7 ‰ (excluding S2-Jun), and the difference varied from 12.0 to

55.7 ‰ (excluding S2-Jun). There was no obvious difference in d_{xylem} between the sunny and cloudy days, except at S2-Jun (Table 5).

3.4 Controlling factors of the d-excess in different water pools

3.4.1 Relationships between the d-excess of various pools and RH

Significantly positive correlations were found between d_{leaf} and RH at all the study sites during the entire study periods (from June to September) (Table 6). Significantly positive correlations were also found between d_{leaf} and RH at all the study sites during the sunny days (Table 7). As RH increased by 1 %, the increasing magnitude of d_{leaf} ranged from 0.49 to 2.53 ‰ in the upper reaches. In the lower reaches, as RH increased by 1 %, the increasing magnitude of d_{leaf} ranged from 1.21 to 1.77 ‰ (Table 6).

Except for near the ground at S1-Sep, significantly negative correlations were found between d_{moisture} and RH at all the study sites when including both the sunny and cloudy days (Table 6). A significantly negative correlation was found between d_{moisture} and RH at S1-Sep when only the sunny days were considered (Table 7). The d_{moisture}/RH values were -0.15 ‰ $\%^{-1}$ at S1-Jun and -0.27 ‰ $\%^{-1}$ at S2-Jun for near-ground air moisture. For the canopy air moisture, the d_{moisture}/RH values were -0.24, -0.32, -0.25, -0.15, -0.13 and -0.68 ‰ $\%^{-1}$ at S1-Sep, S1-Jun, S2-Jun, S3-Aug, S4-Aug and S5-Aug, respectively. During the sunny days, the d_{moisture}/RH values were -0.36 and -0.31 ‰ $\%^{-1}$, respectively, for near the ground and at the canopy in the upper reaches, which were larger than the results based on data including both the sunny and cloudy days (Table 7). In terms of d_{soil}, the correlations between the d_{soil} of 10 cm at S1-Sep, S3-Aug and RH, and between the d_{soil} of 5 cm at S1-Jun and RH, were significant (Table 6).

3.4.2 Relationships between the d-excess of various pools and *T*

Significantly negative relationships were found between d_{leaf} and T in both the upper reaches and the lower reaches, except in Q.S. at S1-Jun (Table 8). The decreasing magnitudes of d_{leaf} with T in Q.S. were -3.27, -1.59 and -6.25 ‰ °C^{-1} at S1-Sep, S2-Jun and S3-Aug, respectively. The magnitudes were -6.45 and -5.10 ‰ °C^{-1} for P.F., and -6.74 and -5.07 ‰ °C^{-1} for P.V. for S1-Sep and S1-Jun, respectively. The magnitude was -2.21 ‰ °C^{-1} in S.C. at S2-Jun. During the sunny days, there were significantly negative relationships between d_{leaf} and T in both the upper and lower reaches (Tables 7 and 8). In the lower reaches, the decreasing magnitudes of d_{leaf} in P.E. and S.A. were -4.40 and -2.15 ‰ °C^{-1}, respectively, at S4-Aug. It was -1.82 ‰ °C^{-1} for R.S. at S5-Aug (Table 8).

There were significantly positive relationships between d_{moisture} and T at all sites except S2-Jun (Table 8). The d_{moisture}/T values near the ground were 0.54 and 0.76 ‰ °C^{-1} at S1-Sep and S1-Jun, respectively. The d_{moisture}/T values at the canopy were 0.81, 0.91, 0.64, 0.54 and 0.83 ‰ °C^{-1} at S1-Sep, S1-Jun, S3-Aug, S4-Aug and S5-Aug, respectively (Table 8). During the sunny days, the d_{moisture}/T values were 1.18 and 1.11 ‰ °C^{-1}, respectively, for near the ground and at the canopy, which were larger than the results based on data including both the sunny and cloudy days (Table 7).

At S2-Jun, there were positive relationships between d_{soil} (both 5 and 10 cm in depth) and T, and the d_{soil}/T values were 0.88 ‰ °C^{-1} ($p = 0.021$) and 0.34 ‰ °C^{-1} ($p = 0.045$) for 5 and 10 cm in depth, respectively. However, at S3-Aug, there were negative relationships between d_{soil} (both 5 and 10 cm in depth) and T, and the d_{soil}/T values were -0.45 ‰ °C^{-1} ($p = 0.009$) and -0.54 ‰ °C^{-1} ($p = 0.002$) for 5 and 10 cm in depth, respectively. A significantly negative relationship was also found between the d_{soil} of 5 cm in depth and T at S1-Sep ($d_{\mathrm{soil}}/T = -0.16$ ‰ °C^{-1}, $p = 0.002$) (Table 8).

3.4.3 Relationships between the d-excess of various pools

During the sunny days, we found an opposite pattern between the diurnal variations in d_{leaf} and d_{moisture} (Fig. 9). A similar pattern was found between d_{soil} and d_{moisture} during the first sunny day after the rain. The d_{leaf} (d_{soil}) became more negative, while d_{moisture} became more positive during the afternoon, and opposite patterns were found during the night (Figs. 9 and 10). There were significantly negative relationships between d_{leaf} and d_{moisture} at three study sites (Table 7). In the upper reaches, d_{leaf} of wood species (Q.S.) were correlated significantly with d_{moisture} both near the ground and at the canopy, and the slopes were -1.47 and -1.40, respectively. Significantly negative relationships were also found between d_{leaf} of shrub/grass and d_{moisture} near the ground, and the slopes were -0.14 and -0.12, respectively. In the lower reaches, the slopes of d_{leaf} and d_{moisture} at the canopy were -0.06 in woody species (P.E.), and -0.10 and -0.28 in shrub (S.A.), at S4-Aug and S5-Aug, respectively (Table 7).

3.5 Modeling results of leaf water $\delta^{18}O$, δD and d-excess

The steady-state Craig–Gordon model captured the diurnal variations in δ^{18}O, δD and d-excess, but a discrepancy existed between modeled and observed values (Fig. 11). During the day, the observed values of δ^{18}O and δD were lower, while d-excess values were higher than those predicted by the steady-state Craig–Gordon model. At night, the observed values of δ^{18}O and δD were higher, while d-excess values were slightly lower than those predicted by the model. On

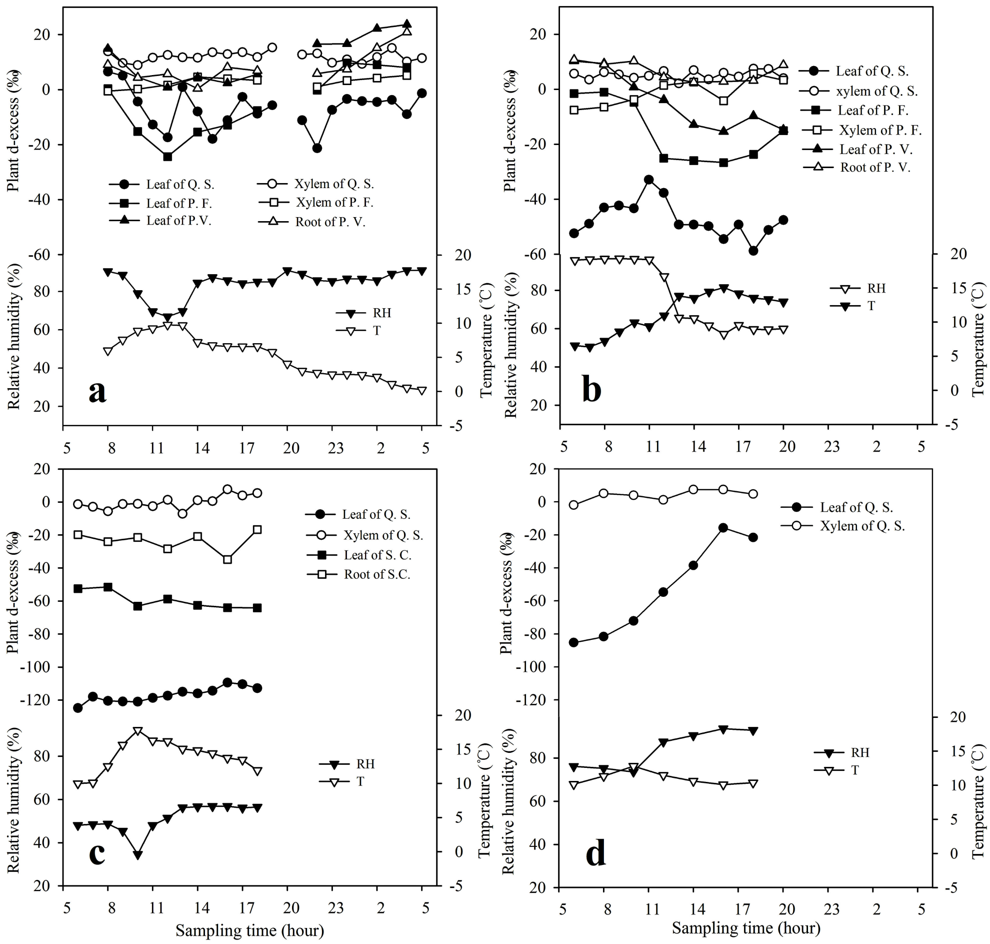

Figure 7. Variations in leaf and xylem water d-excess of the upper reaches of the Heihe River basin during the cloudy days. Note: panels **(a)**, **(b)**, **(c)** and **(d)** refer to the same location as in Fig. 2, and the abbreviations of plant Latin names were the same as in Table 3.

average, the modeled leaf water δ^{18}O and δD values were 1.8 and 6.7 ‰ higher, while d-excess values were 7.5 ‰ lower than those of observed values. The steady-state predictions explained 79.5 % of variations in modeled δ^{18}O, and 63.4 and 64.2 % of variations in modeled δD and d-excess (Fig. 11).

4 Discussion

4.1 Variations in δD and δ^{18}O in different water pools

Our results show that there are significant differences in the δD and δ^{18}O of leaf water, xylem water, soil water and air moisture, and different δD–δ^{18}O patterns due to hydrogen and oxygen isotopic discrimination related to soil evaporation, plant transpiration and plant physiology. For example, compared to those of xylem water and shallow soil water, leaf water has the highest average δD and δ^{18}O values and the largest ranges at all the study sites. In addition, the δD–δ^{18}O regression lines of leaf water highly deviate from their corresponding LMWL (Table 2 and Fig. 3), suggesting a strong transpiration enrichment effect. With the decrease in RH and the increase in T, leaf water δD and δ^{18}O values increased, and the δD–δ^{18}O regression lines gradually deviate from their corresponding LMWL due to stronger transpiration, suggesting that climatic conditions have a significant effect on variations in leaf water δD and δ^{18}O and their correlations by affecting transpiration (Tables 2 and 3).

In the upper reaches, at high-altitude sites such as S1-Sep and S1-Jun, the patterns of δD–δ^{18}O regression lines in shallow soil water and xylem water are similar (Fig. 3a and b), suggesting that the water sources of plants are from shallow soil water, and soil waters are subject to only mild evaporation. These results are consistent with the fact of the horizontal distributions of Q.S. roots and the shallow rooting of herbaceous plants such as P.V. However, at relatively lower altitudes such as at S2-Jun and S3-Aug, the xylem water δD and δ^{18}O of Q.S. are lower than those of soil water, except for the herbaceous plant (S.C.) (Table 3), and the δD–δ^{18}O regression lines of soil water deviate from the LMWL (Fig. 3).

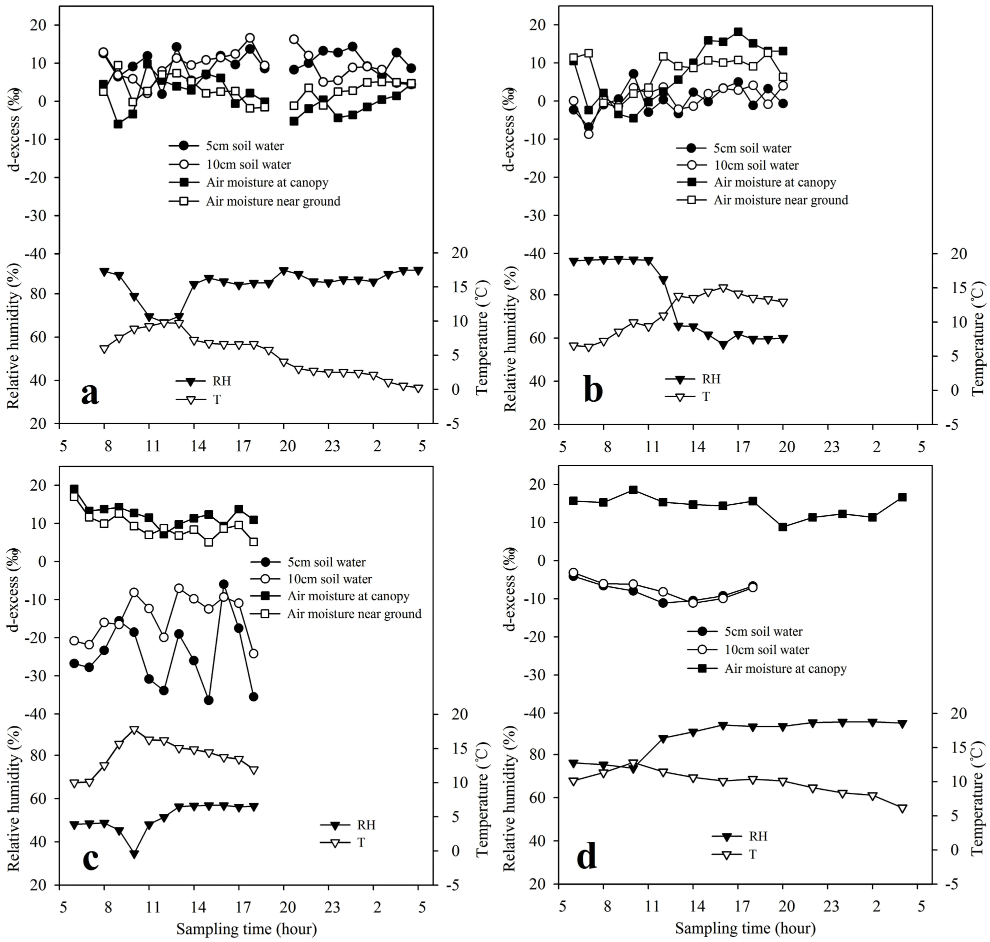

Figure 8. Variations in d-excess of shallow soil water and air moisture during the cloudy days of the upper reaches of the Heihe River basin. Note: panels **(a)**, **(b)**, **(c)** and **(d)** refer to the same locations as in Fig. 2.

These results may be related to stronger soil evaporation in shallow soil layers. In the lower reaches, the δD and δ^{18}O of 10 cm soil water are significantly higher than those of P.E. and R.S. xylem water, and the δD–δ^{18}O regression lines obviously deviate from the LMWL of the lower reaches, suggesting that strong soil water evaporation occurs in shallow soil in the lower reaches.

As expected, the isotopic results show that the soil water at 5 and 10 cm is affected by evaporation, which is indicated by a slope of less than 8.0 (Dansgaard, 1964). In our study, the slopes of 5 and 10 cm of the soil water evaporation line vary from 2.6 to 7.4 (Table 9). Relative high slopes were found at S1-Sep (7.1) and S3-Aug (7.4), likely due to low temperatures during September at S1-Sep and the rain event at S3-Aug. The slopes of other sites are lower than 5.0, especially in the lower reaches, and the values in the slopes are very small at S4-Aug (2.6) and S5-Aug (2.8) (Table 9), revealing strong shallow water evaporation. These slope values are comparable with other studies in vadose zones with evaporation slopes between 2 and 5 (Allison, 1982; Clark and Fritz, 1997; Kendall and McDonnell, 1999; Wenninger et al., 2010; Sutanto et al., 2012). The patterns of the δD–δ^{18}O regression lines from shallow soil water gradually deviate from their corresponding LMWL with the decrease in altitude, suggesting stronger water loss through direct evaporation, especially in extremely arid regions such as the riparian forest site and the Gobi site in the lower reaches of the HRB.

The air moisture has the most depleted δD and δ^{18}O compared to leaf water, xylem water and shallow soil water (Table 3). The air moisture δD and δ^{18}O data cluster around the corresponding LMWL (Fig. 3). These results are consistent with the isotopic fractionation theory (Gat, 1996), and they are also consistent with a previous study in urban settings, agricultural settings, forest and grassland in China, Canada and the USA (Welp et al., 2012).

Table 6. Linear least square fits between the d-excess of various water bodies and the relative humidity (RH) (%) at each site. Here, r is the correlation coefficient, and p is the significance level. $p < 0.001$ indicates statistical significance at the 99.9 % significance level, and $p < 0.05$ indicates statistical significance at the 95 % significance level. The location ID and the abbreviations of plant Latin names are the same as in Tables 2 and 3.

d-excess (‰) vs. RH (%)									
	Slope	Intercept	r	p		Slope	Intercept	r	p
	S1-Sep					S1-Jun			
d_{leaf} of Q.S.	**1.52**	**−146.68**	**0.701**	**< 0.001**	d_{leaf} of Q.S.	**0.82**	**−113.36**	**0.589**	**< 0.001**
d_{leaf} of P.F.	**2.38**	**−212.45**	**0.846**	**< 0.001**	d_{leaf} of P.F.	**1.07**	**−90.47**	**0.825**	**< 0.001**
d_{leaf} of P.V.	**2.53**	**−208.14**	**0.879**	**< 0.001**	d_{leaf} of P.V.	**0.99**	**−72.05**	**0.723**	**< 0.001**
d_{soil} of 5 cm	0.03	6.61	0.198	0.122	d_{soil} of 5 cm	**−0.10**	**9.42**	**−0.483**	**0.001**
d_{soil} of 10 cm	***0.08***	***1.84***	***0.253***	***0.048***	d_{soil} of 10 cm	< 0.01	1.10	−0.046	0.775
$d_{moisture}$ near the ground	−0.11	9.62	−0.168	0.191	$d_{moisture}$ near the ground	**−0.15**	**18.50**	**−0.477**	**0.001**
$d_{moisture}$ at the canopy	**−0.24**	**20.56**	**−0.457**	**< 0.001**	$d_{moisture}$ at the canopy	**−0.32**	**33.83**	**−0.753**	**< 0.001**
	S2-Jun					S3-Aug			
d_{leaf} of Q.S.	**0.49**	**−135.82**	**0.686**	**< 0.001**	d_{leaf} of Q.S.	**1.48**	**−169.36**	**0.716**	**< 0.001**
d_{leaf} of S.C.	***0.56***	***−79.08***	***0.523***	***0.022***					
d_{soil} of 5 cm	−0.21	−10.54	−0.279	0.094	d_{soil} of 5 cm	0.05	−9.86	0.289	0.161
d_{soil} of 10 cm	−0.02	−14.72	0.013	0.941	d_{soil} of 10 cm	***0.08***	***−12.35***	***0.403***	***0.046***
$d_{moisture}$ near the ground	**−0.27**	**26.82**	**−0.682**	**< 0.001**					
$d_{moisture}$ at the canopy	**−0.25**	**27.58**	**−0.689**	**< 0.001**	$d_{moisture}$ at the canopy	**−0.15**	**28.37**	**−0.526**	**0.007**
	S4-Aug					S5-Aug			
d_{leaf} of P.E.	**1.41**	**−171.76**	**0.844**	**< 0.001**	d_{leaf} of R.S.	**1.77**	**−243.96**	**0.716**	**< 0.001**
d_{leaf} of S.A.	**1.21**	**−166.99**	**0.947**	**< 0.001**					
d_{soil} of 10 cm	0.02	−32.08	−0.012	0.939					
$d_{moisture}$ at the canopy	**−0.13**	**17.42**	**−0.602**	**0.003**	$d_{moisture}$ at the canopy	**−0.68**	**18.47**	**−0.526**	**< 0.001**

Table 7. Correlations between the d-excess of various water bodies and RH (%) and T (°C), and between $d_{moisture}$ and d_{leaf} during the sunny days at each site. Here, r is the correlation coefficient, and p is the significance level. $p < 0.001$ indicates statistical significance at the 99.9 % significance level, and $p < 0.05$ indicates statistical significance at the 95 % significance level. The location ID and the abbreviations of plant Latin names are the same as in Tables 2 and 3. The periods of the sunny days are the same as in Fig. 5.

Study area		The d-excess values vs. RH (%)				The d-excess values vs. T (°C)			
		Slope	Intercept	r	p	Slope	Intercept	r	p
	$d_{moisture}$ near the ground	−0.36	27.643	−0.712 (84)	< 0.001	1.18	−4.574	0.771	< 0.001
	$d_{moisture}$ at the canopy	−0.31	28.269	−0.617 (101)	< 0.001	1.11	0.695	0.716	< 0.001
	d_{leaf} of wood	1.26	−131.626	0.600 (102)	< 0.001	−3.84	−19.327	0.630	< 0.001
S1-Sep	d_{leaf} of shrub	1.26	−121.121	0.629 (25)	< 0.001	−3.66	−15.489	0.547	< 0.001
S1-Jun	d_{leaf} of herb	1.21	−99.962	0.635 (37)	< 0.001	−3.17	−1.134	0.563	< 0.001
S2-Jun	d_{leaf} of wood vs. $d_{moisture}$ near the ground	−1.47	− 63.237	−0.360 (84)	< 0.001	–	–	–	–
S3-Aug	d_{leaf} of wood vs. $d_{moisture}$ at the canopy	−1.40	−52.568	−0.340 (101)	< 0.001	–	–	–	–
	d_{leaf} *of shrub* vs. $d_{moisture}$ near the ground	*−0.14*	*3.69*	*−0.599 (24)*	*0.039*	–	–	–	–
	d_{leaf} *of grass* vs. $d_{moisture}$ near the ground	*−0.12*	*12.72*	*−0.648 (12)*	*0.023*	–	–	–	–
S4-Aug	d_{leaf} of wood vs. $d_{moisture}$ at the canopy	−0.06	7.163	−0.543 (32)	< 0.001	–	–	–	–
	d_{leaf} of shrub vs. $d_{moisture}$ at the canopy	−0.10	1.827	−0.534 (32)	< 0.001	–	–	–	–
S5-Aug	d_{leaf} of shrub vs. $d_{moisture}$ at the canopy	−0.28	−57.737	0.540 (25)	< 0.001	–	–	–	–

Table 8. Linear least square fits between the d-excess of various water bodies and the temperature (T) (°C) at each site. Here, r is the correlation coefficient, and p is the significance level. $p < 0.001$ indicates statistical significance at the 99.9 % significance level, and $p < 0.05$ indicates statistical significance at the 95 % significance level. The location ID and the abbreviations of plant Latin names are the same as in Tables 2 and 3.

d-excess (‰) vs. T (°C)									
	Slope	Intercept	r	p		Slope	Intercept	r	p
	S1-Sep					S1-Jun			
Q.S. leaf water	**−3.27**	**−13.20**	**−0.419**	**< 0.001**	Q.S. leaf water	−1.60	−46.89	−0.202	0.220
P.F. leaf water	**−6.45**	**5.88**	**−0.612**	**< 0.001**	P.F. leaf water	**−5.10**	**31.80**	**−0.919**	**< 0.001**
P.V. leaf water	**−6.74**	**22.91**	**−0.575**	**< 0.001**	P.V. leaf water	**−5.07**	**45.80**	**−0.942**	**< 0.001**
5 cm soil water	**−0.16**	**10.17**	**−0.387**	**0.002**	5 cm soil water	0.12	2.36	0.075	0.635
10 cm soil water	0.06	7.62	0.143	0.268	10 cm soil water	−0.09	2.15	−0.087	0.585
Air moisture near the ground	**0.54**	**−1.78**	**0.349**	**0.005**	Air moisture near the ground	**0.76**	**0.86**	**0.610**	**< 0.001**
Air moisture at the canopy	**0.81**	**−2.63**	**0.481**	**< 0.001**	Air moisture at the canopy	**0.91**	**4.12**	**0.494**	**0.003**
	S2-Jun					S3-Aug			
Q.S. leaf water (37)	**−1.59**	**−90.88**	**−0.664**	**< 0.001**	Q.S. leaf water	**−6.25**	**14.67**	**−0.684**	**0.001**
S.C. leaf water (19)	**−2.21**	**−22.15**	**−0.646**	**0.003**					
5 cm soil water	***0.88***	***−32.89***	***0.379***	***0.021***	5 cm soil water	**−0.45**	**−1.15**	**−0.514**	**0.009**
10 cm soil water	***0.34***	***−20.73***	***0.332***	***0.045***	10 cm soil water	**−0.54**	**−0.16**	**−0.589**	**0.002**
Air moisture near the ground	0.42	9.23	0.285	0.087					
Air moisture at the canopy	0.31	12.28	0.173	0.305	Air moisture at the canopy	**0.64**	**9.39**	**0.491**	**0.005**
	S4-Aug					S5-Aug			
P.E. leaf water	**−4.40**	**2.274**	**−0.642**	<	R.S. leaf water	**−1.82**	**−158.14**	**−0.742**	**< 0.001**
S.A. leaf water	**−2.15**	**−64.28**	**−0.560**	**< 0.001**					
10 cm soil water	0.08	−32.97	0.050	0.755					
Air moisture at the canopy	**0.54**	**0.95**	**0.773**	**< 0.001**	Air moisture at the canopy	**0.83**	**−18.23**	**0.684**	**0.001**

Table 9. Equations of soil water δD and δ^{18}O at each site using the linear least squares fit method. Here, r is the correlation coefficient, and p is the significance level. $p < 0.001$ indicates statistical significance at the 99.9 % significance level, and $p < 0.05$ indicates statistical significance at the 95 % significance level.

Sites	Equation	r	p	Sites	Equation	r	p
S1-Sep	$\delta D = 7.114 \times \delta^{18}O + 3.030$	0.921	< 0.001	S3-Aug	$\delta D = 7.355 \times \delta^{18}O - 8.267$	0.914	< 0.001
S1-Jun	$\delta D = 4.998 \times \delta^{18}O - 16.213$	0.825	< 0.001	S4-Aug	$\delta D = 2.615 \times \delta^{18}O - 31.128$	0.890	< 0.001
S2-Jun	$\delta D = 3.952 \times \delta^{18}O - 26.901$	0.888	< 0.001	S5-Aug	$\delta D = 2.840 \times \delta^{18}O - 44.930$	0.642	0.222

4.2 Variations in d_{leaf}, d_{xylem}, d_{soil} and d_{moisture} under different conditions

4.2.1 Variations in d-excess in leaf water and xylem water and their diurnal patterns

The significant differences in d-excess are found between leaf water and xylem water in both the upper reaches and the lower reaches. In order to evaluate the effect of plant transpiration on d_{leaf}, we calculate the difference between d_{leaf} and d_{xylem}, assuming that d_{xylem} represents the d-excess of source water. The differences in averaged d_{xylem} and d_{leaf} vary from 21.9 to 165.6 ‰, and the differences are 70.9 ‰ in Q.S., 30.6 ‰ in P.F., 21.9 ‰ in P.V. and 36.6 ‰ in S.C. in the upper reaches, and 102.0 ‰ in P.E. and 165.6 ‰ in R.S. in the lower reaches (Table 4). These differences reach the maximum value in the afternoon (Fig. 4). Since no isotopic fractionation occurs during water uptake and transport from roots to twigs (Washburn and Smith, 1934), the large differences between d_{xylem} and d_{leaf} found in this study indicate that plant transpiration results in lower d_{leaf} and releases water vapor with higher d-excess values into the atmosphere. These were consistent with those expected from the recycling of surface evapotranspiration (Gat et al., 1994). Therefore, mixing of transpiration moisture in the atmosphere will increase d_{moisture}, except for the conditions with the influence of entrained atmospheric moisture with high d-excess. In addition, during the sunny days, the clear and robust diurnal variations in d_{leaf} with a daily maximum in the early morning and a negative peak in the mid-afternoon are found at all the study sites (Fig. 4 and Table 4), while no diurnal variations in d_{leaf} are found on the cloudy days (Fig. 7). These results indicate that d_{leaf} is affected by meteorological conditions through

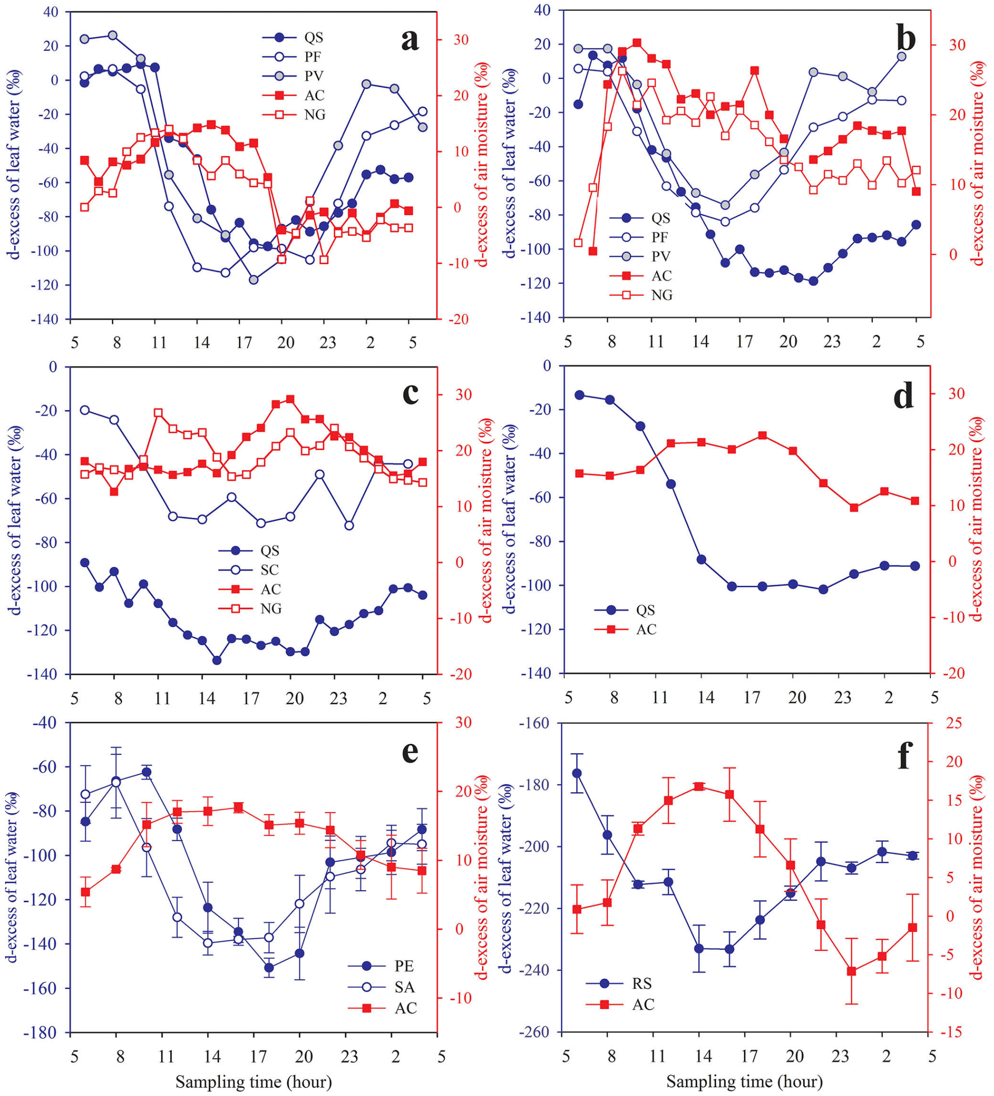

Figure 9. Comparison of leaf water and air moisture d-excess values during the sunny days. Note: panels **(a)**, **(b)**, **(c)**, **(d)**, **(e)** and **(f)** refer to the same locations as in Fig. 2, and the abbreviations of plant Latin names are the same as in Table 3. AC and NG refer to air moisture at the canopy level and near the ground, respectively.

their effect on plant transpiration. At the same time, no diurnal variations in the d_{xylem} of all species are found on either the sunny or cloudy days (Figs. 4 and 7), indicating that d_{xylem} is stable and that the effect of meteorological conditions on d_{xylem} is small. These results also suggested that the d-excess of moisture through plant transpiration has an important role in changing the d_{moisture} of local air moisture during the sunny days.

4.2.2 Variations in d-excess in shallow soil water

No clear diurnal trends in d_{soil} are found, except at S3-Aug. At S3-Aug, there are clear daily variations in d_{soil}, which reaches the lowest value at around 12:00 and slowly climbs up to the previous level the next day (the first sunny day after a rain event) (Fig. 5d). This pattern is similar to d_{leaf}, which is likely due to the strong evaporation during the first sunny day after a rain event (rain stopped at about 22:00, and we started to take samples at 06:00 the next day) (Fig. 5d). At S3-Aug, during the first day after a rain event, we also found a negative relationship between d_{soil} of 5, 10 cm and T (Table 8), and opposite patterns between the diurnal variations in d_{soil} and d_{moisture} (Fig. 10). These results indicate that the d-excess of moisture through soil evaporation also has an important role in changing the d_{moisture} of local air moisture during the sunny day after the rain events. In addition, the effect of soil evaporation on d_{moisture} is similar to the plant transpiration effect, and this effect was mainly controlled by temperature,

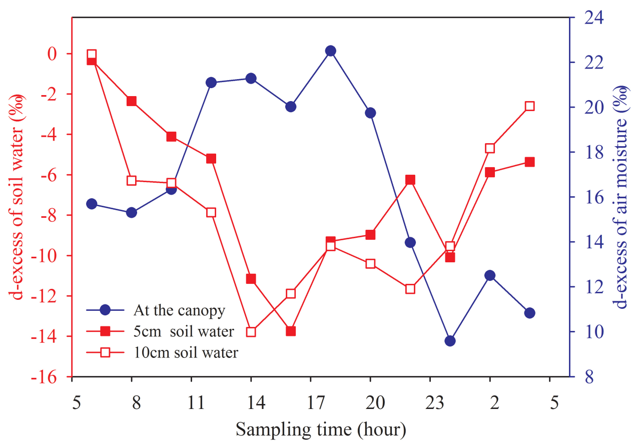

Figure 10. Comparison of soil water and air moisture d-excess values during the sunny days after the 4 h rain event on 2 August 2009 at S3-Aug.

as indicated by the negative relationship between d_{soil} and T (Table 8).

4.2.3 Variations in d-excess in air moisture near the ground and at the canopy

In our study, the peak-to-trough magnitudes vary greatly, and are 39.9 ‰ near the ground and 36.7 ‰ at the canopy in the upper reaches, and 17.3 ‰ (S4-Aug) and 30.6 ‰ (S5-Aug) at the canopy in the lower reaches (Table 4 and Fig. 6). These observed values are higher than those of previous reports that the peak-to-trough magnitudes vary from 3.5 to 17.1 ‰ (Welp et al., 2012). The higher range is likely caused by the large diurnal RH range (an up to 80 % change) in these environments. The lowest d_{moisture} values are found near the ground (1.5 ‰) at high altitudes during September (S1-Sep). The low values may be related to the atmospheric entrainment contribution, as atmospheric entrainment has been found to be responsible for the low d-excess values observed in the Pacific Northwest (Lai and Ehleringer, 2011).

In our study, during the sunny days, the d_{moisture} values vary diurnally, showing a clear and robust pattern of the highest d_{moisture} values at midday, and the lowest d_{moisture} values at night at all the sites (Fig. 6). The same trends were also found in urban settings (New Haven and Beijing), agricultural settings (Rosemount and Luancheng), forest (Borden Forest) and grassland (Duolun) (Welp et al., 2012), at one Beijing site (Wen et al., 2010), and in the Pacific Northwest (Lai and Ehleringer, 2011). These results showed that d_{moisture} diurnal variation is not a pattern unique to any particular location or vegetation type, and the diurnal pattern of d_{moisture} may suggest that d_{moisture} is not a conserved tracer of humidity conditions in the marine moisture source region (Welp et al., 2012), and is strongly controlled by local evaporation and transpiration.

There are no clear diurnal patterns of d_{moisture} during the cloudy days when plant activity is low, which supports the role plants play in regulating d_{moisture}; namely, there are no clear diurnal variations for d_{moisture}, except at S1-Jun (Fig. 8). The d_{moisture} value at S1-Jun shows diurnal variation (Fig. 8b), which corresponds to patterns of d_{leaf} after 08:00 (Figs. 7b and 8b).

4.3 The controlling factors of the d-excess of various pools

4.3.1 Correlations between d_{leaf} and RH or T

Significantly positive correlations are found between d_{leaf} and RH at all the study sites during our study periods (from June to September) (Table 6). Significantly negative relationships are also found between d_{leaf} and T, except in Q.S. at S1-Jun. In addition, during the sunny days, stronger relationships between d_{leaf} and T/RH are found at all study sites (Table 7). These results suggest that meteorological conditions such as RH and T have a strong effect on variations in d_{leaf}, likely through the effect on transpiration.

4.3.2 Correlations between d_{soil} and RH or T

There are significant correlations between d_{soil} and RH or T in several cases. For example, the d_{soil} of 10 cm is positively correlated with RH (Table 6), and the d_{soil} of 5 and 10 cm are negatively correlated with T (Table 8) at S3. The d_{soil} of 10 cm is also positively correlated with RH (Table 6), and the d_{soil} of 5 cm is negatively correlated with T at S1-Sep (Table 8). At S3-Aug, during the first day after rain event, the negative relationship between d_{soil} at 5 and 10 cm and T (Table 8), the clear diurnal variations in d_{soil} at 5 and 10 cm (Fig. 5d) and the opposite patterns between the diurnal variations in d_{soil} and d_{moisture} (Fig. 10), are found. These results indicate that the d-excess of moisture through soil evaporation also has an important role in changing the d_{moisture} of local air moisture during the sunny days after the rain events, and this role is controlled by meteorological conditions. At the same time, the d_{soil}/RH are 0.08 ‰ %$^{-1}$, and the d_{soil}/T vary from −0.16 to −0.54 ‰ °C^{-1}, respectively, which are an order of magnitude lower than those of the d_{leaf}/RH (from 0.49 to 2.53 ‰ %$^{-1}$) and d_{leaf}/T (from −6.74 to −1.59 ‰ °C). This means that even on the sunny day, the contribution of shallow soil water evaporation to d_{moisture} is much less than that of plant transpiration (Tables 6 and 7).

4.3.3 Variations in d_{moisture} and its controlling factors

The main moisture sources of local air moisture come from canopy transpiration, soil evaporation and atmospheric entrainment (Lai and Ehleringer, 2011). If d_{moisture} is a conservative tracer of conditions in the moisture source region, we would not expect it to vary with local relative humidity unless there is a local source of moisture for

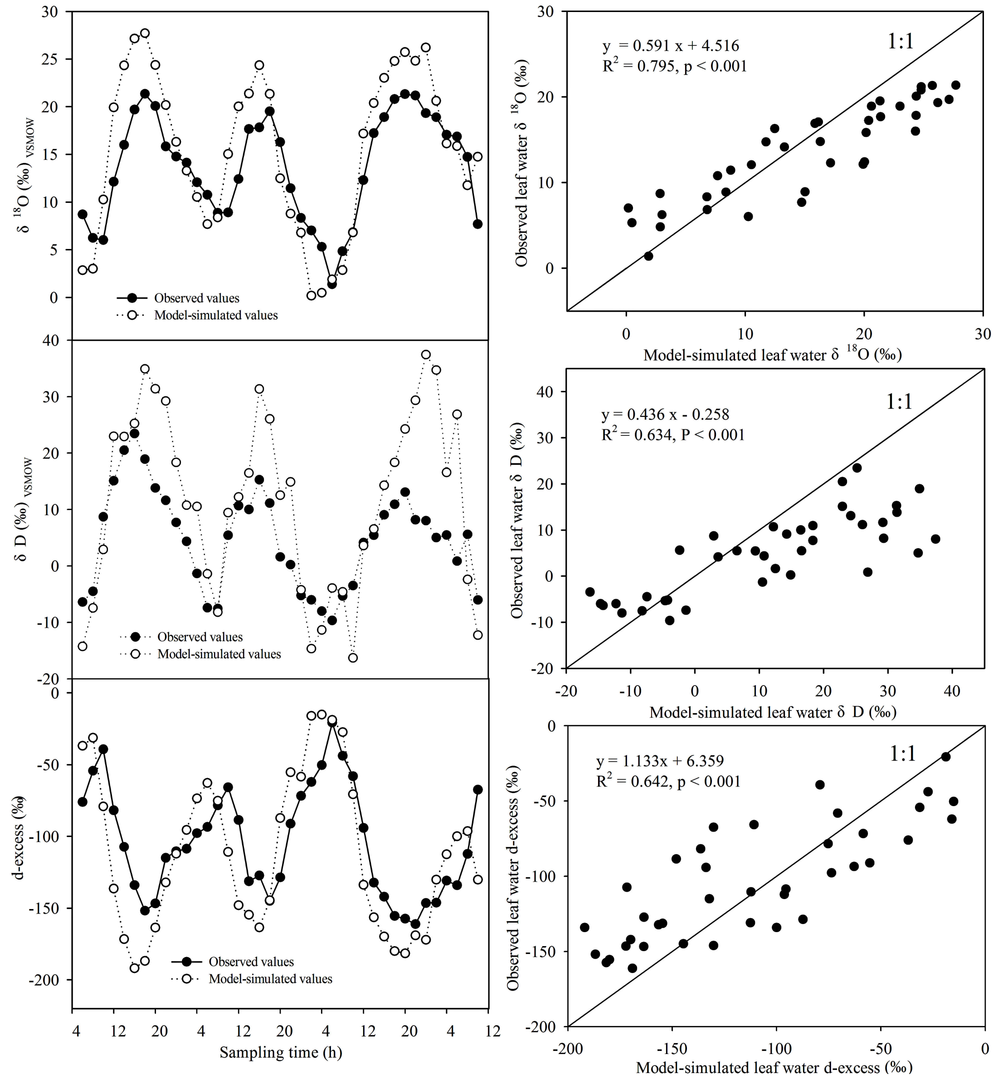

Figure 11. Comparison of leaf water δ^{18}O, δD and d-excess values for *Populus euphratica* between the simulated values (steady-state Craig–Gordon model) and observed values at S5-Aug.

the atmosphere (Welp et al., 2012). In our study, except near the ground at S1-Sep, significantly negative correlations are found between d_{moisture} and RH at all the study sites. The mean d_{moisture}/RH is -0.27 ‰ %$^{-1}$, ranging from -0.68 ‰ %$^{-1}$ (S5-Aug) to -0.13 ‰ %$^{-1}$ (S4-Aug) (Table 6). Except at S5-Aug, the rates of d_{moisture}/RH of all the sites are lower than that of Merlivat and Jouzel's theoretical prediction (-0.43 ‰ %$^{-1}$) (Merlivat and Jouzel, 1979) (Table 6). Aemisegger et al. (2013) reported the importance of continental moisture recycling. It concluded that the contribution of plant transpiration to the continental evaporation flux can be deduced from the d_{moisture}–RH relation at the seasonal timescale and for individual events (Aemisegger et al., 2013). The relationship between d_{moisture} and RH strongly depends on the isotopic composition of the soil moisture and the contribution of transpiration, which can be assumed in first order to be non-fractionating over timescales of longer than 1 day (Harwood et al., 1999; Farquhar et al., 2007). Welp et al. (2012) also reported that afternoon averages (12:00–18:00 LST) of d_{moisture} are correlated with RH at the New Haven (d_{moisture}/RH $= -0.36$ ‰ %$^{-1}$) and Borden Forest (d_{moisture}/RH $= -0.22$ ‰ %$^{-1}$) sites during the summer months (June–August). In addition, except at S2-Jun, there are significantly positive relationships between d_{moisture} and T at all the sites. The mean d_{moisture}/T are 0.72 ‰ °C^{-1}, varying from 0.54 ‰ °C^{-1} (S4-Aug) to 0.91 ‰ °C^{-1} (S1-Jun) (Table 8). This is higher than that of Merlivat and Jouzel's theoretical prediction (0.35 ‰ °C^{-1}) (Merlivat and Jouzel, 1979). These results suggest that local contributions of moisture to d_{moisture} are high, and that local meteorological conditions such as RH and T have an important effect on d_{moisture}. In addition, during the sunny days, the clear diurnal patterns of d_{leaf} (Fig. 4) and d_{moisture} (Fig. 6, except panel c), the opposite patterns between the diurnal variations in d_{leaf} and d_{moisture} (Fig. 9), and a significantly negative relationship between d_{moisture} and d_{leaf} ($p < 0.001$) and highly significant relationships between d_{moisture} and RH/T ($p < 0.001$) (Tables 6, 7 and 8) are found, suggesting that there is a strong linkage between d_{moisture} and d_{leaf}, and that the regulation of plant transpiration on the variations in atmospheric vapor isotopic composition is strong.

4.4 Comparison of modeled and observed leaf water δ^{18}O, δD and d-excess

The modeling results reasonably captured the diurnal variations in δ^{18}O, δD and d-excess, with some discrepancies (Fig. 11). The discrepancies were larger for δD than for δ^{18}O. The results indicate that a better parameterization of δD or non-steady-state modeling is likely needed to simulate the d-excess dynamics in leaf water more accurately. The d-excess values of other components (e.g., soil water, atmospheric vapor) are rarely seen in the literature, and the current study provides a valuable source for validating the modeling work of the d-excess of various components.

5 Conclusions

Through extensive characterization of δD, δ^{18}O and d-excess in different water pools (e.g., leaf water, xylem water, 5 and 10 cm soil water and air moisture) in the HRB, we aimed to investigate the effects of local processes (e.g., plant transpiration and evaporation) on the d-excess variations in different water pools. We concluded the following:

1. There were significant variations in δD and δ^{18}O in different water pools. The most negative δD and δ^{18}O values were found in air moisture. The average δD and δ^{18}O values of air moisture were −101.8 and −14.1 ‰ in the upper reaches and −124.4 and −16.8 ‰ in the lower reaches, respectively. The most positive δD and δ^{18}O values were found in leaf water. The average δD and δ^{18}O values of leaf water were 0.9 and 8.1 ‰ in the upper reaches and 6.6 and 18.2 ‰ in the lower reaches, respectively. The δD–δ^{18}O regression lines of leaf water, xylem water and shallow soil water deviated gradually from their corresponding LMWL with the increase in T and the decrease in RH.

2. Peak-to-trough amplitudes of d_{leaf}, d_{xylem}, d_{soil} and d_{moisture} varied from 52.6 to 147.2 ‰, 10.2 to 48.8 ‰, 25.7 to 51.6 ‰ and 17.3 to 39.9 ‰, respectively, which were an order of magnitude higher than previous observations and predications (e.g., Merlivat and Jouzel, 1979; Welp et al., 2012). The mean d_{moisture} values were the most positive, which were 7.7 ‰ near the ground and 11.2 ‰ at the canopy level in the upper reaches, 12.8 and 5.6 ‰ at the canopy level at the riparian forest site and at the Gobi site in the lower reaches. The d_{leaf} values were the most negative, which were −41.1 ‰ in the upper reaches and −145.0 ‰ in the lower reaches.

3. Several lines of evidence suggest that d_{moisture} is not a conserved tracer of humidity conditions of the marine moisture source region, and is controlled by local transpiration and evaporation. The evidence includes the clear diurnal patterns of d_{moisture} and d_{leaf} during the sunny days, the strong correlations of d_{leaf} with meteorological conditions (T and RH), the significant correlations of d_{moisture} with d_{leaf}, T and RH, and no diurnal patterns of d_{moisture} and d_{leaf} during the cloudy days when plant activity was low. In addition, large differences between average d_{xylem} and d_{leaf} were observed in our study, indicating that the amount of d-excess lost through transpiration into the atmosphere was high. Our results indicate that plant transpiration strongly regulates d_{moisture}, especially during the sunny days. The effect is controlled by local meteorological conditions, such as T, radiation and RH.

4. The influences of shallow soil water evaporation on d_{moisture} variations are generally small. However, the d-excess values of moisture from soil evaporation have a strong effect on d_{moisture} on the first sunny day after a rain event. The size of this effect is related to T and RH.

5. The steady-state Craig–Gordon model can reasonably capture the diurnal variations in δ^{18}O, δD and d-excess with small discrepancies. Non-steady-state models are likely needed to simulate the d-excess dynamics of leaves and other components more accurately.

Our study shows that the d_{moisture} of the surface air at continental locations can be significantly altered by local processes in both mountain areas (Qilian Mountains) and extremely dry environments (Ejin); therefore, such an effect is likely a universal phenomenon across regions with varying climates.

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