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ORIGINAL ARTICLE

Groundwater use by plants in a semi-arid coal-mining area at the Mu Us Desert frontier

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Abstract The hydrogen isotope (deuterium-δD) composition at natural abundance levels of xylem water, soil water, groundwater, river water, and rainwater was used to evaluate whether adult plant species use groundwater and to detect seasonal shifts (dry/wet season) in water sources for plants growing in a semi-arid coal-mining area (located at the frontier of the Mu Us Desert). A direct inference approach and the IsoSource mixing model were used to estimate the contributions of different sources to the plant xylem water. The results showed that (1) the δD values of rainfall fluctuated considerably, while those of groundwater were generally constant during the experimental period; (2) the δD patterns in plant xylem water suggest that groundwater was a significant source of water for transpiration in the dry season, while all five selected species reduced dependence on groundwater sources in the wet season; and (3) soil water from the deep layer (50–100 cm) was used largely by adult species possibly because of interspecific competition. These results indicated that coal mining would significantly affect plant growth by reducing the water supply if it leads to a water table decrease. Therefore, it is necessary to protect groundwater resources during the coal mining operations in the region.

Keywords Groundwater · Plant water sources · Stable isotopes · IsoSource · *Populus simonii*

Introduction

Shenmu County is located in northern Shaanxi Province, China. Since the late 1980s, it has become a large base of energy and heavy chemical industries of northern China because of exploitation of the Shenfu Coalfield. In recent years, the economy of Shenmu County has been booming based on this coal mining. In 2009, the coal production of Shenmu County was over 100 million tons per year, making it the largest county producer of coal in China. China relies on coal for about 70 % of its energy supply (Zhang and Peng 2005), and coal mining in Shenmu County is therefore of vital importance not only for Shaanxi Province but also for China's economy and development; more than 60 % of coal is transported to the eastern and southern regions of China such as Shanghai, Guangdong, and Zhejiang Provinces for energy consumption. However, Shenmu County, in which the ecotone between the grass–pastoral and the agricultural areas that are seriously affected by sandy desertification exists, is in the transitional zone between the aeolian deflation desert area (the Mu Us Desert) and the loess hilly area (Loess Plateau), and between the arid and the semi-arid regions. Most of the surface is covered by sand with little vegetation (Wu and Ci 1999; Zhang et al. 2003). The water resource is very precious in this region. Only one perched aquifer in the

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This manuscript was edited by Dr. Paul Kretchmer who is a native-English speaker and soil scientist.

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Quaternary alluvium directly overlies the coal measures, making possible the loss of large amounts of precious water from the overlying loose water-bearing sand to a large extent during the process of mining (Fan 2005; Ma et al. 2010; Wu et al. 2006).

Coal mining can have drastically adverse environmental effects. These can take the form of interference with groundwater, land subsidence, the effects of water use on river flow, consequences for other land uses, geological hazards, and potential ecological havoc (Bell et al. 2000; Bian and Zhang 2006; Bian et al. 2009; Ripley et al. 1996). In Shenfu Coalfield, abundant coal reserves lie in the shallow depths, where the water-bearing alluvium normally overlies the coal seam. Coal mining itself suffers threats from water and sand inrushes. Water drainage and surface collapse resulting from coal mining are destructive to the groundwater and the surrounding environment. Because of these effects, mining companies are frequently in conflict with local residents (Oscar 2006; Zoltan 2005). The Shendong Coal Mining Company (SDCMC), the largest producer of coal in China (100 million tons per year) has also been involved in a conflict with local residents (Bian et al. 2009). The local residents have complained that coal mining not only causes groundwater table decline, but also vegetation decline. The SDCMC has argued that the local vegetation decline has less to do with coal mining and more to do with the arid climate. Therefore, to resolve this controversial issue, data are needed about whether and how plants in this region use groundwater.

In water-limited environments, where evaporative demand exceeds precipitation and water tends to be unavailable in upper soil horizons, plants are likely to have deep roots and extract water from deep soil layers or groundwater (Romero-Saltos et al. 2005; Sekiya and Yano 2002; West et al. 2008). Previous studies conducted in arid and semiarid regions have proved that groundwater is an important water source for plants due to the lack of reliable surface water resources (Flanagan and Ehleringer 1991; White et al. 1985; Yin et al. 2011). In Shenfu Coalfield, the groundwater table in some areas is usually shallow, with the shallowest depth being only 0.8 m. It is generally believed that groundwater has a direct effect on plant growth and vegetation distribution, and plays a critical role in maintaining the stability of an ecosystem (Wang et al. 2008). However, public reports about plant water sources in the region are lacking, which is one reason that some coal mining companies have been able to claim that coal mining has had almost no effect on local vegetation decline.

Stable isotope techniques provide an opportunity to ascertain the water sources of plants (Ehleringer et al. 2000). The isotopic composition of xylem water in the plant represents a mixture of different plant water sources. Quantification of the proportion of water taken up from these sources is less complex provided that there is no isotopic fractionation during water uptake by terrestrial plants (Ellsworth and Williams 2007). Several greenhouse and field-based studies have verified that water is not altered isotopically during uptake by roots (Dawson and Ehleringer 1993; Thorburn et al. 1993). If samples of all potential water sources can be obtained and the water within the plant xylem sap is also extracted, it is possible to assess which sources of water are being used (Dawson et al. 2002). To identify the most likely sources of water transpired by plants, stable hydrogen and/or oxygen isotopic compositions of stem water are compared with those of potential water sources (Asbjornsen et al. 2007; Li et al. 2007). Using the deuterium (δD) signature of xylem water, soil water, lake water, and groundwater, this study evaluated the groundwater dependency and fluctuations of water sources for adult plants in a semi-arid vegetation community in a transitional zone between the Mu Us Desert and the Loess Plateau.

Materials and methods

Study area

The study was carried out in the Hongjiannao Ecological Reserve (HER) with an area of about 90 km^2, located in Shenmu County, North Shaanxi Province, China (Fig. 1). HER was founded in 1995, and coal mining and any other industrial activities are prohibited within the area. The vegetation and groundwater within the HER are better conserved than that outside of the areas, where groundwater depth has decreased to about 45 m in some coal-mining sections (Bian et al. 2009). Therefore, taking HER as the study area allows the results to reflect the background of water uses by local vegetation. The climate of the region is inland semi-arid temperate with a warm summer. The mean annual precipitation is approximately 450 mm (1970–2008), about 80 % of which falls between June and September; the potential annual evapotranspiration is approximately 1,800 mm. The largest inland lake of Shaanxi Province, Hongjian Lake (HL), lies at the center of the HER. HL is also the largest desert lake in China, with an area of 67 km^2 and a volume of 0.8 billion m^3. In recent years, the area of HL has become smaller because of decreased precipitation and dam construction upstream on inflowing rivers, which are the main water origins of Hongjian Lake (The Compilation Committee of Shenmu County Annals 1990). Because of the existence of HL, the eco-environment of HER is generally healthy. In the east parts of HER, there is natural grassland, and the main plant species are *Artemisia desertorum*, *Stipa bungea*, and *A. capillaris*. In the south and west, there is a distribution of sand dunes that are fixed by vegetation such as *Salix*

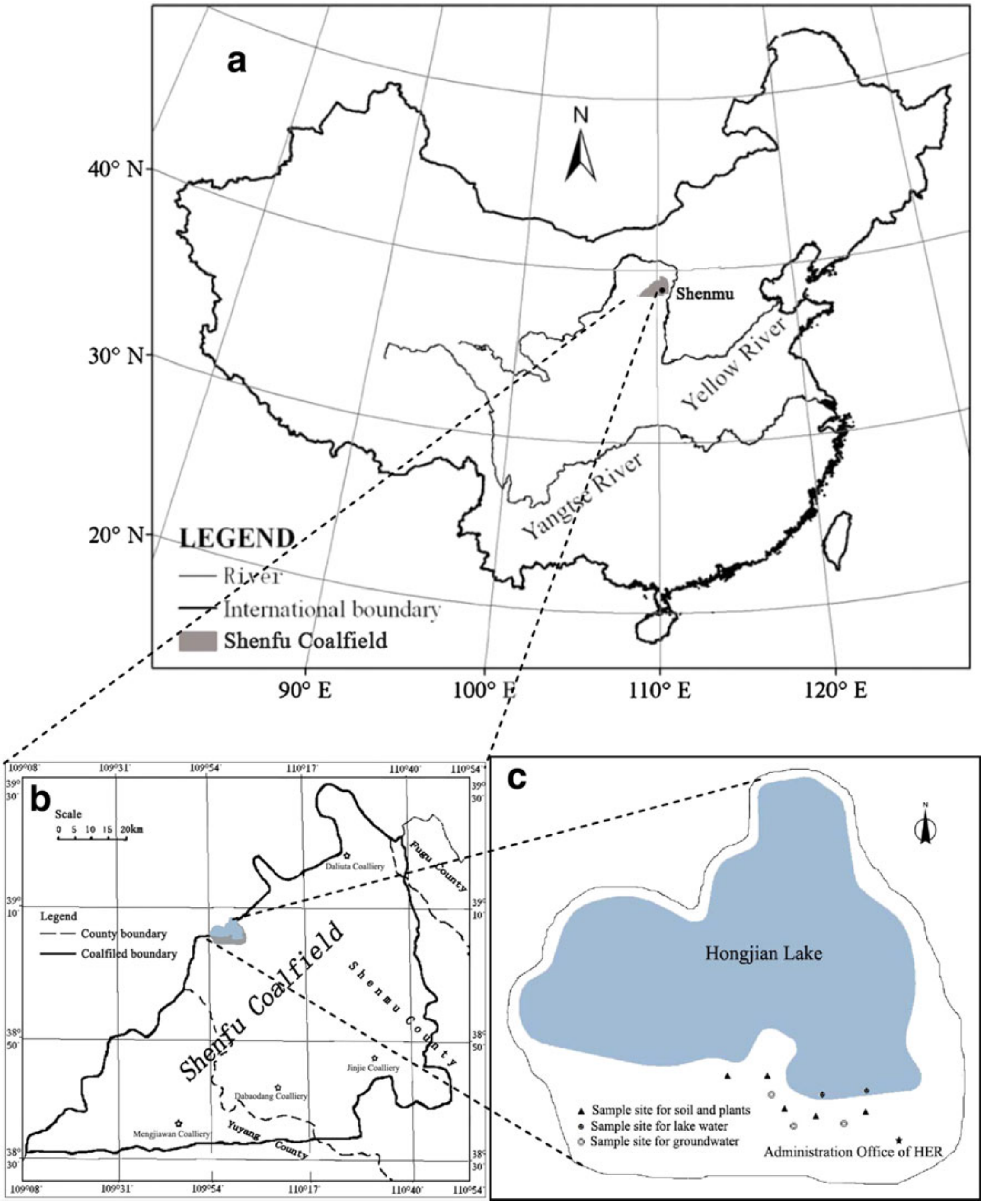

Fig. 1 Maps of the region and field area. **a** Location of the Shenfu Coalfield within China. **b** Location of the Hongjiannao Ecological Reserve (HER) within the Shenfu Coalfield. **c** Location of sampling sites within HER

psammophila and *Caragana korshinskii*, and beach lands in which *S. psammophila*, *Pinus tabuliformis*, *Populus simonii*, and others are planted as protective forest strips against wind and sand. The lowest groundwater depth is about 0.8 m. The soil texture at the experimental site is loamy sand (aeolian sandy soil, 72 % sand, 23 % silt, and 5 % clay) according to the USDA texture classification system (Jury and Horton 2004).

Sampling

Plant and soil sampling was conducted on May 15 (dry season) and August 28 (wet season), 2010. Five adult plant species (*S. psammophila*, *A. desertorum*, *C. korshinskii*, *P. tabuliformis*, and *P. simonii*) were selected for the study, and these species have different ecotypes and leaf phenologies (Table 1).

Table 1 Characteristics of the adult species selected for plant water sources analysis

Species	Life form	Leaf phenology	Distance from Hongjian Lake (m)	Number of individuals sampled
A. desertorum	Subshrub	Deciduous	100	3
S. psammophila	Shrub	Deciduous	100	3
C. korshinskii	Shrub	Deciduous	500	3
P. tabuliformis	Tree	Evergreen	100	3
P. simonii	Tree	Deciduous	1,000	3

Plants and soils were sampled at five sites (Fig. 1c). Stem samples were taken by collecting nine twig samples of 10–25 mm diameter from three individual plants per species (three twig samples per individual) using pruning shears at each site. The trees sampled were mature, with diameter at breast height (DBH) generally ranging from 10 to 30 cm for *P. simonii* and from 5 to 10 cm for *P. tabuliformis*. All leaves and green stem tissue were removed from these stems to avoid contamination of xylem water by isotopically enriched water (Querejeta et al. 2007). The clipped stems of twigs were immediately enclosed in screw cap polypropylene vials, wrapped in Parafilm and tightly sealed with electrical tape, and placed in a cooler with ice for transportation to the laboratory. In the laboratory, samples were stored frozen for later processing and analysis. Soil profiles were sampled by hand-augering to depths of up to 1.0 m, with samples taken at 0.1-m intervals (three samples per each interval). Soil samples were placed in glass jars sealed with screw caps and wrapped in Parafilm to minimize evaporation, and stored in insulated containers for transport from the field to the laboratory. Before analysis, the soil samples were freeze dried and subsequently sieved using a mesh size of 600 μm to facilitate the removal of other coarse materials.

Rainwater sampling was conducted between May and August 2010 based on the amounts of rainfall and the plant growing season. Six rainwater samples were taken during the course of every rainfall event. Due to high infiltration and evaporation rates in the study area, the depth to which infiltrated rainwater can move is shallow and is controlled by the amount of infiltrating water and the tension gradient within the soil profile (Chen et al. 2008a). Furthermore, water uptake by roots in the non-saturated zone results in rapid drying due to high evapotranspiration rates. Therefore, samples from daily rainfall events occurring in the sampling period were used to give representative rainwater samples rather than using a monthly composite rainwater sample. Groundwater samples were collected from three adjacent wells (water surface was 1.0–1.1 m deep below the soil surface during the experimental period) (Fig. 1c), and six samples were taken per well. Sampling times were simultaneous with every rainwater sampling. Lake water samples were collected from close to the bank at an approximately 0.5–1 m depth at two sampling sites (Fig. 1c), and sampling times were same as stem sampling and totally 24 samples were taken. All rainwater, groundwater, and lake water samples were enclosed in screw cap polypropylene vials, wrapped in Parafilm and tightly sealed with electrical tape, and stored in a freezer until stable isotopic analysis could be carried out.

Water was extracted from plant and soil samples using a cryogenic vacuum distillation line (West et al. 2006). The water extracted from stems of *P. tabuliformis* sometimes contained organic compounds that gave the water a milky appearance and a strong odor. In these cases, activated charcoal was added to the extract to adsorb these compounds. The water was then filtered prior to isotopic analysis.

Isotopic analysis was performed at the Stable Isotope Ratio Mass Spectrometer Facility (Chinese Academy of Forestry, Beijing). Microliter quantities of water samples (stem water, soil water, lake water, rainwater, and groundwater) were measured by online high temperature reduction in the modified carbon reactor of a high-temperature elemental analyzer (TC/EA) coupled to an isotope ratio mass spectrometer (Finnigan MAT Delta V). Isotopic concentrations were expressed using the formula

$$\delta \mathrm{D} = [(D/H)_{\mathrm{sample}}/(D/H)_{V-\mathrm{SMOW}} - 1] \times 1,000‰$$

where δ is the different isotope value per mil (‰) of the sample relative to the standard, $(D/H)_{\mathrm{sample}}$ is the ratio of the heavy to the light isotope in a sample, and $(D/H)_{V-\mathrm{SMOW}}$ is the same ratio in a standard (Standard Mean Ocean Water). The error in water δD measurements is less than 1.5 ‰.

Data analysis

The 0–100 cm soil profile was divided into three depth intervals to facilitate the root water uptake study: 0–10 (upper soil layer), 10–50 (middle soil layer), and 50–100 cm (deep soil layer). Below 100 cm was taken as the groundwater layer. The δD value of each layer was expressed by the mean value of samples in each interval. Two methods were used to study root water uptake of plants. One was the direct inference approach. Direct comparison of hydrogen isotopic composition between the soil water profile and the xylem water can indicate the main depth of the soil water resources used by plants, based on the depth of soil water with similar δD values to xylem water. However, this method assumed that root water uptake occurred only in one depth interval. The other method was based on multi-source mass balance. According to the mass balance of environmental water sources and

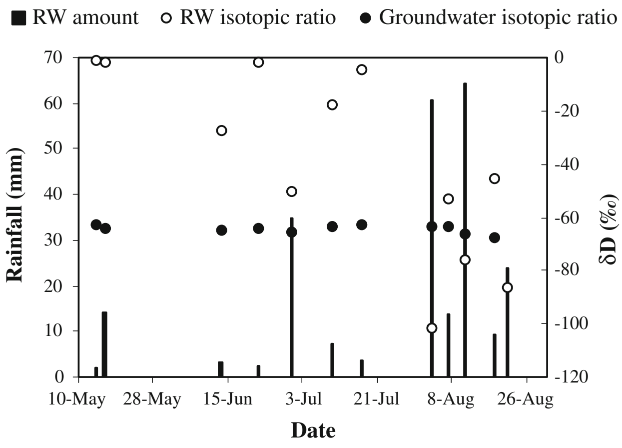

Fig. 2 Rainfall measured in the study area from May 14 to August 21, 2010, and δD (‰) values for rainwater (RW) and groundwater

their isotopic composition, the proportions of each layer ($f_1 - f_4$) can be determined by their isotopic signatures ($\delta X_1 - \delta X_4$) and the mixture (δX_t):

$$\delta X_t = f_1\delta X_1 + f_2\delta X_2 + f_3\delta X_3 + f_4\delta X_4$$

$$f_1 + f_2 + f_3 + f_4 = 1$$

where δX_t was the hydrogen isotope value of xylem water.

IsoSource (Phillips and Gregg 2003; Phillips et al. 2005) was used to evaluate the relative contribution of each possible water source to xylem water. The IsoSource model examined all possible combinations of each source contribution (0–100 %) in small increments. Combinations with totals that were close to the observed mixture isotopic signatures, within a small tolerance, were considered to be feasible solutions from which the frequency and range of potential source contributions could be determined (Phillips and Gregg 2003). In this study, the fractional increment was set at 1 %, and the uncertainty level was set at 0.1. Sensitivity analysis was performed with different fractional increments (0.5, 2 %) and different uncertainty levels (0.1, 0.2, and 0.3). The results showed no significant differences for these changes in fractional increments or uncertainty levels.

Statistical analyses were performed using SPSS 18.0 software. One-way ANOVA was used to analyze the significant differences between species during dry and wet seasons.

Results

Rainfall distribution and isotopic signatures of rainwater and groundwater

Figure 2 shows the rainfall measured in the study area and the δD values of rainfall and groundwater. Before July 2010, the study area experienced a continuous drought from May to the end of June, and only 21.9 mm of rainfall fell in total. This drought was terminated by rain events (34.8 mm in total) on June 30. The hydrogen isotopic compositions of rainwater samples before June 30 varied from −1.1 to −27.9 ‰, and rainfall amounts varied from 2.20 to 14.20 mm. During July, there were only two rainfall events (July 10 and 17); rainfall amounts were 7.2 and 3.5 mm, and their hydrogen isotopic compositions were −18.1 and −4.9 ‰, respectively. In August, 364.1 mm of precipitation fell, about 30 % above the long-term mean rainfall in the study area; the hydrogen isotopic compositions of rainwater samples for five events varied from −46.1 to −102.3 ‰.

The δD values of groundwater ranged from −63.2 to −64.6 ‰ before July. They ranged from −62.9 to −67.9 ‰ during July and August.

Isotopic signatures of soil water

All measured soil water isotopic values fell within the ranges of those of rainwater (Table 2). Soil water δD values in the layers below 10 cm were more negative than in the upper soil layer (0–10 cm). In the 0–10 cm soil layer, soil water isotopic values in the dry season were more positive than in the wet season. In the layers below 10 cm, there were no significant differences between dry and wet seasons.

Isotopic signatures of plant xylem water and plant water sources

In the dry season, *S. psammophila* had δD values (−62.3 ‰) similar to those of groundwater (−63.6 ‰), suggesting that it primarily used groundwater. *Pinus tabuliformis* and *P. simonii* had δD values (−63.6 ‰), similar to those of groundwater and soil water from the deep layer (50–100 cm) (−64.7 and −63.3 ‰), indicating that both species used both groundwater and soil water from the deep layer. *Artemisia desertorum* had δD values (−65.0 ‰), consistent with groundwater (−63.6 ‰) and soil water from the middle layer (10–50 cm) (−62.2 ‰), which showed that both groundwater and soil water from the middle layer were its main water sources. *Caragana korshinskii* had δD values (−58.0 ‰) closer to groundwater and soil layers of 10–100 cm. Overall, the patterns in plant δD values suggest that groundwater was a significant source of water for transpiration in the dry season.

In the wet season, the δD values of plant xylem water were more negative than in the dry season. *Salix psammophila* and *A. desertorum* had δD values much closer to that of soil water, indicating that they mainly used soil water during this time. *Pinus tabuliformis* had δD values

Table 2 The δD values of plant xylem and environmental water sources sampled in the dry (May) and wet (August) seasons

Sampling date	Sample	*S. psammophila*	*A. desertorum*	*C. korshinskii*	*P. tabuliformis*	*P. simonii*	Groundwater	Lake water
2010-5-15	Xylem	−62.3	−65.0	−58.0	−63.6	−63.6	−63.6	−2.2
	0–10-cm soil layer	−27.5	−38.2	−35.4	−34.2	−33.8		
	10–50-cm soil layer	−68.0	−62.2	−62.2	−54.0	−58.9		
	50–100-cm soil layer	−69.4	−69.0	−63.3	−64.7	−63.3		
2010-8-28	Xylem	−73.5	−72.2	−71.2	−70.6	−72.4	−66.5	−1.8
	0–10-cm soil layer	−54.7	−43.2	−44.4	−48.7	−55.3		
	10–50-cm soil layer	−69.3	−70.2	−73.2	−65.3	−60.5		
	50–100-cm soil layer	−79.7	−75.4	−72.4	−76.2	−76.8		

(−70.6 ‰) similar to groundwater (−66.5 ‰) and soil water from the deep layer (−66.2 ‰), showing that it used a combination of these two water sources. *Populus simonii* had δD values (−72.4 ‰) much closer to groundwater, indicating that it relied on deep water sources.

IsoSource estimation of feasible contributions of potential water sources

Table 3 indicates the proportions of feasible water sources (%) for five selected species during the dry season. According to the IsoSource model, *S. psammophila* and *C. korshinskii* had similar patterns of water use and obtained water evenly (28 %) from the groundwater and the soil layers at 10–50 cm and 50–100 cm. *Artemisia desertorum* obtained a relatively large proportion of soil water (mean 50 %) from the 50–100 cm layer. *Pinus tabuliformis* also mainly used water from the soil layer at 50–100 cm (mean 58 %), but it obtained more groundwater (37 %) compared to *A. desertorum*. *Populus simonii* obtained the highest proportion of groundwater (up to 100 %, mean 88 %) while using almost no water from the upper soil layers (0–50 cm).

Table 4 shows the proportions of feasible water sources (%) for five selected species during the wet season. Compared with the dry season, all five species reduced their dependence on deep water sources and obtained more than 70 % of their water from the 10–100 cm soil layers. *Populus simonii* obtained the highest proportion of soil water in the 50–100 cm layer (up to 79 %, mean 69 %), and only 9 % (0–27) water from the 10–50 cm layer. *Caragana korshinskii* obtained almost the same proportion of soil water from the 10–50 cm (43 %) and 50–100 cm (41 %) layers. The other three species showed a similar pattern of water use, mainly using soil water from the 50–100 cm layer.

Discussion

Temporal variations in hydrogen isotopic signatures of rainwater and groundwater

There was a large variation in δD values of rainwater between the dry and wet seasons, which had also been observed in other regions. For example, Gammons et al. (2006) demonstrated that the isotopic data showed an extremely large range in δD values (from −38.0 ‰ in the dry season to −216.0 ‰ in the wet season) for rainwater in semi-arid Montana, USA. Yamanaka et al. (2007) observed the day-to-day variations of hydrogen isotopic signatures in precipitation, and the δD ranged from 15.0 to 230.0 ‰ for daily samples from April to September in eastern Mongolia. Liu et al. (2010) demonstrated that precipitation isotopic signatures were enriched in May and June, depleted in July and August (between −80.0 and −60.0 ‰ for δD values), and were even more depleted in September in the Hilly Loess Region of the Loess Plateau, China. Generally, the large variations in isotopic compositions of rainwater may result from differences in water vapor origins, atmospheric flow paths of vapor trajectories, temperatures, and rainfall amount effects (Ingraham 1998; Longinelli and Selmo 2003). In this study, taken on a daily basis the δD values of the rainwater were negatively related to the amount of precipitation ($\delta D = -1.29P - 13.34$, $R^2 = 0.65$; P is precipitation amount), in agreement with the previous results (Liu et al. 2007; Liu et al. 2010).

Contrary to the large variations of rainfall described above, groundwater exhibited relatively steady δD values (from −62.9 to −67.9 ‰) throughout the dry and wet seasons (Fig. 2). Zhang et al. (1999) demonstrated that the hydrogen isotopic signature of shallow groundwater was stable throughout the growing season on the Riverine Plains of the Murray Basin of southern Australia. Zencich

Table 3 Proportions of feasible water sources for five selected species during the dry season (%)

	S. psammophila	*A. desertorum*	*C. korshinskii*	*P. tabuliformis*	*P. simonii*
Soil (0–10 cm)[a]	12 (5–16)	4 (0–13)	18 (16–20)	0 (0–3)	0 (0–0)
Soil (10–50 cm)	28 (0–79)	20 (0–55)	28 (0–78)	3 (0–10)	0 (0–1)
Soil (50–100 cm)	28 (0–74)	50 (27–82)	28 (0–75)	58 (3–95)	12 (0–28)
Groundwater	32 (0–86)	26 (0–69)	26 (0–74)	37 (0–96)	88 (72–100)

Mean source proportions calculated by the IsoSource model are shown, as well as the ranges of minimum and maximum source proportions (in parentheses). Water source proportions were calculated using the IsoSource model (Phillips and Gregg 2003); soil water at different depths and groundwater were considered as the potential sources for growing plants

[a] Soil water δD values represent mean values of depth intervals

Table 4 Proportions of feasible water sources for five selected species during the wet season (%)

	S. psammophila	*A. desertorum*	*C. korshinskii*	*P. tabuliformis*	*P. simonii*
Soil (0–10 cm)[a]	8 (0–25)	3 (0–10)	3 (0–7)	7 (0–20)	7 (0–21)
Soil (10–50 cm)	21 (0–60)	22 (0–64)	43 (0–83)	18 (0–52)	9 (0–27)
Soil (50–100 cm)	55 (40–75)	63 (36–90)	41 (0–96)	56 (41–79)	69 (56–79)
Groundwater	16 (0–47)	12 (0–37)	13 (0–31)	19 (0–59)	15 (0–44)

Mean source proportions calculated by the IsoSource model are shown, as well as the range of minimum and maximum source proportions (in parentheses). Water source proportions were calculated using the IsoSource model (Phillips and Gregg 2003); soil water at different depths and groundwater were considered as the potential sources for growing plants

[a] Soil water δD values represent mean values of depth intervals

et al. (2002) reported that the δD composition of groundwater on the northern Swan Coastal Plain of western Australia showed little seasonal variation throughout the study, e.g., ranging from −15.3 to −18.5 ‰ at a lower slope site, −15.2 to −18.2 ‰ at an upper slope site, and −19.9 to −21.1 ‰ at a dune crest site. Sekiya and Yano (2002) found that δD values of groundwater in semi-arid Zambia were almost constant between −0.5 and −7.2 ‰ throughout the experimental period, which was in agreement with the results obtained by Craig (1961) investigating the hydrogen isotopic values of groundwater from eastern African. As the groundwater hydrogen isotopic composition integrates the long-term average of rainwater received for a given region, it is common for it to exhibit relatively constant δD values over time. Chen et al. (2012) reported that the main source of recharge of the groundwater in the Mu Us Desert comes from a region where the rainwater is characterized by lower δD and $\delta^{18}O$ values.

Seasonal patterns of soil water isotopic signatures

In the dry season, soil water was more depleted of the heavy hydrogen isotope than rainwater, particularly for the 10–100 cm soil layers. Generally, isotope values of soil water should be more positive than those of rainwater (resulting from equilibrium isotope fractionation during evaporation), especially in the surface layer, or at least within the range of those of rainwater (Nie et al. 2011); however, the data in this study showed more negative δD values of soil water. These negative isotope values of soil water could be explained by "hydraulic lift": the nocturnal uptake of water by roots from deep soil layers (generally containing heavy isotope-depleted water) would be released from shallow roots into upper soil layers (Dawson 1993). This interpretation could be supported by the fact that four of five selected species are deep-rooted plants, making it easy for them to use deep soil water and/or groundwater. Taking these aspects into consideration, the most likely reason for the depleted isotopic compositions of soil water was that deep soil water and groundwater sources recharged the soil water. As an alternative to mixing, fractionation processes during the dry season would be responsible for relatively positive δD values of the 0–10-cm soil water under the condition of high potential evapotranspiration (1,800 mm) in the study area. Usually, transpiration does not result in a significant fractionation of hydrogen isotope in soil water (Walker et al. 2001), while evaporation would tend to make soil water enriched in heavier isotopes near the soil surface (Clark and Fritz 1997).

In the wet season, soil water δD values for layers below 10 cm were within the range of those of rainwater, while those of the 0–10 cm layer were more enriched in the heavy isotopes than the rainwater. As the study area had received a large amount of rainfall in August 2010, soil water should have been displaced by rainwater at the time of the sampling (on August 28). The idea of the displacement or "piston flow" mechanism, which means that the stored soil water is displaced by event rainfall or "new" water, has been commonly used as the interpretation for the isotopic similarity of soil water and recently received rainwater (Brooks et al. 2010; Gazis and Feng 2004). The soil texture of the study area is loamy sand that has a very high hydraulic conductivity (up to 71.34 cm h^{-1}; Xiao et al. 2007) and results in a deep infiltration depth (more than 100 cm). These factors could support the idea that soil water was displaced by rainwater when a large rainfall event occurred. The δD values below 10 cm were close to that of groundwater, indicating that deep water sources still recharged soil water in the wet season. The soil samples were taken at 7 days after the last rainfall event (24 mm, August 21, 2010). Therefore, the relatively enriched δD values of the 0–10-cm soil layer could also be explained by a fractionation effect resulting from soil evaporation.

Seasonal patterns of xylem water sources

In the dry season, direct inference suggested that all five selected adult plant species relied on groundwater sources, and this result was also supported by the IsoSource outputs. The penetration ability of the roots was the key factor that allowed plants to use deep water sources. Previous studies showed that the root depth of *P. simonii* can reach 1,200 cm, *S. psammophila* 870 cm, *C. korshinskii* 605 cm (Bian et al. 2009), and *P. tabuliformis* 2,100 cm (Wang et al. 2009); although *A. desertorum* is not a deep-rooted species, its root depth can reach 130 cm and root width can reach 478 cm (Bian et al. 2009) in the study area. This outcome indicated that the characteristic of deep rooting is necessary for those species to use groundwater in the dry season when soil water is not available. It is understandable that groundwater is important to maintaining their long-term survival because in this region, annual potential evapotranspiration far exceeds precipitation.

As described above, *P. simonii* relied principally on groundwater. The reason for this could be that, being a high water-consumption tree species, soil water was insufficient for its transpiration requirements at the end of the dry season (Chen et al. 2008b), so that it was likely to gradually resort to using deeper soil water and groundwater as the dry season progressed. In contrast, *S. psammophila* and *C. korshinskii* are shrub species that consume less water than *P. simonii*, and groundwater may thus only constitute a proportion of water use for transpiration in this semi-arid area. Although *P. tabuliformis* is a tree species, it is a drought-resistant plant with needle leaves that have a relatively smaller transpiration rate than *P. simonii*. This feature could explain why *P. tabuliformis* used groundwater less than *P. simonii*, while mainly relying on soil water from the deep soil layer during the dry season.

In the wet season, δD values of xylem water were more negative than those in the dry season, and δD values of all five selected species fell between those of groundwater and soil water. This suggested that the five selected species used a combination of soil water and groundwater sources. IsoSource outputs, however, showed that the groundwater effect on plant water use played a less important role in the wet season than in the dry season (Table 4). This finding for *P. simonii* species was consistent with those of previous studies showing that many species exhibited a shift in water use from a dominantly deep water source (e.g., groundwater) during the dry season to a dominantly shallow water source (soil water) during the wet season (Dawson and Pate 1996; McCole and Stern 2007). The other four species also exhibited a similar trend to decreased dependence on groundwater in the wet season. The likely reason for this is that the large amount of precipitation in the wet season infiltrated into the soil layers (as mentioned above, the soil of the study area had a high infiltration rate and depth), and more soil water derived from rainwater was available for plant use. All five species used soil water largely from the 50–100 cm layer (from 41 to 69 %) in the wet season, and *P. tabuliformis* and *A. desertorum* used more than 50 % water from the same layer in the dry season. These findings indicated that although adult species may have roots distributed continuously throughout a soil profile, the most active sites of water absorption seemed to be limited to deeper soil layers. An important ecological implication could arise from this result. By mainly using soil water from a deeper layer and possibly a more constant water source (groundwater), these adult species may avoid interspecific competition with more shallow-rooted shrub and herb species that inhabit the same site. This partitioning might ensure a greater probability of their survival during the droughts that are common to the semi-arid region.

It must be mentioned that in both the dry and wet seasons, xylem δD values of the five selected species were very different from that of the lake water (Table 2), indicating that those species did not use water directly from HL. This phenomenon is similar to a previous finding that streamside trees do not use the stream water (Dawson and Ehleringer 1991). One possible inference from this information is that there would be no direct exchange between the soil water at the sampling sites and the lake water because the distances between them are more than 100 m (Fig. 1c).

Conclusions

On the basis of hydrogen stable isotope measurements, this study analyzed the water sources of five selected plants in a semi-arid coal-mining area. The study detected whether plants are dependent on the groundwater and identified the seasonal fluctuations of water sources for adult plants by directly comparing δD values of xylem water with possible water sources, and by applying a multiple-source mass balance assessment (IsoSource model). The results showed that groundwater is an important water source for adult plants in both the dry and wet seasons, and that tree species such as *P. simonii* and *P. tabuliformis* have a greater dependency on groundwater than shrub (*S. psammophila* and *C. korshinskii*) and subshrub species (*A. desertorum*). All the selected adult species exhibited a trend to decreased dependence on groundwater due to more soil water derived from rainwater in the wet season, especially for tree species. Plants used soil water largely from the 50–100 cm layer (from 41 to 69 %), possibly to avoid interspecific competition, indicating that the main depth for water uptake for those species was the deep soil layer. These results show that coal mining could have a significant effect on plant growth by decreasing depth of the water table and thus reducing the water supply within reach of the plant roots. Therefore, it is necessary to protect the groundwater resources during the course of coal mining operations in the region.

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