



The stable isotopic composition variation characteristics of desert plants and water sources in an artificial revegetation ecosystem in Northwest China

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ABSTRACT

Characterizing the dynamics of plant water availability and the mechanisms through which plants access available water sources are key challenges in ecohydrology, especially in arid and semi-arid regions. The establishment of artificial revegetation of different ages has formed vegetation landscapes with different chronological sequences in the southeast margin of the Tengger Desert. As an important regulatory factor of the Soil Plant Atmosphere Continuum (SPAC) system, changes in vegetation characteristics will affect the water uptake of the entire ecosystem. In this study, the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ isotope ratios in precipitation, plant water, soil moisture, and underground water, and the $\delta^{13}\text{C}$ isotope ratio of plant leaves were measured using the stable isotope technique for artificial revegetation used to fix the sand dunes in the Tengger Desert. The purpose of this study was to establish the isotope content and characteristics of potential water sources for plants and leaf carbon isotopes, to clarify whether the soil moisture condition and duration of sand-fixing influenced the isotopic signal, and to identify the main water source for desert plants. The results indicated that air temperature and amounts of precipitation were two important influencing factors in precipitation isotope ratio change. Soil water isotopic ratios were different under different water conditions, and under the same water conditions, the vertical variation in soil water isotopes in a single area and spatial variation at any depth for different revegetation areas were all significant ($p < 0.01$). Shallow soil waters were enriched in isotope ratios and the value increased with an increase of the sand-fixing duration (as found in older revegetation areas). The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values in *Caragana korshinskii* leaves were higher than they were in *Artemisia ordosica* leaves because the former has a higher transpiration rate. The higher $\delta^{13}\text{C}$ value of *Artemisia ordosica* plant leaves indicated high water use efficiency, which is a result of better adapting to the arid environment compared to *Caragana korshinskii*. Overall, water uptake of these two shrubs was mainly ($> 70\%$) concentrated at a soil depth of 20–150 cm. For *Caragana korshinskii* plants, the 60–150 cm soil layer was the main water supply layer, while the water contribution layer of *Artemisia ordosica* plants focused on the 20–100 cm soil layer and the contribution rate of shallow soil water increased with the increase of sand fixation time in older revegetation areas, regardless of the species used for revegetation.

1. Introduction

Establishment of artificial revegetation is a valid measure for stopping desertification in arid and semiarid northwest China (Li et al., 2017). Successful use of limited water resources is of central importance in determining the evolutionary trends of vegetation in these areas (Wang et al., 2017); the composition, pattern and process of vegetation in these regions depend on the hydrological processes, while the succession of vegetation changes the hydrological processes in turn (Wang et al., 2007; Li et al., 2010). The evolution of revegetation changes the plant community's structural characteristics and soil

hydraulic properties, which influences the potential for soil moisture replenishment by precipitation (Wang et al., 2013).

One of the most useful tools for quantifying water-cycle components and the linkages between plant ecology and physical hydrology is stable-isotope tracing (Yakir and Wang, 1996). The stable hydrogen and oxygen isotope characteristics of the terrestrial ecosystem can provide distinct trace information for water exchange between land and atmosphere and hydrological cycles in the terrestrial ecosystem. They are ideal tracers of water, as they are incorporated in the water molecules, and their behaviors and variations reflect the origin of, and the hydrological and geochemical processes undergone by, natural bodies of

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water (Gat, 1996; Gonfiantin, 1998). This process has been widely used to quantify plant water sources (Dawson and Ehleringer, 1991; Wu et al., 2016), calculate water use efficiency (Ehleringer and Dawson, 1992) and separate evapotranspiration components (Hu et al., 2014; Sun et al., 2014). Isotope analysis has proved to be particularly beneficial for investigating the hydrological processes (Risi et al., 2012; He et al., 2015; Galewsky et al., 2016). Isotope tracer applications rely directly on the isotopic labelling of atmospheric vapour and/or the resultant precipitation.

Plants are an important component of global water cycles, controlling 50–90% of ecosystem evapotranspiration (Jasechko et al., 2013; Coenders-Gerrits et al., 2014; Schlesinger and Jasechko, 2014). No fractionation of isotopes occurs during water uptake by plant roots (White et al., 1985). The isotope composition of water in roots and stems, therefore, reflects the isotopic composition of water available to the plant (Ehleringer, 1991). Leaf water isotopes may provide information on pathways of water movement in leaves (Barbour and Farquhar, 2004), with a modelling approach finding that gradients in leaf water isotope enrichment may vary with differing pathways of water movement between the vein and the evaporating surface (Barbour et al., 2016). Soil moisture is an important water source for desert vegetation. In general, the seasonal variation of water sources used by plants is determined by two factors: the distribution of the plant root system and the seasonal variations in hydrological conditions (Zencich et al., 2002; Asbjornsen et al., 2007). Different water sources have different hydrogen and oxygen isotope compositions, and the differences between isotopes in plant xylem and potential water sources can be used to study the source of water used by the plants (Hall-Aspland et al., 2005; Phillips et al., 2005).

Plant water-use efficiency (WUE) is an important indicator used to explore the adaptability of plants to global environmental changes and to predict the effects of global climate change, and it is a key factor in the relationship between carbon and water cycles of the plant-soil-atmosphere system. The carbon isotope composition ($\delta^{13}\text{C}$ value) of plant leaves involves the integration of photosynthetic activities in the process of leaf tissue formation, which reflects the long-term water use efficiency of plants and the survival strategy under water stress (Peterson and Fry, 1987; Ehleringer and Cooper, 1988; Johnson et al., 1990; Ebdon et al., 1998; Arslan et al., 1999). Thus, stable carbon isotope technology is commonly used around the world to study the long-term water use efficiency of plants, and it is based on the principle that there is a significant positive correlation between plant WUE and leaf $\delta^{13}\text{C}$ value (Knight et al., 1994; Sun et al., 1996; Stokes et al., 2010; Baruch, 2011). The samplings needed for $\delta^{13}\text{C}$ measurement are small and not limited by sampling time or space, and this value can effectively reflect the water condition of plants (West et al., 2007). This technology overcomes the challenges arising from the fact that only short time windows and instantaneous water use efficiency has been previously studied in plants, and it provides a new method and approach for studying long-term water use efficiency of plants that achieves very good results (Stokes et al., 2010; Baruch, 2011).

To prevent more than 40 km of the Baotou to Lanzhou railway bed from wind-blown sand damage, an artificial revegetation area over various years beginning in 1956 to form different sand-fixing duration of artificial revegetation areas. The present survey of typical plants found in the different sand-fixing duration of artificial revegetation area in the Tengger Desert was undertaken in order to establish the isotope variation characteristics of plant water and other water sources of representative sand-fixing plant species, to clarify whether the soil moisture conditions and duration of revegetation influence the isotopic signal, and to identify the main water source of desert plants.

2. Materials and methods

2.1. Measurement site description

The measurement was conducted in the Shapotou Desert Experimental Research Station (SDERS) which borders the Tengger Desert (37°27'N, 104°57'E) with an elevation of 1339 m a.m.s.l. The mean annual precipitation is approximately 180 mm with large seasonal and interannual variation, and approximately 80% of this falls between May and September, with a coefficient of variation as high as 45.7% (Wang et al., 2008). The natural landscape is characterized by reticulated chains of barchan dunes with a vegetation cover of less than 1%, and the predominant native plants are *Hedysarum scoparium* Fish, *Agriophyllum squarrosum* Moq., and *Psammochloa cilliosa* Bor. Biological soil crusts (BSCs) were nearly non-existent in this area before revegetation efforts began 60 years before this study (Pan et al., 2018). To stabilize the moving sand dunes and ensure unimpeded passage of the Baotou-Lanzhou railway through the sand dunes in the Shapotou area, a 16 km-long vegetated protection system (created by planting xerophytic shrubs in the 1 m × 1 m straw checkboards) was established in the 1950s, with widths of 500 m to the north side and 200 m to the south side of the railway (Wang et al., 2007). The unirrigated vegetation system was established in 1956 and extended in 1964, 1973, 1981, 1991 and 2010 by planting several dwarf xerophytic shrubs (Wang et al., 2006; Li et al., 2007; Zhang et al., 2012). The xerophytic shrubs used in the revegetation include *Artemisia ordosica* Krasch, *Caragana korshinskii* Kom., *C. microphylla* Lam., *Calligonum mongolicum* Turcz., *Atraphaxis bracteata* A. Los, *Atraphaxis pungens* Jaub. et Spach., *Elaeagnus angustifolia* L., *Salix gordejewii* Y. L. Chang and *H. scoparium*. Herbaceous species primarily included *Eragrostis poaeoides* Beauv., *Bassia dasyphylla* O. Kuntze, *Corispermum patelliforme* Iljin and *Salsola ruthenica* Iljin. BSCs dominated by cyanobacteria (e.g., *Microcoleus vaginatus* Gom and *Hydrocoleum violaceum* Marten); algae (e.g., *Euglena* sp. and *Hantzschia amphioxys var capitata* Grum), lichen (e.g., *Collema tenax* Ach.), mixed microphytic crusts, and moss-dominated crusts (e.g., *Bryum argenteum* Hedw and *Didymodon constrictus* (Mitt) (Li, et al., 2002) gradually settled on dune surfaces after establishment of revegetation (Li et al., 2004). A desert shrub ecosystem with a dwarf shrub and biological soil crusts cover on the stabilized sand dunes have also formed over the course of this project. Spatial heterogeneity of the study area is characterized by patches of perennial vegetation: after 60 years of evolution, *Caragana korshinskii* and *Artemisia ordosica* are two mainly artificial sand-fixing shrubs in this area. In this study, we chose the 1956, 1981, 1991, 2010 artificial revegetation areas as study subjects and compared with natural moving sand area (control area), because the soil and plant characteristics of the 1964 and 1973 revegetation areas are similar to the 1956 and 1981 revegetation areas, respectively.

2.2. Samples collection and isotope analysis

The samples collection was carried out in May and September in 2017 during the rainy season and growth period of plants in this area. Groundwater samples were collected from a well near the experimental field. Precipitation was collected immediately after a rain event to minimize evaporation effects. Plant xylem, leaf and soil samples of different depths were collected for *Caragana korshinskii* and *Artemisia ordosica* at different revegetation evolution stages where the revegetation was established in 1956, 1981, 1991, 2010 year and the nearby natural moving sand area. The sample collection was carried out on May 30th and September 8th, which was a week after a rainfall event. The infiltration depths of 11.3 mm precipitation on May 23rd and 1.6 mm precipitation on September 8th were approximately 15 cm and 2 cm in 1956 revegetation area, respectively. The characteristics of plants and soil are shown in Table 1. We selected plants of similar size in five experimental areas for our study. The average canopy height of

Table 1
The plant and soil characteristics of study sites (mean \pm stdev, n = 6).

Revegetation year	Shrub coverage (%)	Herb coverage (%)	BSCs coverage (%)	0–300 cm soil water content (%)
1956	11.3 \pm 1.2	43.2% \pm 3.5	78.3 \pm 7.9	1.74 \pm 0.09 (0–100 cm)
1981	16.3 \pm 1.8	36.5 \pm 4.3	42.6 \pm 5.4	1.87 \pm 0.2
1991	35.3 \pm 2.6	23.7 \pm 3.6	36.4 \pm 6.9	1.90 \pm 0.3
2010	30.2 \pm 1.9	12.8 \pm 2.3	24.3 \pm 4.8	2.88 \pm 0.4
Natural	4.8 \pm 0.1	6.4 \pm 0.6	1.7 \pm 0.1	2.89 \pm 0.3

Note: Just 0–100 cm soil water content was measured in 1956 revegetation area and soil moisture content values were the mean of *Artemisia ordosica* and *Caragana korshinskii* plant plots (n = 6). BSCs mean Biological Soil Crusts.

Caragana korshinskii is 177 cm (range of 154–187 cm) and the average diameter is 89 cm (range of 85–99 cm). The average canopy height and diameter of *Artemisia ordosica* are 65 cm (range of 50–80 cm) and 79 cm (range of 60–95 cm) respectively. The xylem was cut from plants, and the epidermis was gently removed using tweezers. The veins of collected leaves were removed. The sample collection time was at local 12:00 and researchers ensured no moisture remained on the leaf surface during sampling. In September, soil samples were collected at layers of 0–5, 5–10, 10–20, 20–40, 40–60, 60–80, 80–100, 100–150, 150–200, 200–250 and 250–300 cm using a 10 cm diameter auger during the experimental period. Only soil samples from above 110 cm could be collected in the 1956 revegetation area because underlying soil layers were too dry and the soil samples could not be obtained. In May, only soil samples above 110 cm in depth were collected. Then, the soil water content was measured through the drying and weighing method. Other parts of the samples were quickly placed into 20 ml screw-cap glass vials sealed with parafilm and stored in a refrigerator at -4 °C until extraction. All soil water and isotope samples were collected in duplicate. Water in xylem, leaf and soil samples was extracted using a fully automatic vacuum condensation extraction system (LI-2100, LICA United Technology Limited, Beijing, China). The extraction rate of water from samples was $> 98\%$. Xylem water, soil water, underground water and precipitation (0.5–1.5 ml) (manual book edited by Los Gatos Research, Inc.) were analysed for $\delta^{18}\text{O}$ and $\delta^2\text{H}$. Leaf water was analysed for $\delta^{18}\text{O}$, $\delta^2\text{H}$ and $\delta^{13}\text{C}$. The water isotopic compositions were analysed using an Isotope Ratio Mass Spectrometer (MAT 253, Thermo Fisher Scientific, Inc., USA). The isotopic compositions were reported in standard δ -notation, representing ‰ deviations from the Vienna Standard Mean Ocean Water standard (V-SMOW), expressed as δ (‰) = $(R_{\text{sample}} - R_{\text{standard}})/R_{\text{standard}} \times 1000 = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$. The leaf carbon isotope ratios ($\delta^{13}\text{C}/\delta^{12}\text{C}$) were measured by isotope ratio mass spectrometry (DELTA V Advantage, Thermo Fisher Scientific, Inc., USA), oven-dried samples (80 °C for 48 h) were finely ground, and the relative abundance of $\delta^{13}\text{C}$ and $\delta^{12}\text{C}$ was determined. Carbon isotope composition $\delta^{13}\text{C}$ (‰) in leaf samples were calculated as: $\delta^{13}\text{C}$ (‰) = $[(R_{\text{sample}} - R_{\text{standard}})/R_{\text{standard}}] \times 1000 = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$, where R_{sample} and R_{standard} are the $^{13}\text{C}/^{12}\text{C}$ ratio in the leaf and standard, respectively. The universally accepted standard of Vienna Pee Dee Belemnite (VPDB) was used. The analytical uncertainties for $\delta^{18}\text{O}$, $\delta^2\text{H}$ and $\delta^{13}\text{C}$ were 1‰, 0.2‰ and 0.1‰, respectively.

2.3. Data analysis

The Iso-Source model (<http://www.epa.gov/wed/pages/models/stable-Isotopes/isosource/isosource.htm>) was employed to quantify the proportion of water uptake from each water source based on the mass balance of the isotope which had been introduced, as detailed by Phillips and Gregg (2003). This model determines the upper and lower limits of the contribution ratio of each potential water source when there are more than three potential sources. We first determine the possible plant water sources as precipitation, soil water at different depths, and underground water, and then we put isotopic values of plant stem water and potential water sources into the Iso-Source model

to calculate the absorption ratios of plants to different water sources. Before running the model, two parameters needed to be established: the first is the source increment, which is generally set as 1‰ and represents the utilization ratio of plants to each water source assigned by 1‰ increments in order to detect the combination of possible proportions. When the number of potential water sources is large, this value can be set as 2‰ to improve the operating efficiency of the software. The second parameter is the mass balance tolerance: if it is set as 0.1‰, the proportional combination is possible to determine when the difference between the sum of the weighted value of the utilization proportion of different water sources' isotope value and the isotope value of plant stem water is no more than 0.1‰. The mass balance tolerance is generally not less than 1/2 of the product of the maximum difference between the source increment and the isotopic value of each possible water source. d excess is the term that indicated the difference of hydrogen and oxygen stable isotopes fractionation, which can be expressed as: $d = \delta\text{D} - 8\delta^{18}\text{O}$, ‰.

A one-way analysis of variance with Duncan's post hoc test ($p \leq 0.05$) was conducted to test for significant differences in isotope ratios of different water sources in different years of revegetation for *Artemisia ordosica* and *Caragana korshinskii* plants. Prior to analysis, all variables were checked for distribution normality (Shapiro-Wilk test) and homogeneity (Levene test). All statistical analyses were performed using SPSS software (SPSS Inc., Chicago, IL, USA).

Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPPLIT) (Stein et al., 2015) was used to track the origin of the precipitation events captured during the study period. Two typical precipitation events occurring during the experimental period on May 23rd and September 1st were analysed to ascertain if the precipitation origin was different for these two events, which can induce a difference in the isotope ratio (Fig. 1).

3. Results

3.1. Precipitation and underground water isotope characteristics

The meteorological conditions, $\delta^2\text{H}$, and $\delta^{18}\text{O}$ time series of precipitation during the observation period are shown in Fig. 2. The total precipitation throughout 2017 was 193.8 mm, more than 67% of which fell from June to September. The mean air temperature was similar between May (19.7 °C) and September (19.6 °C) for isotope measurement, and the average value was 11.43 °C during the observation year. Heavy precipitation and high air temperatures occurred simultaneously.

The average values of precipitation $\delta^2\text{H}$ and $\delta^{18}\text{O}$ were $(-54.83 \pm 33.08)\text{‰}$ and $(-7.32 \pm 5.30)\text{‰}$ during the total observation period with the d -excess average value of 3.73‰, with fluctuation ranges from -107.93‰ to 23.33‰ and from -14.73‰ to 9.57‰, respectively. Low d -excess was measured in months when there was very little rainfall. The d -excess value was low in March and increased gradually with the coming of the rainy season, peaked in July and August, then decreased gradually with the reduction in rainfall and air temperature. The rainfall isotope ratios became more depleted through rain events resulting from Rayleigh distillation of heavy

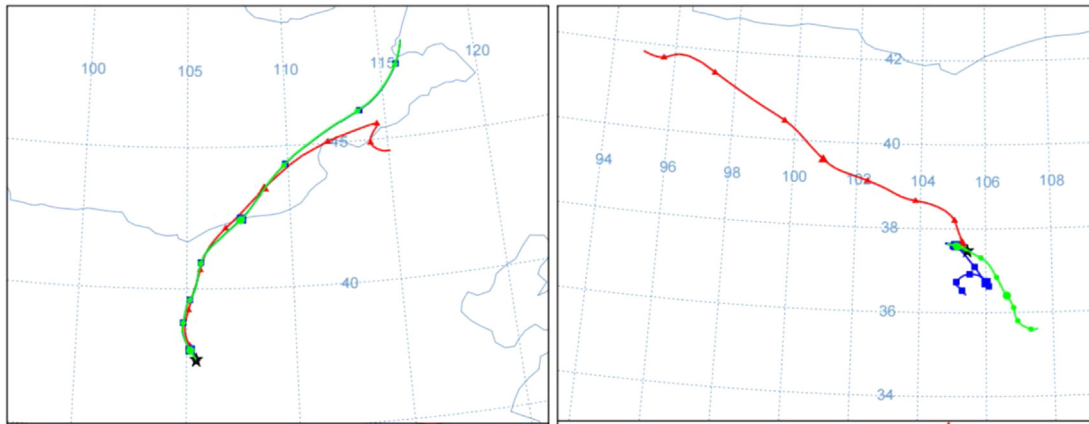


Fig. 1. Hybrid Single Particle Lagrangian Integrated Trajectory model of 48-hour backward trajectory analysis of the two precipitation events captured at Shapotou Desert Research Experimental Station during the observation period. 2017.5.23 and 2017.9.01.

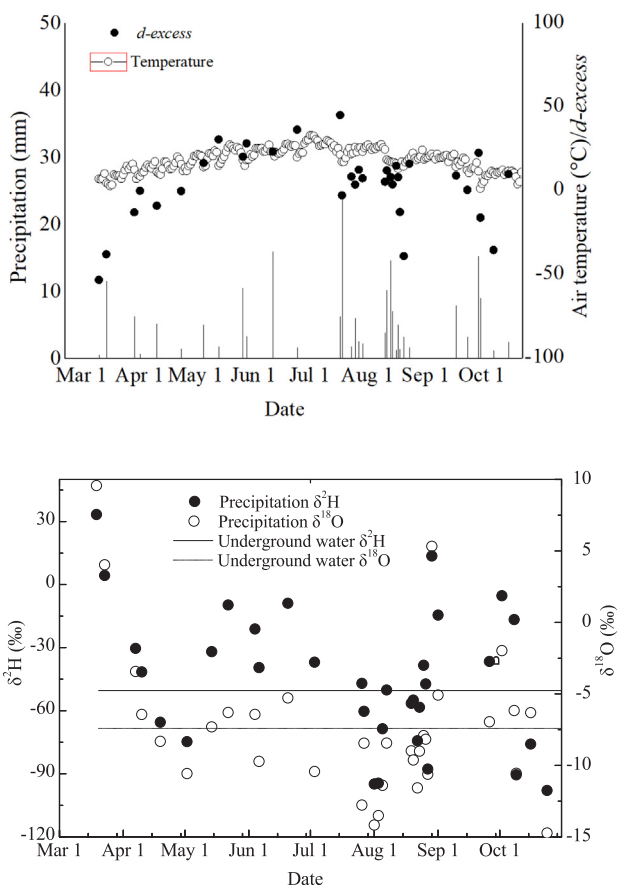


Fig. 2. The meteorological conditions and $\delta^2\text{H}$, $\delta^{18}\text{O}$ variation characteristics of precipitation and underground water.

isotopes, and the variation characteristics of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ were consistent. The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of underground water were $(-50.42 \pm 5.84)\text{‰}$ and $(-7.41 \pm 0.97)\text{‰}$, respectively.

3.2. Soil water and isotope characteristics

The soil water content was low in this area, and the average soil water content of 0–300 cm soil depth for different-year revegetation areas is $(1.95 \pm 0.13)\%$ and $(2.16 \pm 0.18)\%$ in *Artemisia ordosica* and *Caragana korshinskii* plots, respectively. In addition to the younger 2010 revegetation area, there were significant differences between soil water contents in other revegetation areas and natural moving sand areas

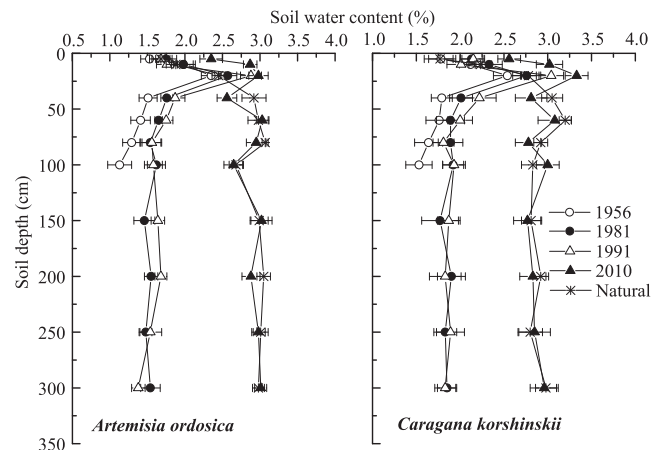


Fig. 3. The soil water variation characteristics at different soil depths after revegetation.

($p < 0.05$). The soil water content decreased gradually with the increasing age of sand-fixing revegetation areas at 0–300 cm in depth, especially in the deep soil layer (below 40 cm) (Fig. 3).

The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of different depths of soil water across various revegetation areas and different observation times are shown in Fig. 4. The variability of shallow soil water $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values was significant ($p < 0.01$) in different revegetation areas and different observation periods. The variation trend tends to be uniform with the increase in soil depth. For *Caragana korshinskii* and *Artemisia ordosica* plants, the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values both increased with the increase of duration of revegetation for different vegetation types. The soil moisture isotope ratios showed a significant difference ($p < 0.01$) from natural moving sand areas after the artificial revegetation was established more than 30 years ago. The soil water $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values in *Artemisia ordosica* revegetation areas were significantly higher ($p < 0.01$) than *Caragana korshinskii* revegetation areas. Compared to artificial revegetation areas, the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of natural moving sand areas were lower.

3.3. Xylem water isotope characteristics

The xylem water's stable isotope values for hydrogen and oxygen showed no significant difference ($p > 0.01$) at different observation times and for different plant species. For different revegetation areas, the xylem water's hydrogen and oxygen stable isotope values increased gradually with the year of sand-fixing revegetation. In both *Caragana korshinskii* and *Artemisia ordosica*, the plant xylem's stable oxygen

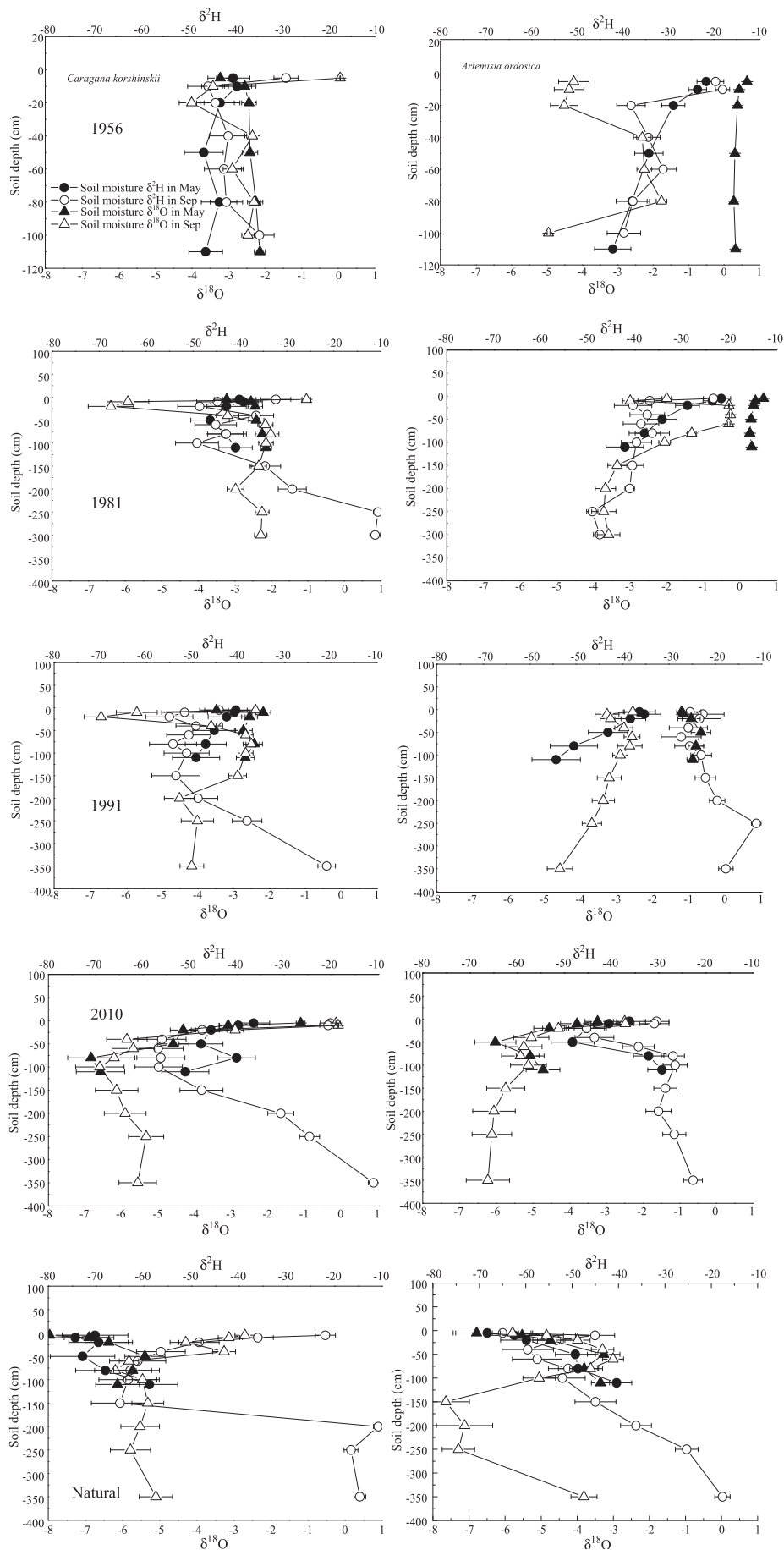


Fig. 4. The δ^2H and $\delta^{18}O$ variation characteristics of soil water at different depths.

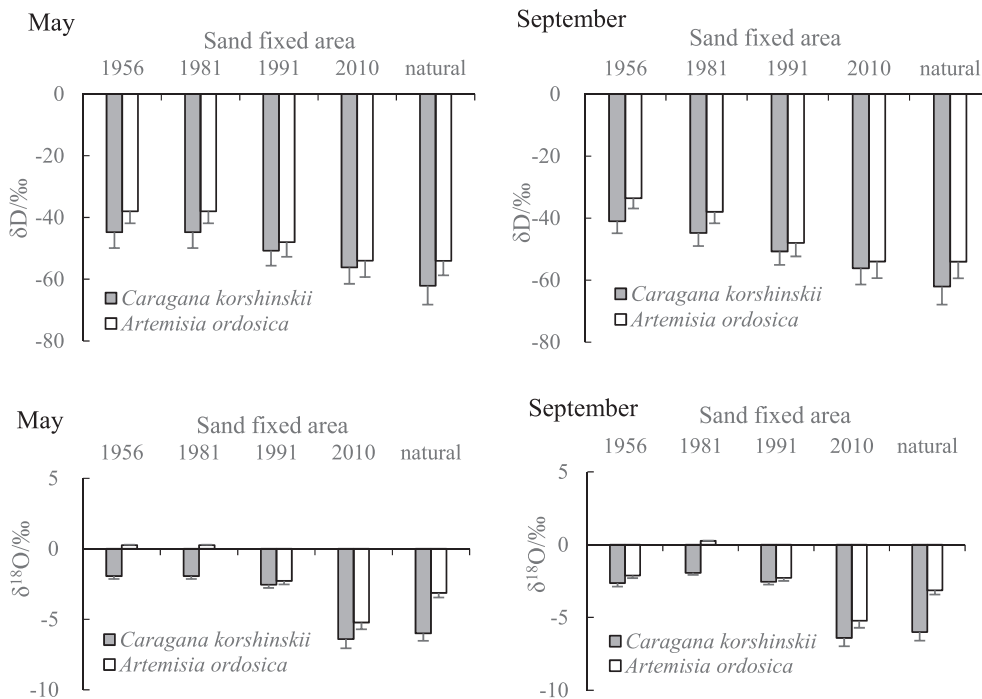


Fig. 5. The hydrogen and oxygen stable isotopes values of xylem water ($p > 0.01$ for $\delta^2\text{H}$ and $p < 0.01$ for $\delta^{18}\text{O}$).

isotope value in 1956 revegetation areas was three times greater than the value from the 2010 revegetation areas and natural moving sand areas over the observation period (Fig. 5).

3.4. Leaf water isotope characteristics

Leaf water $\delta^2\text{H}$ and $\delta^{18}\text{O}$ value variations at different revegetation areas for different observation times were shown in Fig. 6. Leaf water was found to be considerably more enriched in isotopic ratios relative to the other source waters. The stable hydrogen and oxygen isotope values of *Caragana korshinskii* and *Artemisia ordosica* plant leaf water were significantly higher ($p < 0.01$) than the values from xylem water (Figs. 5 and 6). The measurement values were significantly higher

($p < 0.01$) in May than in September. The stable hydrogen isotope values of *Caragana korshinskii* was significant higher ($p < 0.01$) than *Artemisia ordosica* in May, but the measurement values of these two plants were similar in September. The difference of oxygen stable isotopes values was not significant ($p > 0.01$) for *Caragana korshinskii* and *Artemisia ordosica* plants in different revegetation areas during the observation period. For *Artemisia ordosica*, the stable hydrogen and oxygen isotope values of leaf water increased gradually with the increase in sand-fixing time. For *Caragana korshinskii*, the values initially increased and then decreased with the sand-fixing time. There is no significant difference between artificial revegetation areas and natural moving sand areas.

Although the difference was not significant ($p > 0.01$), *Artemisia*

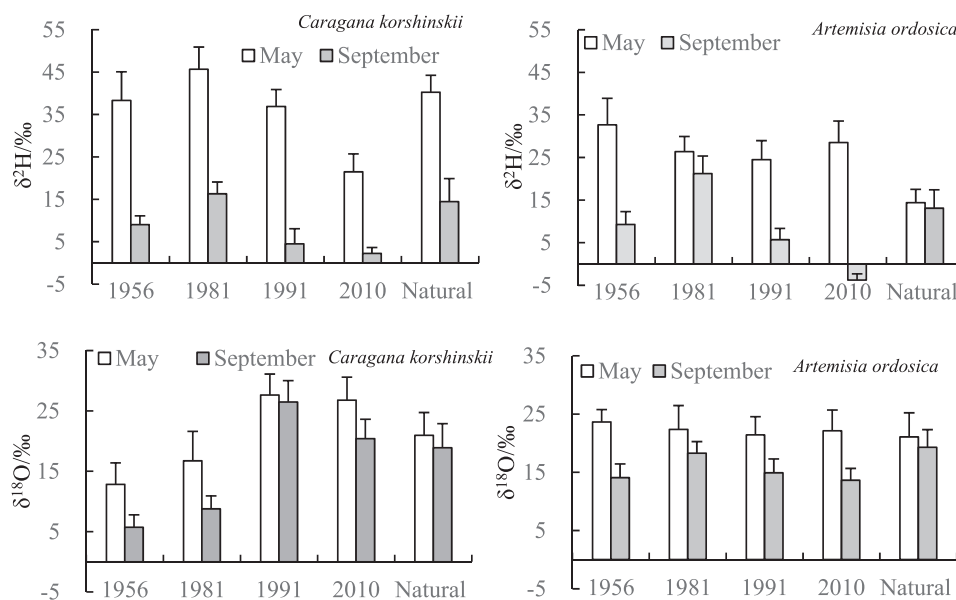


Fig. 6. The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ enrichment variations of leaves at different revegetation areas ($p < 0.01$ for *Artemisia ordosica* and $p > 0.01$ for *Caragana korshinskii*) for different observation times ($p < 0.01$).

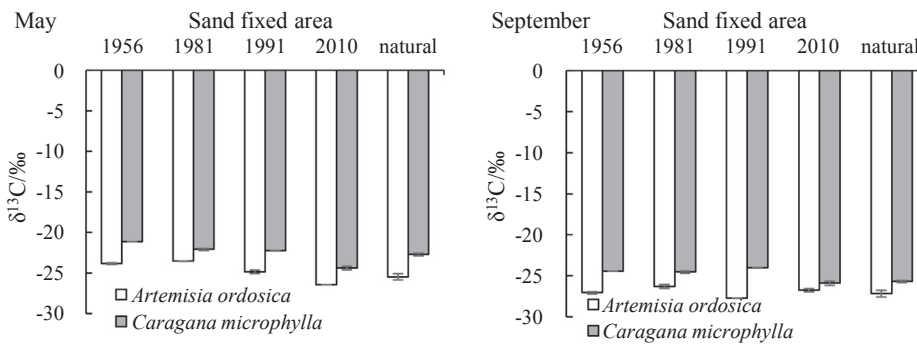


Fig. 7. The value of leaf $\delta^{13}\text{C}$ at different observation times ($p > 0.01$).

ordosica leaf ^{13}C values were higher than those in *Caragana korshinskii* leaves in different revegetation areas and in different observation periods. The ^{13}C values of *Caragana korshinskii* and *Artemisia ordosica* leaves in September were both higher than in May. There is no significant difference between artificial revegetation areas and natural moving sand areas (Fig. 7).

3.5. Water sources of sand-fixation vegetation

In May, the $\delta^{18}\text{O}$ of xylem water was similar to the soil layer of 80–110 cm in the 1956 revegetation areas for *Caragana korshinskii* plants. Measurements were 80–110 cm in the 1981 area, 20–110 cm in the 1991 area, 80–110 cm in the 2010 area, and 80–150 cm in the natural moving sand area. The $\delta^2\text{H}$ of xylem water was similar to the soil layer of 20–110 cm in the 1956 area, 20–110 cm in the 1981 area, 80–110 cm in the 1991 area, 80–110 cm in the 2010 area, and 80–150 cm in the natural moving sand area. For *Artemisia ordosica*, the $\delta^{18}\text{O}$ of xylem water was similar to the soil layer at 50–80 cm in the 1956 area, 80–110 cm in the 1981 area, 80–110 cm in the 1991 area, 80–110 cm in the 2010 area, and 50–150 cm in the natural moving sand area. The $\delta^2\text{H}$ of xylem water was similar to the soil layer of 80–110 cm in the 1956 area, 80–110 cm in the 1981 area, 80–110 cm in the 1991 area, 20–50 cm in the 2010 area, and 20–100 cm in the natural moving sand area (Figs. 4 and 5), that means, although it's not significant, $\delta^2\text{H}$ is a less sensitive indicator for tracing water uptake depth than $\delta^{18}\text{O}$.

With large differences in isotopic composition throughout the root zone, it is obviously difficult to specify the isotope composition of water that is taken up by the plants. Table 2 summarized the contribution proportion of different water sources for plants and analysed the influence of different sand-fixing and measurement times. For *Caragana korshinskii* plants, the relative contribution of the 40–150 cm soil layer was more than 50% regardless of the sand-fixed time. The water contribution layer for *Artemisia ordosica* plants was focused at surface 110 cm soil layer, and the contribution rate of shallow soil water increased with the increase of sand-fixing time regardless of the species of revegetation plant. Compared to the results in May, the soil water contribution layer was shallower in September. Considering the sampling depth limit in May, the results in September were more reliable. For *Caragana korshinskii*, the highest soil moisture contribution layer was 40–60 cm, 80–110 cm, 150–300 cm, 80–110 cm and 150–300 cm in 1956, 1981, 1991, 2010 and natural moving sand areas, while the highest soil moisture contribution layer of *Artemisia ordosica* was 80–110 cm, 0–20 cm, 0–20 cm, 40–60 cm and 80–110 cm, respectively. Soil water was an important water source for artificial revegetation plants in desert areas, and water uptake mainly (> 70%) concentrated at 20–150 cm at different year-classes of sand-fixing revegetation areas. Comparatively speaking, groundwater was not used as a source in this area.

Table 2

Relative contributions from soil water at different depths to revegetation shrubs water use sources at different observation time (May 7 and July 2).

Depth (cm)	Relative contribution rate (standard error)%				
	0–20	40–60	80–110	150–300	
May (<i>Caragana korshinskii</i>)	1956	23.7(2.02)	26.2(3.13)	50.1(5.11)	
	1981	20.2(3.18)	36.5(5.56)	43.3(5.96)	
	1991	45.9(5.22)	15.7(2.62)	38.4(4.68)	
	2010	7.1(2.87)	4.3(1.06)	88.6(10.14)	
	Natural	4.5(1.11)	10.6(2.19)	85(9.77)	
May (<i>Artemisia ordosica</i>)	1956	22.9(5.89)	60.9(8.64)	16.2(4.15)	
	1981	4.9(0.56)	9.9(1.07)	85.3(7.13)	
	1991	17.1(3.01)	16.8(2.89)	66.1(9.08)	
	2010	30.1(5.33)	5(1.25)	64.9(9.03)	
	Natural	9(2.15)	9.1(2.88)	81.8(12.04)	
September (<i>Caragana korshinskii</i>)	1956	35.5(3.13)	38.9(4.25)	25.5(3.48)	
	1981	18.6(2.36)	12.2(1.55)	65.7(5.65)	3.4(0.77)
	1991	23.4(5.17)	17.7(2.14)	18.7(3.04)	40.3(6.07)
	2010	2(0.56)	11(2.07)	85(10.47)	2(0.85)
	Natural	1.2(0.35)	7.9(2.08)	19.7(3.12)	71.1(9.89)
September (<i>Artemisia ordosica</i>)	1956	19.7(4.33)	35.6(7.09)	44.7(9.14)	
	1981	37.9(5.25)	23.3(4.44)	29.8(4.97)	9(1.59)
	1991	41.3(7.16)	26.7(5.11)	9.1(2.13)	22.9(5.86)
	2010	21.1(4.13)	16.8(4.07)	16.7(3.99)	45.4(8.19)
	Natural	2.4(0.76)		89.2(15.28)	8.4(2.58)

4. Discussions

There is a positive relationship between air temperature and the isotope ratios of precipitation, which means precipitation falling during cool times of the observation period has low $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values, while precipitation occurring during warmer months has high isotope ratio values. This result was consistent with the research of Dansgaard (1964) and Ehleringer (1991) at mid-latitudes. HYSPLIT (Stein et al., 2015) was used to track the origin of the precipitation events captured during the study period, and trajectory analysis showed that rain events sampled during May and September originated from different area in the opposite direction; thus, isotopic enrichment of rain relative to other waters is attributed to the “continental effect” and to sub-cloud evaporation (Dansgaard, 1964; Stewart, 1975; Kaseke et al., 2016). d -excess was a second-order parameter of the combined $\delta^2\text{H}$ and $\delta^{18}\text{O}$ isotope ratio measurement in precipitation. Points that fall on the Global Meteoric Water Line (GMWL) have a constant d -excess of 10.0‰ when an equilibrium process was considered. Considering the effect of equilibrium Rayleigh condensation processes, d -excess serve as a conservative tracer of evaporation conditions (Welp et al., 2012). Evaporation usually results in a higher d -excess value (Gat et al., 1994), thus, d -excess can be used to estimate evaporation (Gat et al., 1994; Froehlich et al., 2008). The low d -excess value appears when rainfall is limited (Fig. 2), which was related to the lower relative humidity resulting in less evaporation during this period.

Since the underground water in this region is more than 30 m below the surface and cannot be used by plants in the study area, plant roots may only obtain water from a deep soil water reservoir or recent precipitation. Soil water isotopic ratios at different depths collected in May were not correlated with the isotopic ratios collected in September 2017 in the same revegetation area ($P < F$ for most observation (16 within 20 observations)), indicating that the soil water isotopic ratio is not the same at different times. At the same observation times, the vertical variation in soil water isotopes at a single area and spatial variation at any depth for different revegetation area were all significant ($p < 0.01$). Shallow soil waters are enriched in their isotope ratios due to evaporation from within the soil column (Allison et al., 1983). Additionally, the isotope ratio values of shallow soil moisture (< 50 cm) increased along with the duration of revegetation, which is related to the evaporation from different artificial revegetation ecosystems. Artificial sand fixing vegetation markedly influenced the infiltration and redistribution patterns of precipitation on the stabilized sand dunes. Root withdrawal of soil water and evapotranspiration (reaching 69–90% of precipitation) restricted the wetting front penetration for the vegetated soil (Wang et al., 2008). Considering the lower evaporation under shrub, the higher antecedent soil water content of surface soil also reduces rainfall infiltration depth and cumulative infiltration. Furthermore, with the increase of sand-fixing time, the coverage of shrubs, herbs and cryptogams increased and developed, and the amount of canopy interception increased to 27% (Wang et al., 2005), while the increase of BSCs thickness and gradual development (changing from cyanobacteria-dominated crusts to moss-dominated crusts) significantly reduced precipitation infiltration (Li et al., 2010). These changes led to most of the water being trapped in the shallow soil and resulted in an increase of shallow soil moisture content and a decrease of deep soil moisture, corresponding to an increase in evaporation. The increased proportion of isotope ratios with sand-fixing time was higher in *Artemisia ordosica* revegetation areas than *Caragana korshinskii* revegetation areas (Fig. 4). *Caragana korshinskii* is a multiple-stemmed shrub with smooth stems and ovate leaves, while *Artemisia ordosica* is a highly branched dwarf-shrub with a rough stem and needled leaves. *Caragana korshinskii* and *Artemisia ordosica* can intercept 16.7% and 22.3% of precipitation (Zhang et al., 2015), respectively, which means more rainfall was intercepted in the *Artemisia ordosica* revegetation areas; in addition, most precipitation was less than 5 mm in the Shapotou region, so more rainfall was concentrated in shallow soil and used for evaporation.

Understanding the controls on temporal variation in plant leaf $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values is important for understanding carbon-water dynamics of the biosphere and interpreting a wide range of proxies for past environments (Wang et al., 2018). While there is no fractionation of isotopes during water uptake by plants, fractionation does occur during transpiration. Plant transpiration was strong in arid conditions, leading to strong isotopic enrichment in their leaf water (Dongmann et al., 1974; Gat et al., 2007). Therefore, the difference of leaf $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values between different observation time and plant species indicates a difference in leaf transpiration. The isotope ratio values of *Caragana korshinskii* leaves were higher than *Artemisia ordosica* leaves regardless of the observation date, which indicated that the transpiration of *Caragana korshinskii* was higher than *Artemisia ordosica* (Fig. 6). The variations of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ enrichment at the evaporating sites in a leaf are controlled by the interactions of environmental factors (e.g., air temperature and relative humidity), physiological properties (e.g., transpiration and stomatal conductance), and effective path length (e.g., L_{eff} , where advection and diffusion are obvious) (Wang et al., 2018). In the process of transpiration, the leaf water of terrestrial plants is more enriched in $\delta^2\text{H}$ and $\delta^{18}\text{O}$ than it is in the water taken up by their roots, which is due to the slower diffusion (i.e., the kinetic effect) through the stomata and the lower saturation vapor pressure (i.e., the equilibrium effect) of the heavier molecules compared to the light molecules (Farquhar et al. 2007; Xiao et al. 2012). According to previous research

results, the stable hydrogen and oxygen isotope composition of plant xylem and leaf water were more enriched than the local precipitation (DeNiro and Epstein, 1979; Yakir and DeNiro, 1990), which was consistent with this result (Figs. 5 and 6). The isotope fractionation effects were the reason for this result, which involved the enrichment of the heavy oxygen in the leaf water relative to the water taken up by the roots, and a subsequent biochemical fractionation associated with the photosynthetic process. In the case of the hydrogen isotopes, these two processes appear to work one against each other, so the increases in hydrogen isotope values were relatively small compared to oxygen in plant xylem and leaves (Figs. 5 and 6). In arid desert areas, this stable isotope enrichment should be more obvious, considering the higher soil water isotope ratios and the enrichment of the plant water isotopes under the higher leaf to air vapor pressure deficit (VPD) in this area.

The difference of xylem isotope ratio values between different revegetation areas and different plant species indicated different soil water sources (Fig. 5). A healthy plant-soil ecosystem requires that water utilization by plants does not exceed the supply of soil water, which otherwise leads to water deficits. The isotopic composition reflects the way in which the plants cope with the problems of aridity and water deficits: at the intake site (roots), by means of the differential use of suitable water along the soil profile, either shallow or deep (Yakir and Yechieli, 1995); at the discharge point through enrichment of the isotope ratios in the leaf water associated with evapotranspiration; and by the timing of stomatal opening and the humidity which prevails at that time. Large differences were observed in the extent of enrichment of the isotope ratios in leaf water relative to local precipitation during the observation period. The difference of isotope ratio between different plant species is apparently caused by the species-dependent strategies adopted by the plants to cope with water stress, primarily by differences in the depth of water uptake in the soil and through the timing of stomatal openings during the daily cycle (Gat et al., 2007). Evidently, different plant species, which grow in the same habitat during any particular time, show differences in the main water sources they utilize, which is most likely dictated by the depth of the roots (Table 2). The lateral and vertical distribution characteristics were different for *Caragana korshinskii* and *Artemisia ordosica* plants. *Artemisia ordosica* has a much larger lateral distribution of roots than *Caragana korshinskii*, particularly in shallow soil layers (Zhang et al., 2008; Zhang et al., 2009), so the soil layer used for water uptake by *Artemisia ordosica* was shallower. Furthermore, the soil water content in the *Caragana korshinskii* plant plot was higher than it was among *Artemisia ordosica* plants. In general, the seasonal variation of water sources used by plants is determined by two factors: the distribution of the plant root system and seasonal variations in hydrological conditions (Zencich et al., 2002; Asbjornsen et al., 2007). Compared to natural moving sand areas, the water uptake soil layer became shallower according to sand fixation year. The decrease of deep soil water content along with the evolution of revegetation was an important reason for this change. The capacity to adjust water use strategy along with the highly variable rainfall pattern and resulting soil water content is crucial for a plant to survive in these ecosystems (Wu et al., 2016; Grossiord et al., 2017).

Carbon isotopic composition ($\delta^{13}\text{C}$) in C_3 plants has been widely used as an index of long-term photosynthetic water use efficiency (WUE), because carbon isotope discrimination during photosynthesis linearly correlates to the ratio of absorbed CO_2 (Farquhar et al., 1982). The variation of the $\delta^{13}\text{C}$ value was lower in different revegetation areas for *Artemisia ordosica* and *Caragana korshinskii*. The $\delta^{13}\text{C}$ value of *Artemisia ordosica* was higher than *Caragana korshinskii*, although the difference was small (Fig. 7). As typical dry land plants, both plant species have high water use efficiency that has adapted them to the arid environment, but the water use efficiency of *Artemisia ordosica* is higher than *Caragana korshinskii*.

As typical sand-fixing plants in arid area, both *Artemisia ordosica* and *Caragana korshinskii* have favorable physiological and ecological characteristics adapt to arid environment. *Artemisia ordosica* showed higher

WUE and lower transpiration rate, combined with its strong horizontal roots, which was dominant in water competition with *Caragana korshinskii* in water limited arid desert area. Furthermore, with the obvious shallower infiltration of rainfall after the establishment of artificial vegetation, the water condition was benefit to the shallow root *Artemisia ordosica* plant. However, the moisture niche-fitness value of pure-planted *Artemisia ordosica* plant was lower than that of mix-planted *Artemisia ordosica* and *Caragana korshinskii* (Li et al., 2004). *Artemisia ordosica* is a shallow-rooted plant mainly using upper layer soil moisture and *Caragana korshinskii* is a deep-rooted plant using sub-layer soil moisture, the reasonable allocation and effective utilization of soil moisture when mix-planted lead to higher moisture-fitness degree value. The difference of plant height and shape for two plant species increased the soil surface roughness, obtained higher windy-resistance and sand-fixing efficiency.

5. Conclusions

One of the most useful tools for quantifying water-cycle components and the linkages between plant ecology and physical hydrology is stable-isotope tracing. This method was used to analyse the isotope ratio characteristics of typical revegetation plants and relative water sources in artificially revegetated desert areas. The precipitation isotope ratio was positively related to air temperature. The low *d*-excess value in this area was related to limited rainfall and lower relative humidity. The isotope ratio characteristics of soil moisture were influenced by sand-fixing time, soil layer depth and observation time. Compared to the natural moving sand area, the isotope ratio values of shallow soil moisture (< 50 cm) increased along with the duration of revegetation. The plant species influence leaf isotope ratio characteristics, and the isotope ratio values of *Caragana korshinskii* leaves were higher than *Artemisia ordosica* leaves. Although the difference was small, the $\delta^{13}\text{C}$ value of *Artemisia ordosica* was higher than the value for *Caragana korshinskii*. Furthermore, the soil layer used for water uptake by varying plant species was different. For *Caragana korshinskii*, the relative contribution of the 60–150 cm soil layer was more than 50%, regardless of the sand-fixing time, while the water contribution layer of *Artemisia ordosica* plants focused on the 20–100 cm soil layer and the contribution rate of shallow soil water increased along with sand-fixing time regardless of plant species. While *Artemisia ordosica* had higher adaptation to water limited arid environment, *Artemisia ordosica* and *Caragana korshinskii* mixed planting is an optimal way of sand fixation considering their separation of time and space in the utilization of resource.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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