Hydrol. Earth Syst. Sci. Discuss., 11, 4433–4476, 2014
www.hydrol-earth-syst-sci-discuss.net/11/4433/2014/
doi:10.5194/hessd-11-4433-2014

Hydrology and Earth System Sciences
Discussions
Open Access

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

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Received: 4 April 2014 – Accepted: 10 April 2014 – Published: 28 April 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Deuterium excess (d-excess) of air moisture is traditionally considered as 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 is not well documented. In this study, we quantified d-excess of air moisture, leaf and xylem water of multiple dominant species as well as shallow soil water (5 and 10 cm) at hourly interval during three extensive field campaigns at two climatically different locations within the Heihe River Basin. The results showed that with the increase of temperature (T) and decrease of relative humidity (RH), the δD-δ^{18}O plots 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 among 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 (−85.6 ‰) were found in leaf water. 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 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 the opposite diurnal variations for d_{leaf} and d_{moisture} during the sunny day, and for d_{soil} and d_{moisture} during the first sunny day after rain event. Significant negative relationships were found between d_{leaf} and d_{moisture} in all the sites during the sunny day. 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 the sunny days. The role of shallow soil water on d_{moisture} is generally much smaller but could be large at the 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 cycle, ecological processes, and palaeoclimate 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; Zhang et al., 2011; Good et al., 2012). Plant uptake does not fractionate source water (White et al., 1985), δD or δ^{18}O therefore can be used to track 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 the catchment water movements (Brooks et al., 2010), geographic origin of water vapor (Clark and Fritz, 1997), basin-level water recycling (Salati et al., 1979), and to reconstruct the past environmental parameters such as ambient temperature (T) and relative humidity (RH) (e.g. Helliker and Richter, 2008).

Deuterium-excess (d-excess) is defined as d-excess = δD − 8.0 × δ^{18}O (Dansgaard, 1964). Points that fall on the Global Meteorology Water Line (GMWL) have a constant d-excess of 10.0 ‰. This is because rainout isotopic fractionation affects the position of the data points on the GMWL, but 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 as 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 thought to be a useful tracer for identifying moisture source locations when there are no contributions from surface evapotranspiration (Uemura et al., 2008). Transpiration shouldn't change d-excess since transpiration does not fractionate source water. Evaporation, however, usually results in a higher d-excess (Gat et al., 1994). The application of d-excess in evaporation estimation has been conducted in the past. For example, d-excess was

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used for quantifying sub-cloud evaporation in Alpine regions (Froehlich et al., 2008) and estimating contribution of evaporation from the Great Lakes to the continental atmosphere (Gat et al., 1994).

Using a meta-analysis approach to synthesize the d-excess measurements from multiple sites, Welp et al. (2012) showed that d-excess can be significantly altered by local processes and it is not a conserved tracer of humidity from the marine moisture source region as previously assumed. In addition, modeling simulation also showed that plant transpiration plays an important role in diurnal d-excess variations (Welp et al., 2012), which contradicts with the conventional understanding. Based on isotopic observations from a US Pacific northwest temperate forest and modeling exercise, Lai and Ehleringer (2011) concluded that atmospheric entrainment appears to drive the isotopic variation of water vapor in the early morning when the convective boundary layer rapidly develops, while evapotranspiration becomes more important in the mid-afternoon as a primary moisture source of water vapor in their 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 location. With these new understanding of biological and environmental controls on d-excess variations, field observations of the role of direct vegetation effect on diurnal d-excess variations, however, is not readily seen in literature. In addition, theory predicts that d-excess is affected both T and RH, and d-excess of evaporating vapor increases with T ($0.35\,‰\,^{\circ}\mathrm{C}^{-1}$) but decreases with RH ($-0.43\,‰\,\%^{-1}$) (Merlivat and Jouzel, 1979). The field-testing of this theoretical relationship is lacking, and the quantitative relationship will enhance our predication 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 exists for evapotranspiration similar to the d-excess–RH relationship of ocean evaporation Evaporation of water from the earth surface is a key coupling process in the hydrological cycle between the earth surface and the atmosphere. Studying the evaporation process and its link to the atmospheric circulation is thus central for a better understanding

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of the feedbacks between the earth surface and the atmosphere (Aemisegger et al., 2013).

In this study, we quantified the d-excess dynamics of air moisture, leaf and xylem of multiple dominant species as well as shallow soil water (5 and 10 cm) at hourly interval during three extensive field campaigns at two climatically different locations within the Heihe River Basin, China. We aim to provide a field-based fine-resolution d-excess record and explore the underlying mechanisms. The specific questions to be answered for this study are (1) what's the diurnal patterns of d-excess in the air moisture, leaf, root, xylem and shallow soil water under different climatic and meteorological conditions? (2) What are the mechanisms of the observed patterns?

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 (the HRB), northwestern China (Fig. 1). Dayekou is located at the upper reaches (Fig. 1). The mean annual temperature of Dayekou is about 0.7 °C, with a mean January temperature of −10.1 °C and a mean July temperature of 16.3 °C. Mean annual precipitation is 369.2 mm. Ejin is located at the lower reaches (Fig. 1). The mean annual temperature of Ejin is 8.8 °C, with a mean January temperature of −11.0 °C and a mean July temperature of 27.0 °C. Mean annual precipitation from 1960 to 2007 is 35.0 mm yr^{-1}, with 75 % of the rainfall occurring between June and September. With a strong potential evapotranspiration of 3700 mm, Ejin is considered one of the driest regions in China.

At Dayekou, three sites were selected with two sites (S1 and S2) at the Pailugou valley and the other (S3) at the Guantan valley. The S1 site (100°18′ E, 38°33′ N, 2900 m) was dominant by tree species *Qinghai Spruce* (Q.S.), shrub species *Potentilla fruticosa* (P.F.), and grass species *Polygonum viviparum* L (P.V.). The S2 site (100°17′ E,

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38°33′ N, 2700 m) was dominant by tree species Q.S., and grass species *Stipa capillata* Linn (S.C). The S3 site (100°15′E, 38°32′N, 2800 m) was dominated by tree species Q.S. Two sites were selected at Ejin, one is at the riparian forest (S4: 101°14′ E, 42°01′ N, 930 m) with dominant species of *Populus euphratica* Oliv (P.E.) and *Sophora alopecuroides* (S.A.), another is at the Gobi (S5: 101°07′ E, 42°16′ N, 906 m) with the main species of *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. In the upper reaches, at the S1 site, samples were taken from 06:00 LT 23 June to 18:00 LT 25 June 2011 with 1 h intervals for leaf and stem of Q.S., 5 and 10 cm soil as well as atmospheric vapor near the ground and at the canopy. Leaf and stem of P.F. as well as leaf and root of P.V. were taken from the same period with 2 h intervals. All these samples were refereed as S1-Jun in September (all these samples were refereed as S1-Sep), samples were taken from 08:00 LT 6 September to 17:00 LT 8 September 2011 with 1 h interval for leaf and stem of Q.S., 5 and 10 cm soil and atmospheric vapor near the ground and at the canopy. Leaf and stem of P.F. as well as leaf and root of P.V. were taken from the same period with 2 h intervals. At the S2 site, leaf and stem of Q.S., 5 and 10 cm soil and atmospheric vapor near the ground and at the canopy were sampled from 06:00 LT of 27 June to 18:00 LT of 28 June 2011 with 1 h intervals, while leaf and root of *Stipa capillata* (S.C.) were taken from 06:00 LT of 27 June to 18:00 LT of 28 June 2011 with 2 h intervals. At the S3 site, it rained twice during the sampling period (from 17:00 LT 31 July to 04:00 LT 1 August and from 10:40 to 22:00 LT 2 August 2009). Leaf and stem of Q.S. as well as 5 LT 1 August to 18:00 LT 2 August and from 06:00 to 18:00 LT 3 August 2009 with 2 h intervals. The atmospheric vapor at canopy was collected from 06:00 LT 2 August to 04:00 LT 3 August 2009 with 2 h intervals.

In the lower reaches of the HRB, at the riparian forest (S4), leaf and stem of *Populus euphratica* (P.E.) and leaf of *Sophora alopecuroides* (S.A.), 10 cm soil and atmospheric

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vapor at canopy were taken from 06:00 LT 6 August to 22:00 LT 7 August 2009 with 2 h intervals. At Gobi, leaf and stem of *Reaumuria soongorica* (R.S.), 10 cm soil and atmospheric vapor at canopy were taken from 18:00 LT 10 August to 18:00 LT 12 August 2009 with 2 h intervals. When samples were taken during rainy day and morning, napkins were used to wipe off water from the leaf and stem surfaces.

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., 2011). The extracted water was frozen into 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 within a canopy and near ground (about 20 cm above the ground). Air was sucked by a small diaphragm pump through low adsorption plastic tubes and a small cryogenic trap at $-80\,^{\circ}$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 the tubings were 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 for the water samples were measured using Euro EA3000 element analyzer coupled to an Isoprime Isotope Ratio Mass Spectrometer (Isoprime Ltd, UK) at 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 periods, relative humidity (RH), air temperature (T) and photosynthetically available radiation (PAR) at S2 (2700 m at Pailugou) and S3 (2800 m at Guantan) were measured every 30 min with a weather station permanently installed at the station. At S1-Sep and S1-Jun (2900 m at Pailugou), S4 (930 m at the riparian forest) and S5 (906 m at Gobi), RH, T and PAR were measured every 10 min with two portable weather stations. We measured T, RH and PAR due to their significant effects on soil evaporation and transpiration.

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 day, whereas high RH, and low T and PAR were found during the cloudy day at each site (Fig. 2). The RH decreased and T increased from the upper reaches to the lower reaches, except at S2 with the lowest mean RH (42.2 %) (Table 2 and Fig. 2).

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

Figure 3 shows measured isotopic composition 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 the relatively small

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ranges, compared to those of leaf water and air moisture (Table 3, 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, of all species. The δD and δ^{18}O of air moisture at canopy ranged from −188.9 to −25.7 ‰ and from −24.9 and −6.0 ‰, respectively in all study sites. The δD and δ^{18}O of air moisture near the ground ranged from −133.0 and −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 in all study sites that increased with rising altitude (Table 3). The δD-δ^{18}O plots followed closely with 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 ‰ in the riparian forest site and −136.3 and −17.7 ‰ in the Gobi site, respectively.

Leaf water had the highest average δD and δ^{18}O values, and leaf δD-δ^{18}O plots highly deviated 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 of altitude and increase of T (Tables 2 and 3). In the upper reaches, the average δD in 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 in leaf water of Q.S., P.F., P.V. and S.C. were 8.3, 3.0, 1.5 and 8.2 ‰, respectively. In the lower reaches, the average δD in 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 in leaf water of P.E., S.A and R.S 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 soil water and −43.2 and −5.2 ‰ in 10 cm soil in the upper reaches, and −34.2 and 1.4 ‰ in 10 cm water in the lower reaches, respectively. With the increase of T and decrease of altitude, the δD-δ^{18}O plots gradually deviated from their corresponding LMWL, and the

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variations of 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 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 of d-excess in each water pools in the HRB

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

The diurnal variations of 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 day, we found clear and robust diurnal variations of d_{leaf} in all the study sites. The maximum values of d_{leaf} occurred from 6.00 a.m. to 10.00 a.m., gradually decreasing to a minimum value in the mid-afternoon (from 14:00 to 18:00 LT), and increasing again to a maximum value from 04:00 to 08:00 LT in 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 ‰) in the riparian forest site were higher than those of R.S. (−210.4 ‰) in the Gobi site (Table 4). The peak-to-trough amplitudes of d_{leaf} varied greatly. They were 147.2 ‰ in tree (Q.S.), 122.6 ‰ in shrub (P.F.) and ranging from 143.1 to 52.6 ‰ in grass (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., 96.9 ‰ in S.A., and 80.6 ‰ in R.S. (Table 4).

Compared to d_{leaf}, the diurnal variations of d_{xylem} of all species were more stable, and showed no clear diurnal variations (Fig. 4). In the upper reaches, the mean d_{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 ‰ (in the riparian forest site) and −44.8 ‰ (in the

Gobi site), and the differences between d_{xylem} and d_{leaf} were 102.2 and 165.6 ‰ for S4 and S5 in the lower reaches, respectively (Table 4).

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

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. In the riparian forest and the Gobi sites, 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 of T and decrease of RH (Tables 2 and 4). Except at S3-Aug, there were no temporal trends of d_{soil} at 5 and 10 cm (Fig. 5a–e). The d_{soil} of the 5 and 10 cm were the lowest near 00:00 LT and were the highest about from 04:00 to 08:00 LT for site S3-Aug (Fig. 5d).

Figure 6 shows the diurnal variations of air moisture d-excess ($d_{moisture}$) from each study site at 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 ‰ in S4 and 30.6 ‰ in S5, respectively (Table 4 and Fig. 6). Except S2-Jun (Fig. 6c), the $d_{moisture}$ values varied diurnally, showing a clear and robust pattern of maximum $d_{moisture}$ during the mid-day (about from 10:00 to 16:00 LT) (Fig. 6).

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

The d_{leaf} values during the cloudy day were significantly higher than those of the sunny day and d_{leaf} values were significantly lower than those of d_{xylem} values. During the cloudy day with low PAR, at 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 depth, except of $d_{moisture}$ and d_{leaf}

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at S1-Jun site (Figs. 7 and 8). In addition, at S3-Aug site, the d_{leaf} increased gradually from 06:00 to 16:00 LT and showed the opposite diurnal variations compared to those of the sunny day. The reason is the leaf absorption of precipitation with high d-excess (11.8 ‰ in Zhao et al., 2011) during the rainy conditions (precipitation occurred from 10:40 to 22:00 LT on 2 August).

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

3.4.1 Relationships between d-excess of various pools and RH

Significantly positive correlations were found between d_{leaf} and RH at all the study sites during the study periods (from June to September) in the upper reaches of the HRB (Table 5). As RH increased by 1 %, the increasing magnitude of d_{leaf} ranged from 0.49 ‰ (S2-Jun) to 1.52 ‰ (S1-Sep) in Q.S., from 1.07 ‰ (S1-Jun) to 2.38 ‰ (S1-Sep) in P.F., and from 0.99 ‰ (S1-Jun) to 2.53 ‰ (S1-Sep) in P.V. The increasing magnitude of S.C. was 0.56 ‰. In the lower reaches, as RH increased by 1 %, the amount of d_{leaf} increase was 1.41 ‰ in P.E., 1.21 ‰ in S.A. at S4, and 1.77 ‰ in R.S. at S5. Significantly positive correlations were also found between d_{leaf} and RH at all the study sites during the sunny day (Table 6).

Except near the ground at S1-Sep, significantly negative correlations were found between $d_{moisture}$ and RH at all the study sites during our study periods (June–September) (Table 5). The $d_{moisture}$/RH were −0.15 ‰%$^{-1}$ at S1-Jun and −0.27 ‰%$^{-1}$ at S2 near the ground air moisture. For the canopy air moisture, the $d_{moisture}$/RH were −0.24, −0.32, −0.25, −0.15, −0.13 and −0.68 ‰%$^{-1}$ at S1-Sep, S1-Jun, S2, S3, S4 and S5, respectively. During the sunny day, the $d_{moisture}$/RH were 0.36 and 0.31 ‰%$^{-1}$, respectively, for near the ground and at the canopy, which were larger than the overall values except S5 (Table 6). Except at site S1-Jun, S1-Sep and S3-Aug, no significant relationship was found between d_{soil} (5 and 10 cm) and RH at any study site (Table 5).

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3.4.2 Relationships between d-excess of various pools and T

Significantly negative relationships were found between d_{leaf} and T except in Q.S. at S1-Jun in the upper reaches (Table 7). 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 and S3, respectively. The magnitudes were −6.45 ‰ °C^{-1} and −5.10 ‰ °C^{-1} for P.F., −6.74 ‰ °C^{-1} 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. In the lower reaches, the decreasing magnitudes of d_{leaf} in P.E. and S.A. were −4.40 and −2.15 ‰ °C^{-1} at S4, respectively. It was −1.82 ‰ °C^{-1} for R.S. at S5 (Table 7). During the sunny day, there were significantly negative relationships between d_{leaf} and T (Table 6).

There were significantly positive relationships between d_{moisture} and T at all sites except S2 (Table 7). 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 canopy were 0.81, 0.91, 0.64, 0.54 and 0.83 ‰ °C^{-1} at S1-Sep, S1-Jun, S3, S4 and S5, respectively (Table 7). During the sunny day, the d_{moisture}/T were 1.18 and 1.11 ‰ °C^{-1}, respectively, for near the ground and at the canopy, which were larger than the overall values (Table 6).

At S2, there were positive relationships between d_{soil} (both 5 cm and 10 cm 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 depth, respectively. However, at S3, there were negative relationships between d_{soil} (both 5 cm and 10 cm 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 cm and 10 cm depth, respectively. Significantly negative relationship was also found between d_{soil} of 5 cm depth and T at S1-Sep ($d_{\mathrm{soil}}/T = -0.16$ ‰ °C^{-1}, $P = 0.002$) (Table 7).

3.4.3 Relationships between d-excess of various pools

During the sunny day, we found an opposite pattern between the diurnal variations of d_{leaf} and d_{moisture}. Similar pattern was found between d_{soil} during the first sunny

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day after rain and $d_{moisture}$. 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 6). In the upper reaches, d_{leaf} of wood species (Q.S.) were correlated significantly to $d_{moisture}$ both near the ground and at the canopy, and the slopes were −1.47 and −1.40, respectively. The 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 canopy were −0.06 in woody species (P.E.), −0.10 in shrub (S.A.) in the riparian forest site and −0.28 in the Gobi site (Table 6).

4 Discussion

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

The isotopic compositions of water (δD and δ^{18}O) 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., 2011), groundwater (Zhao et al., 2012) and precipitation (Dalai et al., 2002; Karim and Veizer, 2002; Zhao et al., 2011; Soderberg et al., 2013). However, fewer investigations were conducted to simultaneously measure δD and δ^{18}O of leaf water, xylem water, shallow soil water and air moisture, especially on the diurnal variations of these pools at ecosystem scale.

Our results show that there are significant differences in δD and δ^{18}O among leaf and xylem water, soil water and air moisture and different δD-δ^{18}O plots patterns due to different processes related to soil evaporation, plant transpirations and plant physiology. For example, compared to that of xylem water and shallow soil water, leaf water have the highest average δD and δ^{18}O values and the largest ranges, and showing the greatest variation in δ^{18}O values in all the study sites. In addition, the δD-δ^{18}O plots of

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leaf water highly deviate from their corresponding LMWL (Table 2; Fig. 3), suggesting a strong transpiration enrichment effect. With the decrease of RH and increase of T, leaf water δD and δ^{18}O values increased and the δD-δ^{18}O plots gradually deviate from their corresponding LMWL due to stronger transpiration, suggesting that climatic conditions have significant effect on variations of 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, the patterns of δD-δ^{18}O plots 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 water are subject to mild evaporation. These results are consistent with the fact of the horizontal distributions of QS root and shallow rooting of herbaceous plants such as PV. However, at relatively lower altitude such as S2-Jun and S3, the xylem water δD and δ^{18}O of QS. are lower than that of soil water except the herbaceous plant (SC) (Table 3), and the δD-δ^{18}O plots of soil water deviate from the LMWL (Fig. 3). These results may be related to stronger shallow soil evaporation. In the lower reaches, the δD and δ^{18}O of 10 cm soil water are significant higher than those of P.E. and R.S. xylem water, and the δD-δ^{18}O plots obviously deviate from the LMWL of the lower reaches, suggesting that the strongest soil water evaporation occur 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 less than 8.0 (Dansgaard, 1964). In our study, the slopes of 5 and 10 cm soil water evaporation line varied from 2.6 to 7.4 (Table 8). Relative high slopes were found in S1-Sep (7.1) and S3-Aug (7.4) likely due to low temperature during September at S1-Sep and rain event occurring at S3. The slopes of other sites are lower than 5.0, especially in the lower reaches, and the values in slopes are very small in the riparian forest site (2.6) and the Gobi site (2.8) (Table 8), 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 δD-δ^{18}O plots from shallow soil water gradually deviate

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from their corresponding LMWL with the decrease of altitude, suggesting a stronger water loss through direct evaporation especially in extremely arid region 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 previous study in urban settings, agricultural settings, forest and grassland in China, Canada and USA (Welp et al., 2012).

4.2 Variations of $d_{\text{leaf}}, d_{\text{xylem}}, d_{\text{soil}}$ and d_{moisture} under different conditions

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

The significant differences of d-excess are found between leaf water and xylem water in both the upper reaches and lower reaches. In order to evaluate the effect of plant transpiration on d-excess value of air moisture, we calculate the difference between d_{leaf} and d_{xylem} assuming d_{xylem} represents the d-excess of source water. The differences of averaged d_{xylem} and d_{leaf} vary from 21.9 to 165.6 ‰, and the differences of these values are 70.9 ‰ in S.Q., 30.6 ‰ in P.F., 21.9 ‰ in P.V. and 36.6 ‰ in S.C. in the upper reaches, and are 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 high differences between d_{xylem} and d_{leaf} found in this study indicate that plant transpiration results in lower d_{leaf} values of leaf water, and releasing water vapor with higher d-excess values into atmosphere. These were consistent with those expected from the recycling of surface evapotranspiration (Gat et al., 1994). Therefore, mixing of transpiration moisture into atmosphere will increase d_{moisture}. In addition, during the sunny days, the clear and robust diurnal variations of

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d_{leaf} with daily maximum in the early-morning and negative peak in the mid-afternoon are found in all the study sites (Fig. 4 and Table 4), while no diurnal variations of d_{leaf} are found at the cloudy days (Fig. 7). These results indicate that d_{leaf} is affected by meteorological conditions through their effect on plant transpiration. At the same time, no diurnal variations of d_{xylem} of all species are found at both the sunny and cloudy days (Figs. 4 and 7), indicating that d_{xylem} is stable and 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 on changing the $d_{moisture}$ of local air moisture during the sunny day.

4.2.2 Variations of d-excess in shallow soil water

The mean d-excess values of shallow soil water are −0.9 ‰ at 5 cm and −1.2 ‰ at 10 cm in the upper reaches; and −31.0 and −59.1 ‰ at 10 cm in the lower reaches, and the peak-to-trough magnitudes of d_{soil} are significantly lower than those of d_{leaf} (Table 4). No clear diurnal trends of d_{soil} are found except at S3. At S3, there are clear daily variations of d_{soil}, which reaches the lowest value about 12:00 LT and reaches the highest value about 04:00–06:00 LT at the first sunny day after rain event (Fig. 5d). This pattern is likely due to the strong evaporation during the first sunny day after rain event (rain stopped about 22:00 LT and we sampled at 06:00 LT the next day) (Fig. 5d). Our results indicate that d-excess of moisture through soil evaporation also has an important role on changing the $d_{moisture}$ of local air moisture during the sunny day after the rain events, and this role was controlled by meteorological conditions.

4.2.3 Variations of 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 are 17.3 ‰ (S4) and 30.6 ‰ (S5) at the canopy in the lower reaches (Table 4 and Fig. 6). These observed values are higher than that of previous reports that the peak-to-trough magnitudes vary from

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3.5 to 17.1‰ (Welp et al., 2012). The lowest $d_{moisture}$ values are found near the ground (1.5‰) at high altitude during the September (S1-Sep). The low values may be related to 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 day, the $d_{moisture}$ vary diurnally, showing a clear and robust pattern of the highest $d_{moisture}$ at midday, and the lowest $d_{moisture}$ values at night at all the sites (Fig. 6). The same trends also found in urban settings (New Haven and Beijing), agricultural settings (Rosemount and Luancheng), and forest (Borden Forest) and grassland (Duolun) (Welp et al., 2012); in 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 at the marine moisture source region (Welp et al., 2012), and is strongly controlled by local evaporation and transpiration.

No diurnal patterns during the cloudy day support the role vegetation plays in d-excess variation. Namely, there are no clear diurnal variations for $d_{moisture}$ except at S1-Jun (Fig. 8). The $d_{moisture}$ at S1-Jun shows diurnal variation (Fig. 8b), which corresponds to patterns of d_{leaf} after 08:00 LT (Figs. 7b and 8b).

4.3 The controlling factors of d-excess of various pools

4.3.1 Correlations between d_{leaf} and RH or T

The significantly positive correlations are found between d_{leaf} and RH at all the study sites during our study periods (from June to September) (Table 5). The d_{leaf}/RH ranges from 0.49 to 2.53‰%$^{-1}$. Significantly negative relationships are also found between d_{leaf} and T except in Q.S. at S1-Jun The d_{leaf}/T ranges from −6.74 to −1.59‰°C^{-1} in the upper reaches, and from −4.40 to −1.82‰°C^{-1} in the lower reaches (Table 7). In addition, during the sunny day, high significantly relationships between d_{leaf} and

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T/RH are found at all study sites (Table 6). These results suggest that meteorological conditions such as RH and T have strong effect on variations of 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 5), and d_{soil} of 5 and 10 cm are negatively correlated with T (Table 7) at S3. The d_{soil} of 10 cm is also positively correlated with RH (Table 5), and d_{soil} of 5 cm is negatively correlated with T at S1-Sep (Table 7). These results suggest that the water evaporation of soil surface may play a similar role to leaf transpiration as an important source to affect the isotopic composition of atmospheric vapor. However, 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 ‰°C^{-1} % to −1.59 ‰°C^{-1}). This means that even at the sunny day, the contribution of shallow soil water evaporation on d_{moisture} is much less than that of plant transpiration (Tables 5 and 6).

During the first sunny day after eight hours of rain, significantly positive relationships between d_{soil} of 10 cm and RH (Table 5) and significantly negative relationships between d_{soil} of 5 and 10 cm and T (Table 7) are found at the S3, showing the same correlations of d_{leaf} with RH and T. This suggests that soil evaporation plays the same role as plant transpiration during the sunny day after rainfall events, and the d_{soil} of shallow soil water after the rain was controlled by meteorological conditions. In addition, the opposite diurnal variations of d_{soil} and d_{moisture} (Fig. 10) suggest that soil evaporation has strong effect on d_{moisture} at the sunny day after rainfall events. However, the duration and strength of the soil evaporation effect and its correlations with precipitation amount/intensity need to be further studied.

4.3.3 Variations of d_{moisture} and its controlling factors

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 to the atmosphere (Welp et al., 2012). In our study, except near the ground in 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) to -0.10 ‰ $\%^{-1}$ (S4) (Table 5). Except of S5, the d_{moisture}/RH of all the sites are higher than that of Merlivat and Jouzel's theoretic prediction (-0.43 ‰ $\%^{-1}$) (Merlivat and Jouzel, 1979) (Table 5). Aemisegger et al. (2013) reported that 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 > 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 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, there are significantly positive relationships between d_{moisture} and T at all the sites. The mean d_{moisture}/T are 0.72 ‰ $^{\circ}\mathrm{C}^{-1}$, varying from 0.52 ‰ $^{\circ}\mathrm{C}^{-1}$ (S4) to 0.91 ‰ $^{\circ}\mathrm{C}^{-1}$ (S1-Jun) (Table 7). This is higher than that of Merlivat and Jouzel's theoretic prediction (0.35 ‰ $^{\circ}\mathrm{C}^{-1}$) (Merlivat and Jouzel, 1979). These results suggest that local contributions of moisture on d_{moisture} are high, and local meteorological conditions such as RH and T have an important effect on d_{moisture}. In addition, during the sunny day, the clear diurnal patterns of d_{leaf} (Fig. 4) and d_{moisture} (Fig. 6, except Fig. 6c), the opposite patterns between the diurnal variations of d_{leaf} and d_{moisture} (Fig. 9) and

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significantly negative relationship between $d_{moisture}$ with d_{leaf} and high significantly relationships between $d_{moisture}$ with RH/T (Tables 5–7) are found, suggesting that there is a strong linkage between $d_{moisture}$ and d_{leaf}, and the regulation of plant transpiration on the variations of atmospheric vapor isotopic composition is strong.

5 Conclusions

Through extensive characterization of δD, δ^{18}O and d-excess in different water pools (e.g. leaf water, xylem water, 5 cm 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 d-excess variations of different water pools. Here are our main findings:

1. The significant variations of δD and δ^{18}O in different water pools were found. The most negative δD and δ^{18}O were found in air moisture. The averaged δD and δ^{18}O 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 were found in leaf water. The averaged δD and δ^{18}O 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 plots of leaf water, xylem water and shallow soil water deviated gradually from their corresponding LMWL with the increase of temperature and decrease of relative humidity.

2. We found the 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 is an order of magnitude higher than previous observations and theoretical predications. The mean $d_{moisture}$ values were the most positive, and were 7.7 ‰ near the ground and 11.2 ‰ at the canopy in the upper reaches, 12.8 and 5.6 ‰ at the canopy in the riparian forest site and in the Gobi site in the lower reaches. The d_{leaf} values were the most negative, and 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 at the marine moisture source region, and is controlled by local transpiration, vegetation activity and meteorological conditions. The evidence includes the diurnal variations of $d_{moisture}$ and d_{leaf} with meteorological conditions, the diurnal variations of $d_{moisture}$ and d_{leaf} during the sunny days, the significant correlations of $d_{moisture}$ with d_{leaf}, T and RH, and no diurnal pattern of $d_{moisture}$ and d_{leaf} during the cloudy days. In addition, large differences of averaged d_{xylem} and d_{leaf} were found in this study, indicating d-excess losing through transpiration into atmosphere is high. Our results indicate plant transpiration strongly regulates $d_{moisture}$, especially during the sunny day. The strength is controlled by local meteorological condition, such as temperature, radiation and relative humidity.

4. The effects of shallow soil water evaporation on $d_{moisture}$ variations are generally small. However, the d-excess values of moisture from soil evaporation have strong effect on $d_{moisture}$ at the first sunny day after the rain event. The strength of this effect is related to temperature and relative humidity.

Acknowledgements. This research is supported by the National Science Foundation China (Grants 91325102, 91125025, 91025016), the Hundred Talents Program of the Chinese Academy of Sciences (No. 29Y127D11) and the International Development Fund from IUPUI. Special thanks are due to Guobao Xu, Wenling An, Xiaomei Peng, Heng Wei, Wenzhi Wang and Xiaomin Zeng for field sampling and laboratory analyses.

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Table 1. The sampling site vegetation types, sampling dates and time (LT), and sampling types in the Heihe River Basin.

Study region	Vegetation type	Altitude (m)	Locations	Time and interval	Meteorological condition	Sample types
The upper reaches	Forest	2900 m	S1-Sep: Pailugou	Sep 2011 1 h interval Sep 2011 2 h interval	The cloudy day: 6 Sep 2011 The sunny day: 7 and 8 Sep 2011	Qinghai Spruce – leaf and stem 5cm soil water 10cm soil water Atmospheric vapor near ground Atmospheric vapor at canopy Potentilla fruticosa – leaf and stem Polygonum viviparum – leaf and root
	Forest	2900 m	S1-Jun: Pailugou	Jun 2011 1 h interval Jun 2011 2 h interval	The sunny day: 23 Jun 2011 The drizzle day: from 9:00 to 20:00 on 24 Jun 2011 The cloudy day: 25 Jun 2011	Qinghai Spruce – leaf and stem 5 cm soil water 10 cm soil water Atmospheric vapor near ground Atmospheric vapor at canopy Potentilla fruticosa – leaf and stem Polygonum viviparum – leaf and root
	Forest	2700 m	S2-Jun: Pailugou	Jun 2011 1 h interval Jun 2011 2 h interval	The sunny day: 27 Jun 2011 The cloudy day: 28 Jun 2011	Qinghai Spruce – leaf and stem 5 cm soil water 10 cm soil water Atmospheric vapor near ground Atmospheric vapor at canopy Stipa capillata – leaf and root
The lower reaches	Forest	2800 m	S3-Aug: Guantan	Aug 2009 2 h interval	Rain time: from 17:00 31 Jul to 4:00 1 Aug; From 10:40 to 22:00 2 Aug The sunny day: 1 Aug Sampling time: from 6:00 1 Aug to 4:00 3 Aug	Qinghai Spruce – leaf and stem 5 cm soil water 10 cm soil water Atmospheric vapor at canopy
	Riparian forest	930 m	S4-Aug: Qidao-qiao	Aug 2009 2 h interval	The sunny day	Populus euphratica – leaf and stem Sophora alopecuroides – leaf 10 cm soil water Atmospheric vapor at canopy
	Gobi	906 m	S5-Aug: Gobi	Aug 2009 2 h interval	The sunny day	Reaumuria soongorica – leaf and stem 10 cm soil water Atmospheric vapor at canopy

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Table 2. Meteorological data at each site in the observed periods.

	2900 m Sep 2011 in Pailugou (S1-Sep)			2900 m Jun 2011 in Pailugou (S1-Jun)			2700 m Jun 2011 in Pailugou (S2-Jun)		
	RH (%)	T (°C)	PAR	RH (%)	T (°C)	PAR	RH (%)	T (°C)	PAR
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
Standard diviation	15.5	3.9	637.6	21.9	5.0	625.9	14.3	4.5	713.1
	2800 m Aug 2009 in Guantan (S3-Aug)			930 m Aug 2009 in Riparian forest (S4-Aug)			906 m Aug 2009 in Gobi (S5-Aug)		
	RH (%)	T (°C)	PAR	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	
Standard deviation	19.4	4.0	676.5	21.6	6.5		7.0	7.1	

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Table 3. Spatial and temporal variations of $\delta^{18}O$ and δD in different water pools in the Heihe River Basin. The numbers in the parenthesis indicate the sample number. The S1-Sep, S1-Jun, S2-Jun, S3-Aug, S4-Aug and S5-Aug indicate the Qinghai spruce forest at 2900 m in Sep 2011, 2900 m in Jun 2011, 2700 m in Jun 2011 and 2800 m in Aug 2009 in the upper reaches, the riparian forest at 930 m and the Gobi site at 906 m in Aug 2009 in the lower reaches. In the upper reaches, Q.S., P.F., P.V. and S.C. refer to *Qinghai Spruce*,*Potentilla fruticosa*, *Polygonum viviparum L.*, and *Stipa capillata* Linn in the forest ecosystem. In the lower reaches, P.E. and S.A. refer to *Populus euphratica Oliv.* and *Sophora alopecuroides* L. in the riparian forest ecosystem. R.S. refers to *Reaumuria soongorica* (Pall.) Maxim. at the Gobi site.

Study sites	The Qinghai Spruce forest (S1-Sep, S1-Jun, S2-Jun and S3-Aug)							
Plant species	Q.S. ($n = 166$)		P.F. ($n = 51$)		P.V. ($n = 51$)		S.C. ($n = 23$)	
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}
Mean	8.3	1.9	3.0	−5.6	1.5	−2.2	8.2	10.4
Minimum	−4.8	−29.4	−5.0	−37.6	−6.2	−35.0	1.7	−6.1
Maximum	18.5	22.8	17.7	31.6	20.1	44.0	11.4	22.8
SD	6.8	13.3	6.4	17.1	7.0	20.1	2.5	7.9
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}
Mean	−6.7	−47.2	−5.0	−39.1	−6.5	−44.6	−1.7	−32.7
Minimum	−9.0	−65.7	−7.5	−60.1	−8.5	−61.5	−5.4	−46.6
Maximum	−2.1	−21.6	−2.9	−23.6	−4.8	−32.7	1.0	−21.4
SD	1.6	10.1	1.1	8.8	1.0	7.4	1.6	7.3
$\delta X_{xylem} - \delta X_{leaf}$	**−15.0**	**−49.1**	**−8.0**	**−33.5**	**−8.0**	**−42.4**	**−9.9**	**−43.1**
Soil water	5 cm depth ($n = 166$)				10 cm depth ($n = 166$)			
	$\delta^{18}O_{soil}$		δD_{soil}		$\delta^{18}O_{soil}$		δD_{soil}	
Mean	−4.2		−34.9		−5.2		−43.2	
Minimum	−8.9		−62.0		−9.9		−67.4	
Maximum	2.5		−6.3		−0.7		−12.0	
SD	2.5		10.7		2.1		10.1	
Air moisture	At the canopy ($n = 172$)				Near the ground ($n = 172$)			
	$\delta^{18}O_{moisture}$		$\delta D_{moisture}$		$\delta^{18}O_{moisture}$		$\delta D_{moisture}$	
Mean	−13.3		−99.1		−14.1		−101.7	
Minimum	−18.5		−135.4		−19.7		−133.0	
Maximum	−6.0		−25.7		−7.9		−40.6	
SD	1.8		17.3		2.2		16.6	

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Table 3. Continued.

Study sites	The riparian forest (S4-Aug)				The Gobi (S5-Aug)	
Plant species	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}
Mean	14.6	6.2	15.6	10.4	27.2	7.5
Minimum	3.4	−9.7	5.8	−3.8	22.2	−5.0
Maximum	21.3	23.4	20.3	19.1	32.4	23.4
SD	5.0	8.2	3.9	5.8	2.5	6.6
Xylem water	$\delta^{18}O_{xylem}$	δD_{xylem}	$\delta^{18}O_{leaf}$	δD_{leaf}	$\delta^{18}O_{xylem}$	δD_{xylem}
Mean	−5.2	−48.9	/	/	−2.4	−64.2
Minimum	−5.6	−51.7	/	/	−4.9	−72.7
Maximum	−4.2	−43.9	/	/	2.9	−50.0
SD	0.3	1.7	/	/	1.9	6.1
$\delta X_{xylem} - \delta X_{leaf}$	**−19.8**	**−55.1**	**/**	**/**	**−29.6**	**−71.7**
Soil water	10 cm depth (n = 36)				10 cm depth (n = 4)	
	$\delta^{18}O_{soil}$		δD_{soil}		$\delta^{18}O_{soil}$	δD_{soil}
Mean	0.0		−31.2		2.7	−37.1
Minimum	−2.0		−36.7		1.1	−46.8
Maximum	2.4		−21.0		5.1	−27.5
SD	1.1		3.3		1.9	8.3
Air moisture	At the canopy (n = 36)				At the canopy (n = 23)	
	$\delta^{18}O_{moisture}$		$\delta D_{moisture}$		$\delta^{18}O_{moisture}$	$\delta D_{moisture}$
Mean	−16.2		−116.7		−17.7	−136.3
Minimum	−23.1		−167.2		−24.9	−188.9
Maximum	−11.6		−78.0		−11.7	−96.3
SD	3.0		22.5		3.3	23.2

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Table 4. Spatial and temporal variations of d-excess (‰) in each water pools in the Heihe River Basin. The numbers in the parenthesis indicate the sample number. The S1-Sep, S1-Jun, S2-Jun, S3-Aug, S4-Aug and S5-Aug indicate the Qinghai spruce forest at 2900 m in September 2011, 2900 m in Jun 2011, 2700 m in Jun 2011 and 2800 m in August 2009 in the upper reaches, the riparian forest at 930 m and the Gobi site at 906 m in August 2009 in the lower reaches. In the upper reaches, Q.S., P.F., P.V. and S.C. refer to *Qinghai Spruce*, *Potentilla fruticosa*, *Polygonum viviparum L.*, and *Stipa capillata* Linn in the forest ecosystem. In the lower reaches, P.E. and S.A. refer to *Populus euphratica Oliv*. and *Sophora alopecuroides* L. in the riparian forest ecosystem. R.S. refers to *Reaumuria soongorica* (Pall.) Maxim. at the Gobi site.

Study sites	The Qinghai Spruce forest (S1-Sep, S1-Jun, S2-Jun and S3-Aug)				The riparian forest (S4-Aug)		The Gobi (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. Linear least square fits between d-excess of various water bodies and relative humidity (RH) (%) at each site. Here m = slope, b = intercept, r = coefficients of determination. Bold values indicate statistical significance at the 99 % significance level, and bold italic values indicate statistical significance at the 95 % significance level. In the upper reaches, Q.S., P.F., P.V. and S.C. refer to *Qinghai Spruce*,*Potentilla fruticosa*, *Polygonum viviparum L.*, and *Stipa capillata* Linn in the forest ecosystem. In the lower reaches, P.E. and S.A. refer to *Populus euphratica Oliv*. and *Sophora alopecuroides* L. in the riparian forest ecosystem. R.S. refers to *Reaumuria soongorica* (Pall.) Maxim. at the Gobi site.

d-excess (‰) vs. RH (%)									
	m	*b*	*r*	*p*		*m*	*b*	*r*	*p*
S1-Sep: 2900 m Sep 2011					S1-Jun: 2900 m Jun 2011				
Q.S. leaf water	**1.52**	**−146.68**	**0.701**	**< 0.001**	Q.S. leaf water	**0.82**	**−113.36**	**0.589**	**< 0.001**
P.F. leaf water	**2.38**	**−212.45**	**0.846**	**< 0.001**	P.F. leaf water	**1.07**	**−90.47**	**0.825**	**< 0.001**
P.V. leaf water	**2.53**	**−208.14**	**0.879**	**< 0.001**	P.V. leaf water	**0.99**	**−72.05**	**0.723**	**< 0.001**
5 cm soil water	0.03	6.61	0.198	0.122	5 cm soil water	**−0.10**	**9.42**	**−0.483**	**0.001**
10 cm soil water	***0.08***	***1.84***	***0.253***	***0.048***	10 cm soil water	< 0.01	1.10	−0.046	0.775
Air moisture near the ground	−0.11	9.62	−0.168	0.191	Air moisture near the ground	**−0.15**	**18.50**	**−0.477**	**0.001**
Air moisture at the canopy	**−0.24**	**20.56**	**−0.457**	**< 0.001**	Air moisture at the canopy	**−0.32**	**33.83**	**−0.753**	**< 0.001**
S2-Jun: 2700 m Jun 2011					S3-Aug: 2800 m Aug 2009				
Q.S. leaf water	**0.49**	**−135.82**	**0.686**	**< 0.001**	Q.S. leaf water	**1.48**	**−169.36**	**0.716**	**< 0.001**
S.C. leaf water	***0.56***	***−79.08***	***0.523***	***0.022***					
5 cm soil water	−0.21	−10.54	−0.279	0.094	5 cm soil water	0.05	−9.86	0.289	0.161
10 cm soil water	−0.02	−14.72	0.013	0.941	10 cm soil water	***0.08***	***-12.35***	***0.255***	***0.046***
Air moisture near the ground	**−0.27**	**26.82**	**−0.682**	**< 0.001**					
Air moisture at the canopy	**−0.25**	**27.58**	**−0.689**	**< 0.001**	Air moisture at the canopy	**−0.15**	**28.37**	**−0.526**	**0.007**
S4-Aug: 930 m Jul 2009					S5-Aug: 906 m Jul 2009				
P.E. leaf water	**1.41**	**−171.76**	**0.844**	**< 0.001**	R.S. leaf water	**1.77**	**−243.96**	**0.716**	**< 0.001**
S.A. leaf water	**1.21**	**−166.99**	**0.947**	**< 0.001**					
10 cm soil water	0.02	−32.08	−0.012	0.939					
Air moisture at the canopy	**−0.13**	**17.42**	**−0.602**	**0.003**	Air moisture at the canopy	**−0.68**	**18.47**	**−0.526**	**< 0.001**

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Table 6. Correlations of d-excess of various water bodies with RH (%) and T (°C) and $d_{moisture}$ with d_{leaf} during the sunny days at each site, Here m = slope, b = intercept, r = correlation coefficient.

Study area		The d-excess values vs. RH (%)				The d-excess values vs. T (°C)			
		Slope	Intercept	Correlation coefficient	P values	Slope	Intercept	Correlation coefficient	P values
In the forest	$d_{moisture}$ 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
	d_{leaf} of shrub	1.26	−121.121	0.629 (25)	< 0.001	−3.66	−15.489	0.547	< 0.001
	d_{leaf} of herb	1.21	−99.962	0.635 (37)	< 0.001	−3.17	−1.134	0.563	< 0.001
	d_{leaf} of wood vs. $d_{moisture}$ near the ground	−1.47	−63.237	−0.360 (84)	< 0.001	/	/	/	/
	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 ground	**−0.14**	**3.69**	**−0.599(24)**	**0.039**	/	/	/	/
	d_{leaf} of grass vs. $d_{moisture}$ near ground	**−0.12**	**12.72**	**−0.648(12)**	**0.023**	/	/	/	/
In riparian forest	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	/	/	/	/
In Gobi	d_{leaf} of shrub vs. $d_{moisture}$ at the canopy	−0.28	−57.737	0.540 (25)	< 0.001	/	/	/	/

Table 7. Linear least square fits between d-excess of various water bodies and temperature (T) (°C) at each site, Here m = slope, b = intercept, r = correlation coefficient. Bold values indicate statistical significance at the 99 % significance level, and bold italic values indicate statistical significance at the 95 % significance level.

d-excess (‰) vs. T (°C)									
	m	b	r	p		m	b	r	p
S1-Sep: 2900 m Sep 2011					S1-Jun: 2900 m Jun 2011				
QS leaf water	**−3.27**	**−13.20**	**−0.419**	**< 0.001**	QS leaf water	−1.60	−46.89	−0.202	0.220
PF leaf water	**−6.45**	**5.88**	**−0.612**	**< 0.001**	PF leaf water	**−5.10**	**31.80**	**−0.919**	**< 0.001**
PV leaf water	**−6.74**	**22.91**	**−0.575**	**< 0.001**	PV 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 ground	**0.54**	**−1.78**	**0.349**	**0.005**	Air moisture near ground	**0.76**	**0.86**	**0.610**	**< 0.001**
Air moisture at canopy	**0.81**	**−2.63**	**0.481**	**< 0.001**	Air moisture at canopy	**0.91**	**4.12**	**0.494**	**0.003**
S2-Jun: 2700 m Jun 2011					S3-Aug: 2800 m Aug 2009				
QS leaf water (37)	**−1.59**	**−90.88**	**−0.664**	**< 0.001**	QS leaf water	**−6.25**	**14.67**	**−0.684**	**0.001**
SC 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 ground	0.42	9.23	0.285	0.087					
Air moisture at canopy	0.31	12.28	0.173	0.305	Air moisture at canopy	**0.64**	**9.39**	**0.491**	**0.005**
S4-Aug: 930 m Aug 2009					S5-Aug: 906 m Aug 2009				
PE leaf water	**−4.40**	**2.274**	**−0.642**	**< 0.001**	RS leaf water	**−1.82**	**−158.14**	**−0.742**	**< 0.001**
SA 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 canopy	**0.54**	**0.95**	**0.773**	**< 0.001**	Air moisture at canopy	**0.83**	**−18.23**	**0.684**	**0.001**

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Table 8. Equations of soil water δD and $\delta^{18}O$ at each site using linear least squares fits method.

Sites	Equation	R^2	Sites	Equation	R^2
S1-Sep	$\delta D = 7.114 \times \delta^{18}O + 3.030$	0.849^{**}	S3-Aug	$\delta D = 7.355 \times \delta^{18}O - 8.267$	0.836^{**}
S1-Jun	$\delta D = 4.998 \times \delta^{18}O - 16.213$	0.681^{*}	S4-Aug	$\delta D = 2.615 \times \delta^{18}O - 31.128$	0.792^{**}
S2-Jun	$\delta D = 3.952 \times \delta^{18}O - 26.901$	0.789^{**}	S5-Aug	$\delta D = 2.840 \times \delta^{18}O - 44.930$	0.412 ns

*, **, and ns indicate the 99 % significance level, the 95 % significance level and not significant, respectively.

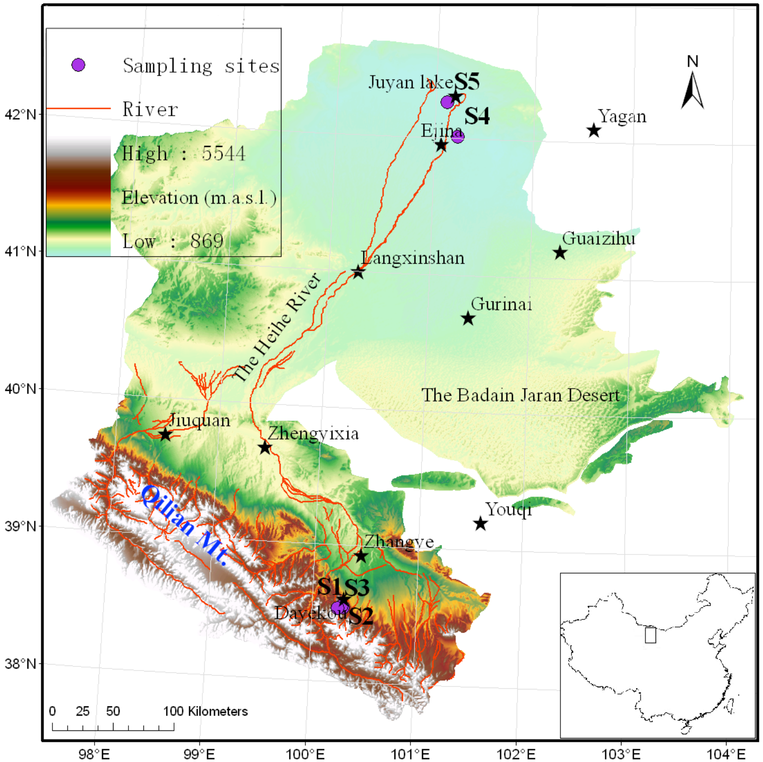

Fig. 1. Locations of the sampling sites in the Heihe River Basin. Note: the information of sampling locations, altitude, period of sampling and climatic conditions are listed in the Table 1.

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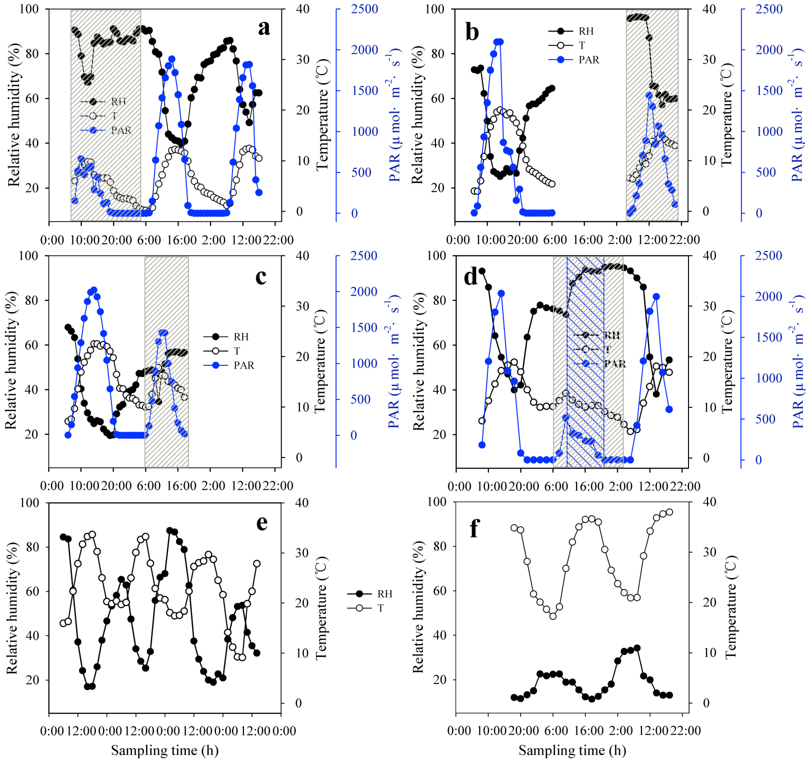

Fig. 2. Comparison of mean hourly average relative humidity (RH), air temperature (T) and photosynthetically active radiation (PAR) during the experimental period. The dark cycles and white cycles indicate the RH and T at each site. The S1-Sep, S1-Jun, S2-Jun, S3-Aug, S4-Aug and S5-Aug indicate the Qinghai spruce forest at 2900 m in September 2011, 2900 m in June 2011, 2700 m in June 2011 and 2800 m in August 2009 in the upper reaches, the riparian forest at 930 m and the Gobi site at 906 m in August 2009 in the lower reaches. In the upper reaches, gray shades indicate cloudy period with low PAR and the blue shade indicates rainy period.

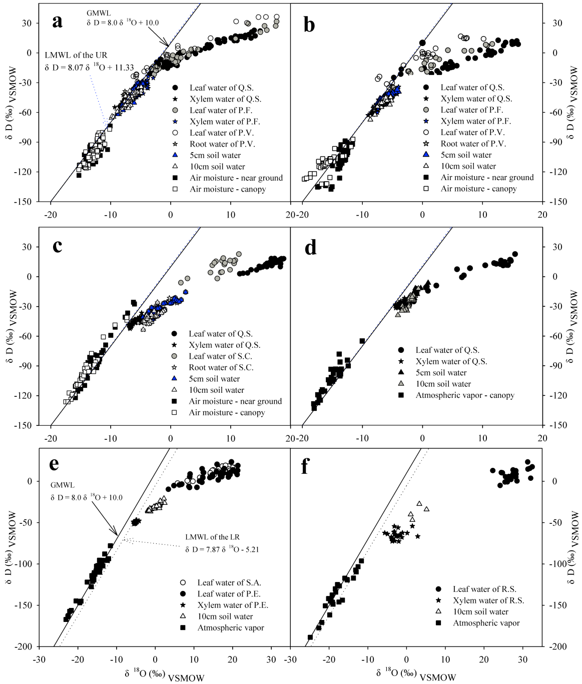

Fig. 3. Plot of δD and δ^{18}O of different water pool at each site. For reference, the local meteoric water line (LMWL: cited from He, 2011) is plotted for each site (dark line is the GMWL, blue dotted line and black dotted lines are the LMWL of the upper and the lower reaches, respectively). Note: **(a)–(f)** refer to the Qinghai spruce forest at 2900 m in September 2011, 2900 m in June 2011, 2700 m in June 2011 and 2800 m in August 2009, in the upper reaches, the riparian forest at 930 m and the Gobi site at 906 m in August 2009 in the lower reaches. In the upper reaches, Q.S., P.F., P.V. and S.C. refer to Qinghai Spruce, *Potentilla fruticosa*, *Polygonum viviparum L.*, and *Stipa capillata Linn* in the forest ecosystem, respectively. In the lower reaches, P.E. and S.A. refer to *Populus euphratica Oliv.* and *Sophora alopecuroides L.* in the riparian forest ecosystem. R.S. refers to *Reaumuria soongorica* (Pall.) Maxim. at the Gobi site.

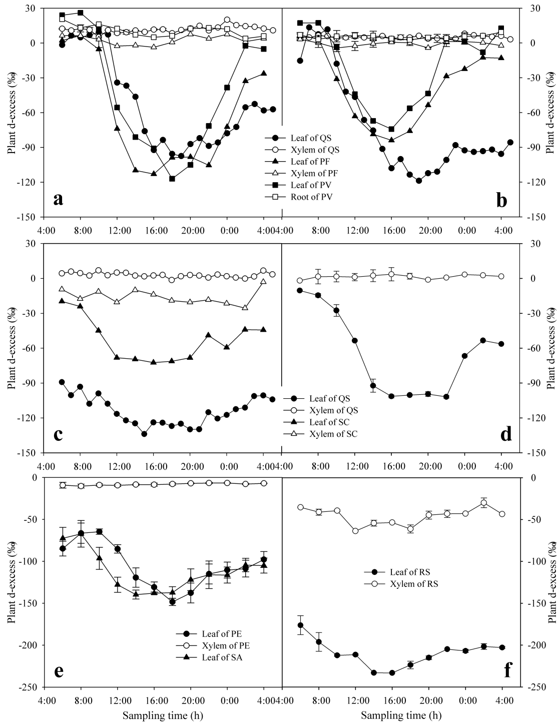

Fig. 4. Variations of leaf and xylem water d-excess in the sunny day of the upper reaches and lower reaches of the Heihe River Basin. Note, in the upper reaches, Q.S., P.F., P.V. and S.C. refer to Qinghai Spruce, *Potentilla fruticosa*, *Polygonum viviparum L.*, and *Stipa capillata* Linn in the forest ecosystem. In the lower reaches, P.E. and S.A. refer to *Populus euphratica Oliv*. and *Sophora alopecuroides* L. in the riparian forest ecosystem. R.S. refers to *Reaumuria soongorica* (Pall.) Maxim. at the Gobi site. **(a)–(d)** refer to the Qinghai spruce forest at 2900 m in September 2011, 2900 m in June 2011, 2700 m in June 2011 and 2800 m in August 2009 in the upper reaches. The panel e and f refer to the riparian forest at 930 m and the Gobi site at 906 m in August 2009 in the lower reaches.

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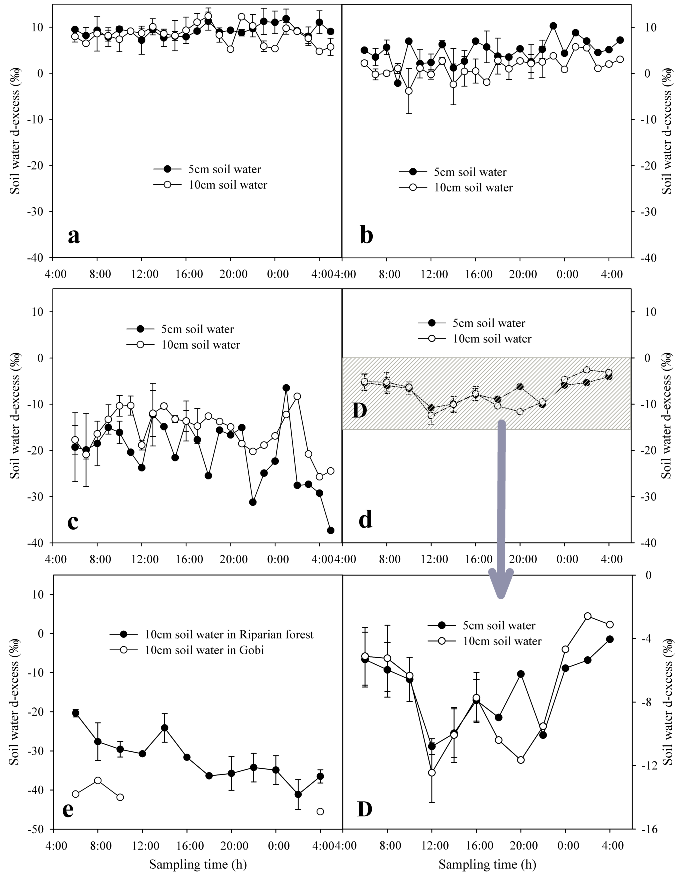

Fig. 5. Spatial and temporal variation of soil water d-excess in the Heihe River Basin. Note: **(a)–(d)** refer to the Qinghai spruce forest at 2900 m in September 2011, 2900 m in June 2011, 2700 m in June 2011, and 2800 m in August 2009 in the upper reaches. The panel e and f refer to the riparian forest at 930 m and the Gobi site at 906 m in August 2009 in the lower reaches.

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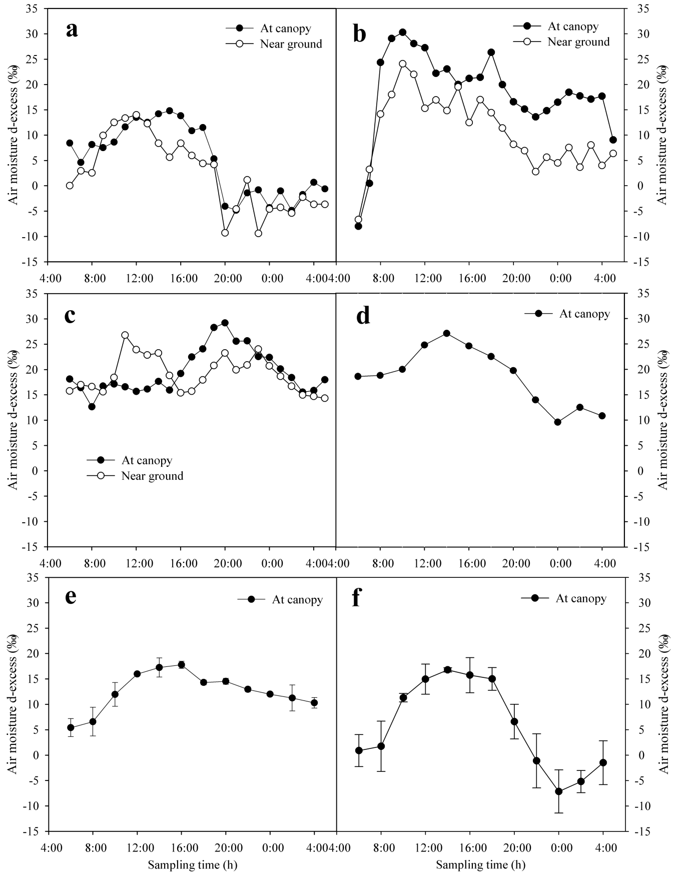

Fig. 6. The d-excess of air moisture during the sunny day. Note: **(a)–(d)** refer to the Qinghai spruce forest at 2900 m in September 2011, 2900 m in June 2011, 2700 m in June 2011, and 2800 m in August 2009 in the upper reaches. **(e)** and **(f)** refer to the riparian forest at 930 m and the Gobi site at 906 m in August 2009 in the lower reaches.

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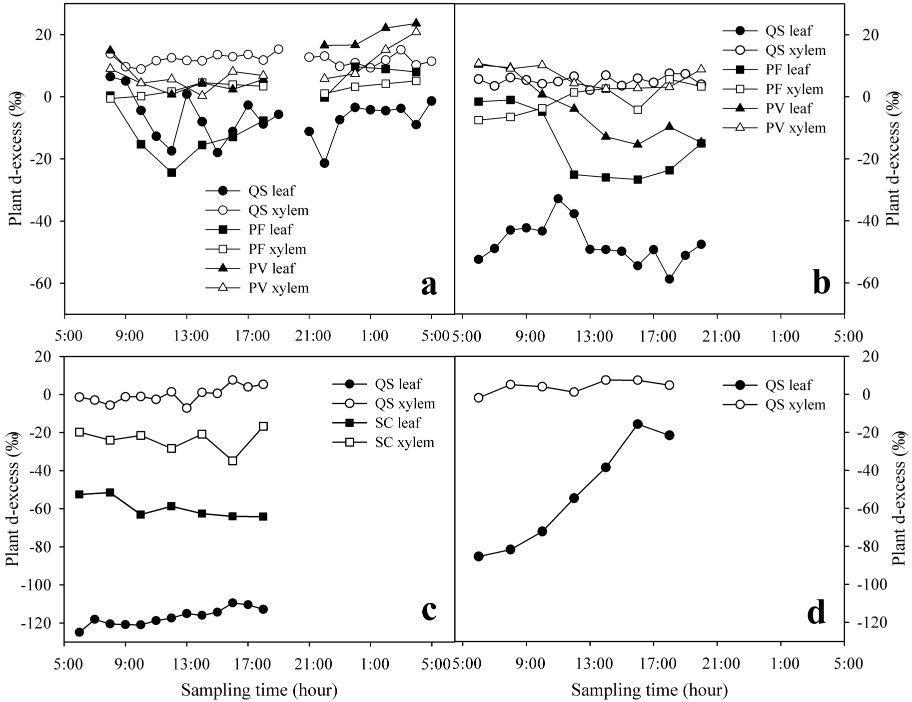

Fig. 7. Variations of leaf and xylem water d-excess during the cloudy day of the upper reaches of the Heihe River Basin. **(a)–(d)** refer to the Qinghai spruce forest at 2900 m in September 2011, 2900 m in June 2011, 2700 m in June 2011 and 2800 m in August 2009.

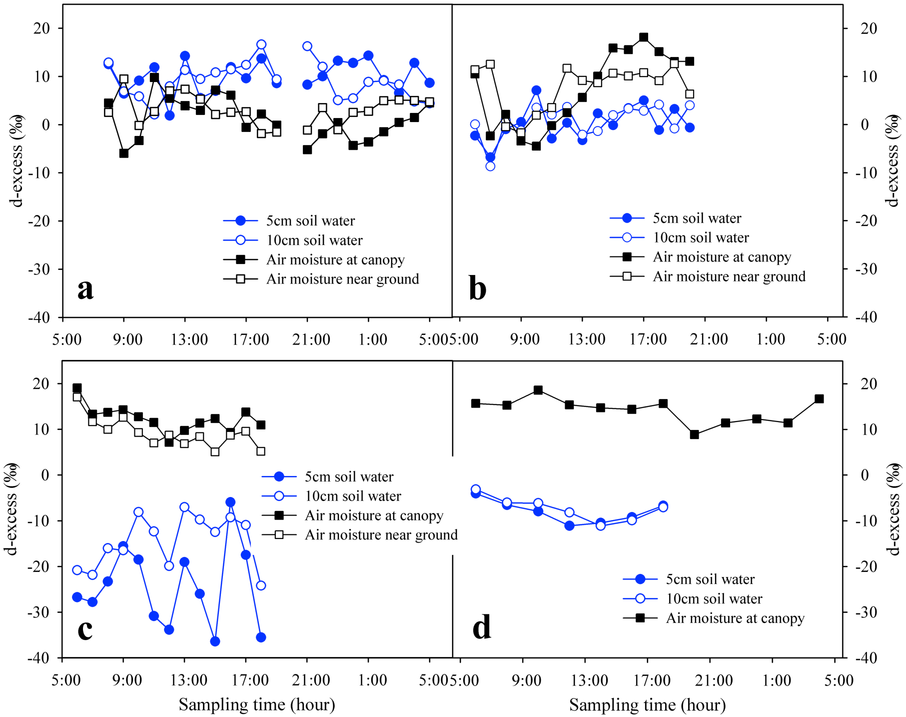

Fig. 8. Variations of d-excess of shallow soil water and air moisture during the cloudy day of the upper reaches of the Heihe River Basin. **(a)–(d)** refer to the Qinghai spruce forest at 2900 m in September 2011, 2900 m in June 2011, 2700 m in June 2011 and 2800 m in August 2009.

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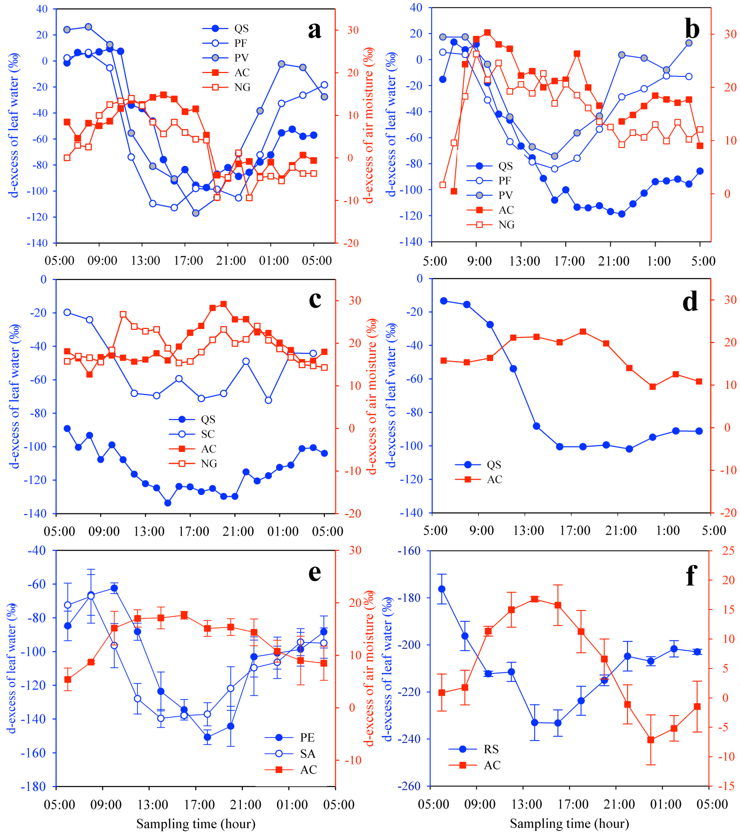

Fig. 9. Comparison of leaf water and air moisture d-excess values during the sunny day. **(a)**–**(f)** refer to the Qinghai spruce forest at 2900 m in September 2011, 2900 m in June 2011, 2700 m in June 2011 and 2800 m in August 2009 in the upper reaches, the riparian forest and the Gobi site in the lower reaches.

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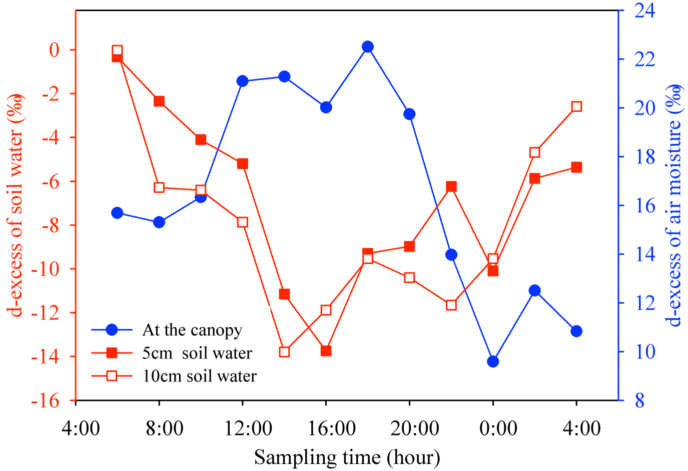

Fig. 10. Comparison of soil water and air moisture d-excess values during the sunny day after 4 h rain event on 2 August 2009 at S3 site (2800 m).