
Water Use Strategy of Four Desert Shrubs in Gonghe Basin, Qinghai-Tibetan Plateau

Yajuan Zhu

Additional information is available at the end of the chapter

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Abstract

Gonghe basin is located in the ecotone from the semi-arid to arid zone on the northeastern Qinghai-Tibetan Plateau. *Caragana intermedia* and *Caragana korshinskii* are dominant on sand dunes. *Salix psammophila* and *Salix cheilophila* are mainly distributed on interdune. Water source of four desert shrubs was examined by δD and $\delta^{18}O$, and their long-term water use efficiency (WUE) was compared by leaf $\delta^{13}C$. Four desert shrubs used different depths of soil water depending on their availability in different seasons, including shallow soil water recharged by rain in spring or summer and deep soil water recharged by ground water. The reliability on ground water of two *Salix* shrubs on interdune was more significant than two *Caragana* shrubs on sand dunes. Moreover, the WUE of four shrubs decreased in drought spring. Two shrubs in *Caragana* had similar WUE in the growing season. However, the WUE of *S. psammophila* was always higher than that of *S. cheilophila*, which might have more adaptability in Gonghe Basin.

Keywords: water source, water use efficiency (WUE), stable isotope, soil water, ground water

1. Introduction

In desert ecosystems, water is a restrictive factor for plant survival and growth because of low and unpredictable precipitation and high evaporation [1, 2]. The ability to use rainwater in

spring and summer is important for plant phenology and growth [3]. Additionally, the sustainable water source is necessary for plant growth especially in the drought period, such as deep soil water or ground water [4]. A stable isotope technology is often used to study the water use strategy of desert plants. Generally, there is no stable isotope fractionation during water uptake by root system or water transportation in the xylem of most plant species. Thus, the main water source can be distinguished by comparing the δD or $\delta^{18}O$ value of xylem water with that of the potential water source, for example, rain, snow, river, lake, soil water or ground water [1]. Further, leaf $\delta^{13}C$ value of C_3 plants is positively related to their long-term water-use efficiency (WUE). The $\delta^{13}C$ value decreased from spring to autumn in the growing season and increased in the drought period [4].

Previous studies with the stable isotope of hydrogen or oxygen indicated that woody plant species used different water sources in desert or other arid and semi-arid ecosystems. Firstly, many trees and shrubs mainly used shallow soil water recharged by rain, for example, *Artemisia ordosica* in Mu Us Sandy Land [5], *Pinus edulis* and *Juniperus osteosperma* in Utah [6], *Larix sibirica* and *Potentilla fruticosa* in the mountain forest along the Kherlen River of Mongolia [7], *Senecio filaginoides* and *Mulinum spinosum* in Patagonian steppe [8], *Nitraria tangutorum* and *Artemisia arenaria* in Badain Jaran Desert [9], *Sarcobatus vermiculatus* in San Luis Valley of Colorado [10] and *Haloxylon persicum* in Gurbantunggut Desert [11]. Secondly, some deep-rooted shrubs and trees mainly used ground water, for example, *Sabina vulgaris* and *Salix matsudana* in Mu Us Sandy Land [12], *Populus fremontii* in the non-saline habitat of Colorado River Basin [13], *Ericameria nauseosa* in San Luis Valley [10], *Ulmus pumila* in Hunshandake Sandy Land [14], *Pinus sylvestris* var. *mongolica* in Horqin Sandy Land [15], *Populus euphratica* along Heihe River [16] and *Haloxylon ammodendron* in Gurbantunggut Desert [11]. Thirdly, few shrubs or trees with dimorphic root systems used both soil water recharged by rain and deep soil water recharged by ground water and even ground water. *S. vermiculatus* used ground water during dry periods but used deep soil water large amounts of rainfall in San Luis Valley [10].

Gonghe Basin is located in the northeastern Qinghai-Tibetan Plateau, which is the ecotone from semi-arid to arid region, with the altitude varying from 2600 to 3400 m. It contains part of Gonghe County, Guinan County and Xinghai County of Qinghai Province. The dominant vegetation is steppe and desert steppe. The basin is as long as 210 km in East and West, and as wide as 60 km in South and North, with a total area of 13,800 km². It is one of the most vulnerable land desertification area in Qinghai Province. The area of desertified land is 3530 km², which accounts for 25.58% of the total area. The ecological security in the upper reaches of Yellow River has been affected significantly by land desertification in Gonghe Basin, especially Longyangxia Reservoir [17]. In order to control and prevent land desertification, large areas were planted with trees and shrubs to form the shelterbelt system in the ecotone between oasis and desert to protect farms, villages and roads in Gonghe Basin. Some trees in *Populus* were planted by transplanting inside oasis. Some shrubs in *Caragana* were planted by seeding on sand dunes. Other shrubs in *Salix* were planted by cutting on interdune.

In this chapter, the main water source of four dominant desert shrubs is compared by stable hydrogen and oxygen isotopes in the growing season (May, July and September). The water

use ratio of different sources was analysed by Iso-source 1.3.1 software [18]. Two shrubs in *Caragana* on sand dunes may use shallow soil water recharged by rain and deep soil water recharged by ground water. Two shrubs in *Salix* on interdune may use shallow soil water recharged by rain, deep soil water recharged by ground water and even ground water. Further, the long-term WUE is compared using their leaf stable carbon isotope. The WUE of four shrubs may be higher in drought spring than in summer and autumn.

2. Water source and long-term WUE of four desert shrubs

2.1. Four dominant desert shrubs in Gonghe Basin

This study was conducted at Gonghe Desert Ecosystem Research Station, which is located in the mid-west Gonghe Basin and belongs to Shazhuyu Town, Gonghe County (36°16'N, 100°16'E, altitude 2874 m). The mean annual air temperature is only 2.4 °C, and the mean annual forest free day is only 91 days. The mean annual precipitation is 246.3 mm, which is concentrated from July to September. Two shrubs in *Caragana* and *Salix psammophila* were introduced from Ordos City, Inner Mongolia Autonomous Region. *Salix cheilophila* was introduced from Guinan County, which is located in the eastern Gonghe Basin.

Caragana intermedia (pea shrub) is a shrub with a height of 0.7–1.5 m growing on fixed sand dunes or flat sandy land. It is used as a good sand-fixing and afforest plant [19]. The mean height of *C. intermedia* was 1.04 m at Gonghe Station. The root system of *C. intermedia* was as deep as 1.3 m at Gonghe Station [20]. *Caragana korshinskii* (white pea shrub) is a shrub or small tree with a height of 1–4 m growing on fixed sand dunes. It is a good sand-fixing and soil conservation plant [21]. The mean height of *C. korshinskii* was 1.82 m at Gonghe Station.

S. psammophila (sandy willow) is a shrub with a height of 2–4 m, which inhabits on moving or semi-fixed sand dunes and interdune. *S. psammophila* is fast growing, tolerant to drought and sand burial and a good sand-fixing plant [21]. The mean height of *S. psammophila* was 2.82 m at Gonghe Station. The fine root of *S. psammophila* was 1.5 m deep in its original distribution area (Mu Us Sandy Land) [22]. *S. cheilophila* (black willow) is a small tree or big shrub, which is as tall as 5.4 m and inhabits slope, valley and riverbank. *S. cheilophila* is a mesophyte and hygrophyte and is often used as a sand-fixing or riparian plant [23]. The mean height of *S. cheilophila* was 3.72 m at Gonghe Station. The root system of *S. cheilophila* was 2.0 m deep at Gonghe Station [24].

2.2. Precipitation in the growing season and soil moisture in four desert shrubs plantation

The total precipitation at the study site was 137.5 mm from May 1 to September 13, 2014. The monthly precipitation was 8.8, 61.6, 37.8 and 28.7 mm in May, June, July and August, respectively (Figure 1). The maximal daily precipitation (18.9 mm) occurred on June 12. Before field sampling in July, 6.4 mm rain occurred on July 8, and in September, the precipitation was only 0.4 mm.

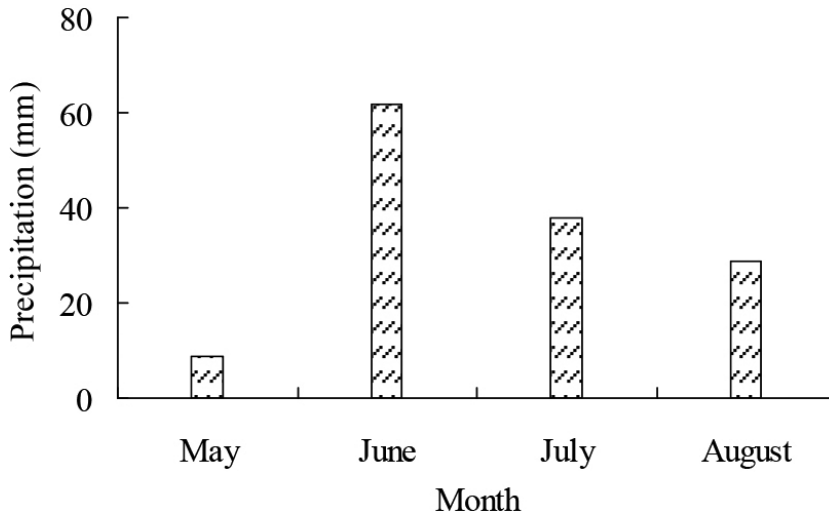


Figure 1. Precipitation at Gonghe Station from May to August, 2014.

Soil water content in *C. intermedia* plantation was significantly different in different depths on May 27 and July 20 but was similar on September 11 (**Figure 2**). On May 27, the water content in shallow soil (10 and 25 cm) was significantly higher than that in deeper soil (75–150 cm). On July 20, the water content in surface soil (10 cm) and subsurface soil (25 cm) was significantly higher than that in deeper soil (50–150 cm).

Soil water content in *C. korshinskii* plantation was similar in different depths on May 27 but was significantly different in different depths on July 23 and September 11 (**Figure 2**). On July 23, the water content in surface soil (10 cm) was significantly higher than in deeper depths (25–150 cm), and the water content in 150 cm was significantly higher than in medium depths (25–100 cm). On September 11, the water content in 150 cm was significantly higher than in shallower soil (10–100 cm).

Soil water content in *S. psammophila* plantation was significantly different in different depths on May 26, July 17 and September 11 (**Figure 2**). On May 26, the water content in middle and deep soil (50–150 cm) was significantly higher than that in shallow soil (10 and 25 cm). On July 17, the water content in middle and deep soil (50–150 cm) was significantly higher than that in shallow soil (25 cm). On September 11, the water content in middle soil (50 cm) and deep soil (150 cm) was significantly higher than that in shallow soil (10 and 25 cm).

Soil water content in *S. cheilophila* plantation was significantly different in different depths on May 26 and September 11 but was similar in different depths on July 17 (**Figure 2**). On May 26, the water content in middle and deep soil (50–200 cm) was significantly higher than that in surface soil (10 cm). On September 11, the water content in deep soil (100–200 cm) was significantly higher than in surface soil (10 cm) and middle soil (50 cm).

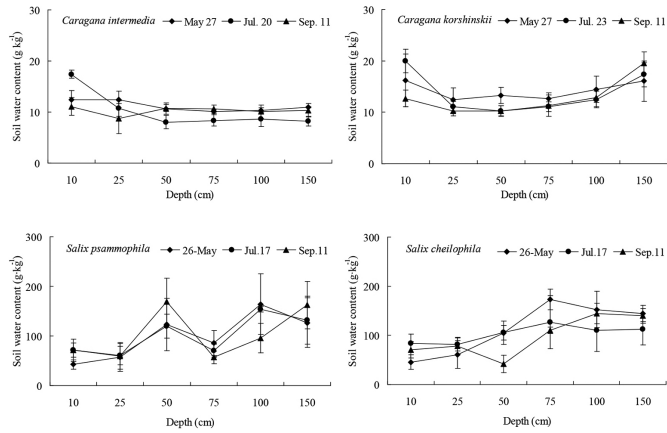


Figure 2. Soil water content in different depths in four desert shrub plantations.

2.3. Water source of four desert shrubs in different seasons

The $\delta^{18}\text{O}$ ratio of xylem water of *C. intermedia*, *C. korshinskii*, *S. psammophila* and *S. cheilophila* was located in the right side of global meteoric water line (Figure 3), which indicated that the water source of four shrubs was affected by isotope enrichment induced by evaporation. The δD and $\delta^{18}\text{O}$ value of some soil water were closer to ground water, which indicated deep soil water was recharged by ground water. The δD and $\delta^{18}\text{O}$ value of some soil water were closer to some rainwater, which indicated that shallow soil water is recharged by rain. The δD and $\delta^{18}\text{O}$ value of xylem water of two *Salix* shrubs were closer to ground water, which indicated that they might use ground water.

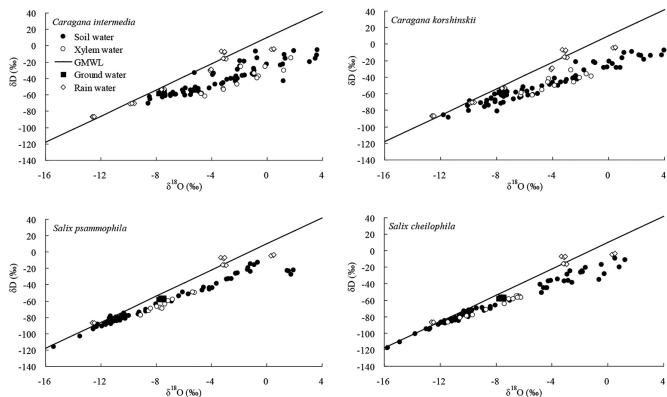


Figure 3. The value of δD and $\delta^{18}\text{O}$ in xylem and soil water of four desert shrubs, ground water, rainwater and global meteoric water line (GMWL) [4].

2.3.1. Water source of two *Caragana* shrubs on sand dunes

On May 27, the value of δD and $\delta^{18}O$ in xylem water of *C. intermedia* was closer to soil water in 50 cm (**Figure 4**). On July 20, the value of δD and $\delta^{18}O$ in xylem water of *C. intermedia* was closer to soil water in 10–50 cm, and the value of δD and $\delta^{18}O$ of soil water in 10 cm was closer to rain water on July 8 (6.4 mm). On September 11, the value of δD and $\delta^{18}O$ in xylem water of *C. intermedia* was closer to soil water in 100–150 cm and ground water.

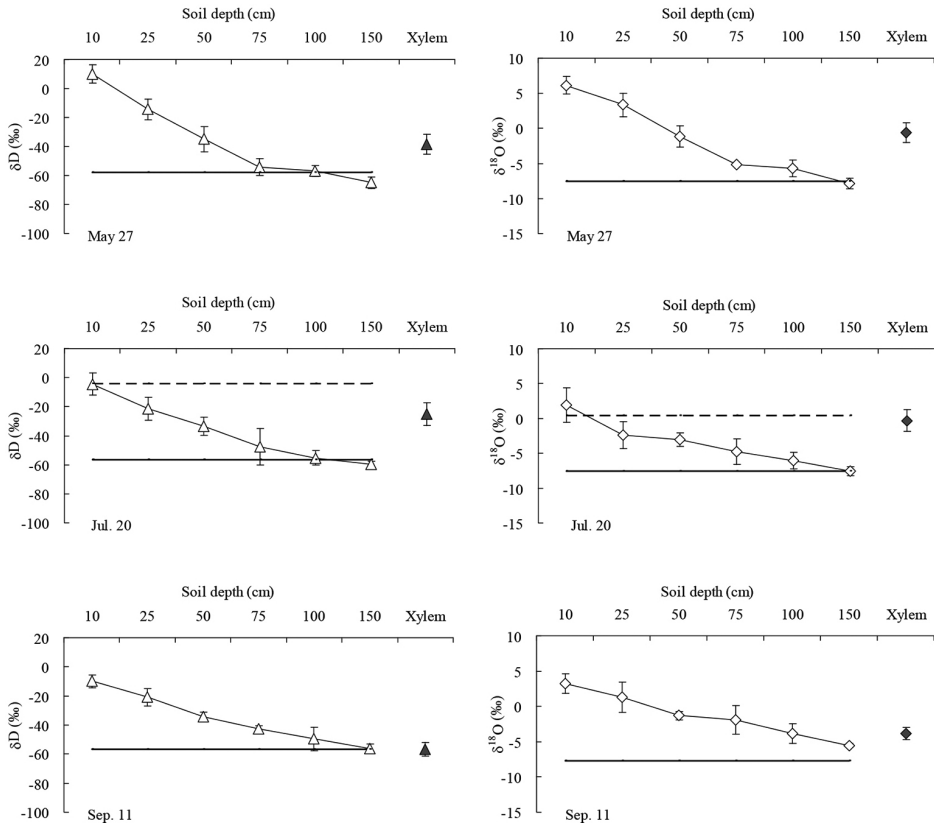


Figure 4. The value of δD and $\delta^{18}O$ in xylem water of *Caragana intermedia*, soil water and ground water. Full line is ground water. Dot line is 6.4 mm rainwater on July 8.

On May 27, the ratio of δD and $\delta^{18}O$ in xylem water of *C. korshinskii* was closer to soil water in 50–100 cm and ground water (**Figure 5**). On July 23, the value of δD and $\delta^{18}O$ in xylem water of *C. korshinskii* was closer to soil water in 50–75 cm, which was closer to rain water on July 21 (8.0 mm). On September 11, the value of δD and $\delta^{18}O$ in xylem water of *C. korshinskii* was closer to soil water in 25–75 cm.

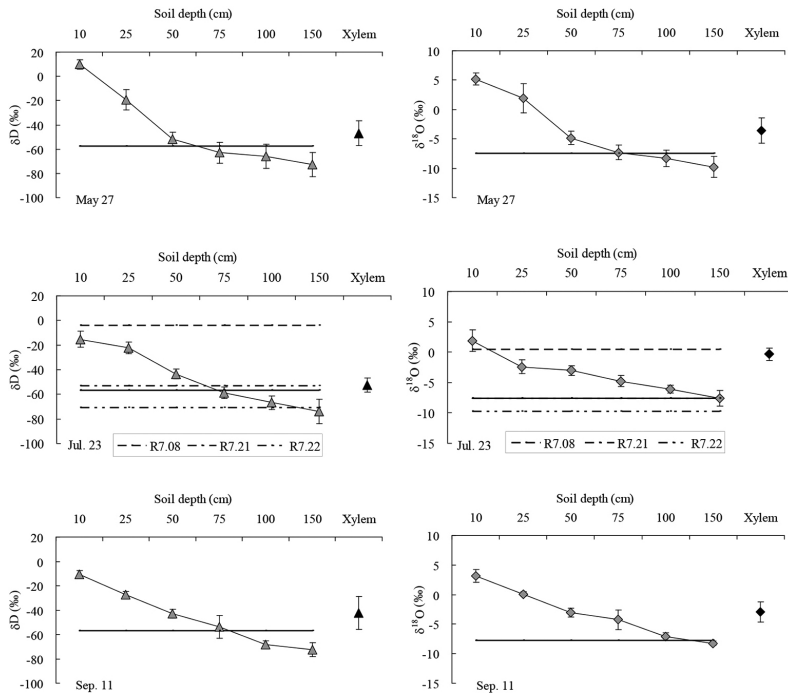


Figure 5. The value of δD and $\delta^{18}O$ in xylem water of *Caragana korshinskii*, soil water and ground water. Full line is ground water. R is rainwater.

Iso-Source analysis showed that *C. intermedia* mainly used 10–100 cm soil water on May 27, which accounted for 82.0% of its total water source. On July 20, *C. intermedia* mainly used 10 cm soil water, which accounted for 65.7% of its total water source. On September 11, *C. intermedia* mainly used 50–150 cm soil water and ground water, which accounted for 86.5% of its total water source (**Table 1**).

Water source	May 27	July 20	September 11
Soil water 10 cm	22.8 ± 12.2	65.7 ± 4.5	6.1 ± 5.3
25 cm	22.0 ± 15.3	8.8 ± 7.9	7.4 ± 6.5
50 cm	15.9 ± 13.8	7.6 ± 6.9	10.5 ± 9.1
75 cm	10.9 ± 9.3	5.8 ± 5.3	11.6 ± 1.0
100 cm	10.4 ± 8.9	4.5 ± 4.2	16.7 ± 14.5
150 cm	8.9 ± 7.5	3.7 ± 3.6	22.2 ± 16.8
Ground water	9.1 ± 7.8	3.8 ± 3.6	25.5 ± 12.9

Table 1. Water use ratio of *Caragana intermedia* to different sources (% , mean ± SD).

Iso-Source analysis showed that *C. korshinskii* evenly used 10–150 cm soil water and ground water on May 27. On July 23, *C. korshinskii* mainly used 25–150 cm soil water, which accounted for 82.8% of its total water source. On September 11, *C. korshinskii* mainly used 10–150 cm soil water, which accounted for 94.6% of its total water source (**Table 2**).

Water source	May 27	July 23	September 11
Soil water 10 cm	16.8 ± 9.3	9.7 ± 7.3	18.2 ± 10.6
25 cm	18.3 ± 12.2	12.0 ± 8.1	20.9 ± 14.5
50 cm	15.5 ± 13.4	17.9 ± 13.9	20.0 ± 16.6
75 cm	13.1 ± 11.1	13.9 ± 10.8	11.1 ± 8.2
100 cm	12.3 ± 10.4	10.4 ± 7.6	12.8 ± 9.2
150 cm	11.2 ± 9.4	28.6 ± 6.1	11.6 ± 7.8
Ground water	12.9 ± 11.0	7.5 ± 5.8	5.4 ± 3.7

Table 2. Water use ratio of *Caragana korshinskii* to different sources (% , mean ± SD).

On sand dunes of Gonghe Basin, *C. intermedia* used 10–100 cm soil water in spring, 10 cm shallow soil water recharged by rain in summer and 50–150 cm medium and deep soil water and ground water in autumn (**Figure 4, Table 1**). However, *C. korshinskii* used 10–150 cm soil water and ground water in spring, 25–150 cm soil water in summer and 10–150 cm soil water in autumn (**Figure 5, Table 2**). Therefore, two *Caragana* shrubs used shallow soil water recharged by rain and deep soil water recharged by ground water in spring or autumn, and even used few ground water when soil water is not enough for their water requirements (**Figure 2**). In summer, surface soil water recharged by rain was enough for *C. intermedia* (**Figures 1 and 4**), whereas *C. korshinskii* still needed both of shallow water recharged by rain and deep soil water recharged by ground water (**Figures 1 and 5**).

The resource-dependent water use strategy of two *Caragana* shrubs on sand dunes is an ecological adaptation to the semi-arid climate in Gonghe Basin, which is similar to other shrubs in arid and semi-arid regions. *A. ordosica* mainly used soil water within 50 cm in Mu Us Sandy Land [12]. In San Luis valley of Colorado, *Chrysothamnus Greenei* only occurs in sites with water table deeper than 2 m and only use soil water recharged by rain [25]. *Caragana microphylla* mainly used 100 cm deep soil water recharged by snow in Xilin River Basin of Inner Mongolia [26]. Both of *N. tangutorum* and *A. arenaria* used 30–90 cm middle soil water in May, within 30 cm shallow soil water in July and below 120 cm deep soil water in September on sand dunes of Badain Jaran Desert [9]. *Ceratoides lateans* used 10–50 cm soil water in Qaidam Basin [27]. In Gurbantunggut Desert, *H. persicum* used 40–100 cm middle soil water on sand dunes when upper soil was abundant in early spring; however, it used 100–300 cm deep soil water when upper soil was depleted in summer [11].

The temporal difference in the main water source for a typical desert shrub is associated with precipitation change in different years. In this study, the ground water table is less than 3 m

on interdune. *C. intermedia* also used ground water in September when precipitation was only 137.5 mm in the total growing season. However, *C. intermedia* mainly used soil water within 50 cm recharged by rain in middle August of 2009 with 155.5 mm precipitation since May [20]. On the other side, the spatial difference in the main water source for a typical desert shrub is associated with ground water table in different sites. *C. korshinskii* used 0–30 cm and 60–90 cm soil water in Ulanbuh Desert with ground water table deeper than 6 m [28]. At sites with water table less than 2 m in San Luis Valley, *S. vermiculatus* and *Chrysothamnus nauseosus* used top 50 cm soil water recharged by rain in a wet year. At sites with water table deeper than 2 m, they used ground water in the pre-monsoon season, whereas they used 30–40 cm upper soil water recharged by rain in the monsoon season [25].

2.3.2. Water source of two *Salix* shrubs on interdune

On May 26 and July 17, the value of δD and $\delta^{18}O$ in xylem water of *S. psammophila* was closer to ground water and soil water at depths of 25 and 50 cm (**Figure 6**). On July 17, the value of δD and $\delta^{18}O$ of soil water at a depth of 10 cm was closer to rainwater on July 8 (6.4 mm). On September 11, the value of δD and $\delta^{18}O$ in xylem water of *S. psammophila* was closer to that of ground water and soil water at depths of 50–150 cm.

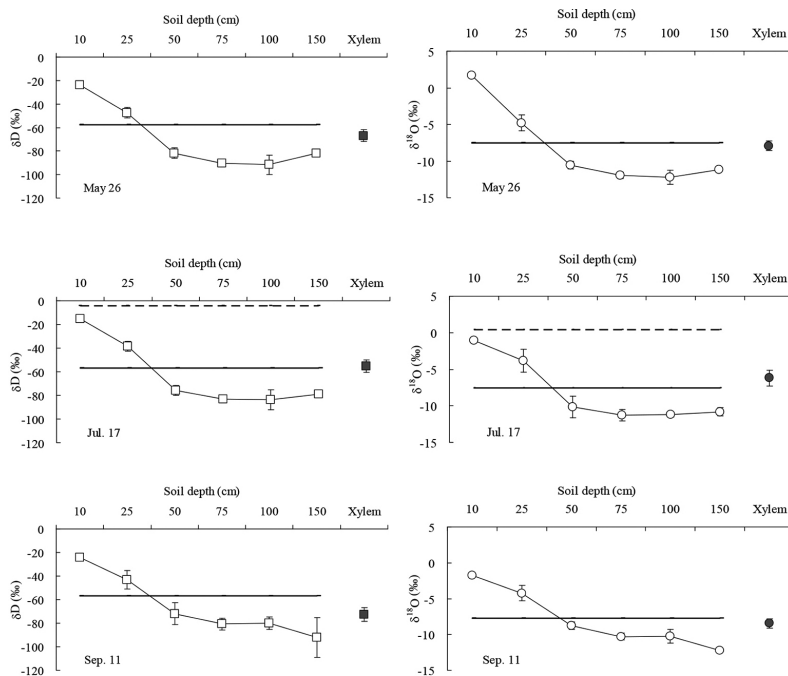


Figure 6. The value of δD and $\delta^{18}O$ in xylem water of *Salix psammophila*, soil water and ground water. Full line is ground water. Dot line is 6.4 mm rainwater on July 8.

On May 26, the value of δD and $\delta^{18}O$ in xylem water of *S. cheilophila* was closer to ground water and soil water in 25 and 50 cm (**Figure 7**). On July 17, the value of δD and $\delta^{18}O$ in xylem water of *S. cheilophila* was closer to ground water; and the value of δD and $\delta^{18}O$ of soil water in 10 cm was closer to rainwater on July 8 (6.4 mm). On September 11, the value of δD and $\delta^{18}O$ in xylem water of *S. cheilophila* was closer to ground water and soil water in 50 and 100–200 cm.

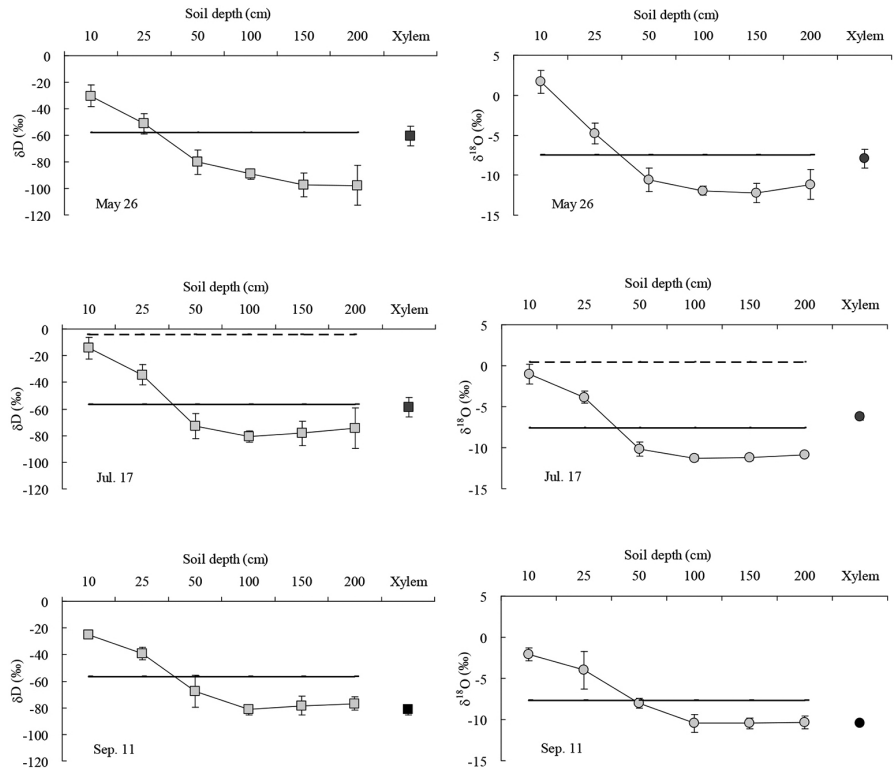


Figure 7. The value of δD and $\delta^{18}O$ in xylem water of *Salix cheilophila*, soil water and ground water. Full line is ground water. Dot line is 6.4 mm rainwater on July 8.

Iso-Source analysis showed that *S. psammophila* evenly used 10–150 cm soil water and ground water on May 26. On July 17, *S. psammophila* mainly used 10 and 25 cm soil water and ground water, which accounted for 63.0% of its total water source. On September 11, *S. psammophila* mainly used 50–150 cm soil water and ground water, which accounted for 79.6% of its total water source (**Table 3**).

Iso-Source analysis showed that *S. cheilophila* mainly used 10 and 25 cm soil water and ground water on May 26, which accounted for 70.7% of its total water source. On July 17, *S. cheilophila* evenly used 10–200 cm soil water and ground water. On September 11, *S. cheilophila* mainly used 100–200 cm soil water, which accounted for 81.8% of its total water source (**Table 4**).

Water source	May 26	July 17	September 11
Soil water 10 cm	13.0 ± 8.0	26.2 ± 12.0	9.0 ± 6.3
25 cm	16.0 ± 12.0	23.0 ± 16.9	11.3 ± 8.4
50 cm	14.3 ± 11.9	9.9 ± 8.6	16.8 ± 14.6
75 cm	12.8 ± 10.4	8.9 ± 7.7	16.1 ± 13.1
100 cm	12.6 ± 10.2	8.9 ± 7.7	16.2 ± 13.2
150 cm	14.3 ± 11.9	9.3 ± 8.0	14.4 ± 10.9
Ground water	17.0 ± 14.1	13.8 ± 12.0	16.1 ± 13.7

Table 3. Water use ratio of *Salix psammophila* to different sources (% , mean ± SD).

Water source	May 26	July 17	September 11
Soil water 10 cm	16.7 ± 7.1	17.0 ± 8.8	2.2 ± 2.1
25 cm	31.4 ± 20.2	18.8 ± 13.2	2.2 ± 2.1
50 cm	9.2 ± 7.7	13.1 ± 11.2	7.6 ± 6.8
100 cm	7.7 ± 6.4	11.5 ± 9.7	27.9 ± 19.9
150 cm	6.2 ± 5.2	11.7 ± 9.9	28.0 ± 19.9
200 cm	6.2 ± 5.2	12.3 ± 10.5	25.9 ± 19.9
Ground water	22.6 ± 12.2	15.6 ± 13.6	5.5 ± 5.0

Table 4. Water use ratio of *Salix cheilophila* to different sources (% , mean ± SD).

On interdune of Gonghe Basin, *S. psammophila* used 10–150 cm soil water and ground water in spring, 10–25 cm shallow soil water and ground water in summer and 50–150 cm medium and deep soil water and ground water in autumn (**Figure 6, Table 3**). However, *S. cheilophila* used 10–25 cm shallow soil water and ground water in spring, 10–200 cm soil water and ground water in summer and 100–200 cm deep soil water in autumn (**Figure 7, Table 4**). Therefore, two *Salix* shrubs used ground water or deep soil water recharged by ground water as long-term stable water source. Moreover, *S. psammophila* and *S. cheilophila* also used shallow soil water recharged by rain in spring and summer, respectively (**Figures 1, 6, and 7**).

The resource-dependent water use strategy of two *Salix* shrubs in Gonghe Basin is similar to other trees or shrubs in arid and semi-arid regions. *S. matsudana* and *S. vulgaris* mainly used deep soil water and ground water in Mu Us Sandy Land [12]. In San Luis Valley of Colorado, *S. vermiculatus* and *C. nauseosus* used soil water recharged by rain in a wet year but deep soil water and ground water in a dry year [25]. *E. nauseosa* depended on ground water, whereas *S. vermiculatus* used ground water during dry periods but used deep soil water after large rainfall in San Luis valley [10]. *J. osteosperma* absorbed shallow soil water in early spring and gradually depended on deep soil water with soil drought in Utah [6]. *P. sylvestris* var. *mongolica* primarily used 20–60 cm soil water both at the top of fixed sand dune and in interdune lowland

in Horqin Sandy Land [29]. Moreover, it only used soil water during the higher precipitation year, whereas it used soil water and relied on ground water during the lower precipitation year [15]. *U. pumila* always used stable ground water in Hunshandake Sandy Land [14]. *N. tangutorum* mainly used 50–100 cm soil water and ground water from June to September in Golmud of Qaidam Basin [30]. In Nuomuhong of Qaidam Basin, *N. tangutorum* and *Tamarix ramosissima* used 50–70 cm soil water, whereas *Ephedra sinica* and *Calligonum mongolicum* evenly used 0–90 cm soil water. Moreover, these four shrubs increased to use ground water in the late growing season [27]. Along the lower reaches of Heihe River, different aged *P. euphratica* used different water sources. Young forests primarily relied on soil water from 0 to 50 cm (mean > 45%), while mature and over-mature forests used water from deeper than 100 cm which derived primarily from ground water [16]. When the upper soil water was abundant in early spring, *H. ammodendron* mainly used shallow soil water on sand dunes of Gurbantunggut Desert. When the upper soil water was depleted in summer, *H. ammodendron* mainly used ground water [11]. Therefore, ground water is an important water source for trees and shrubs in arid and semi-arid regions, especially in the drought period. Global climate change may result in the increase of extreme drought in the arid region [31]. Plant species using stable ground water or deep soil water may have more adaptability than those only using shallow soil water recharged by rain in the drought period.

2.4. Long-term WUE of four desert shrubs

Leaf carbon discrimination (Δ , ‰) was converted from its $\delta^{13}\text{C}$ value using an atmospheric carbon dioxide ratio of -8‰ [32]. The leaf Δ value was significantly different ($P < 0.001$) in different months for *C. intermedia*, *C. korshinskii*, *S. psammophila* and *S. cheilophila*, respectively (Figure 8). The leaf Δ value of *C. intermedia*, *C. korshinskii* and *S. psammophila* increased significantly on May 26, and from July 17 to September 11. The leaf Δ value of *S. cheilophila* was significantly lower on May 26 than that on July 17 or September 11. The leaf Δ value of *C. intermedia* was similar to *C. korshinskii* in three months. The leaf Δ value of *S. psammophila* was lower than *S. cheilophila* in three months.

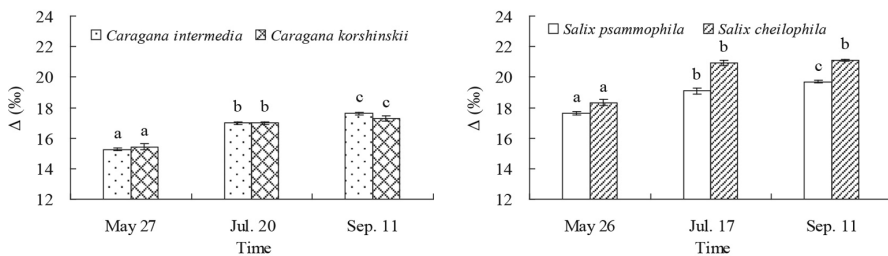


Figure 8. Leaf carbon discrimination of four desert shrubs. Different lower case letters indicate significant difference in different months, according to Duncan's test ($P < 0.05$).

The long-term WUE is negatively related to the leaf Δ value of C_3 plants. There were seasonal dynamics of WUE in two *Caragana* shrubs on sand dunes of Gonghe Basin, which were lower

in spring and increased in summer and autumn (**Figure 6**). Soil water content at surface soil was lower in spring than in summer (**Figure 2**) because of low precipitation (**Figure 1**). It was suggested that both of two *Caragana* shrubs increased WUE to adapt to drought. Similarly, the WUE of *N. tangutorum* was higher in summer than in autumn in Ulanbuh Desert [28]. The WUE of *P. euphratica* was highest in May and decreased in the middle and late growing season in lower reaches of Heihe River, west Inner Mongolia [33].

There were seasonal dynamics of long-term WUE indicated by the leaf Δ value in two *Salix* shrubs on interdune of Gonghe Basin, which were higher in spring than in summer and autumn (**Figure 7**). Soil water content of two *Salix* plantations at surface soil was lower than at deeper depths (**Figure 2**) because of low precipitation in spring (**Figure 1**). It was suggested that both of two *Salix* shrubs increased WUE to adapt to drought. There was intra-species difference in WUE between the two *Salix* shrubs. The WUE of *S. psammophila* was always higher than that of *S. cheilophila* (**Figure 8**), which is related to their eco-physiology. The xerophyte *S. psammophila* has higher drought resistance than the mesophyte *S. cheilophila*. Further, the WUE of different shrubs is affected by their life form. The evergreen *S. vulgaris* had higher WUE than *S. matsudana* and *A. ordosica* in Mu Us Sandy Land [12]. The long-term WUE of evergreen *Ammopiptanthus mongolicus*, *N. tangutorum* and *C. korshinskii* was higher than that of *A. ordosica* in Ulanbuh Desert [28]. In arid and semi-arid regions, shrubs with higher WUE may have more adaptability to extreme drought, resulting from global climate change. Moreover, the leaf $\delta^{13}\text{C}$ value (-25.11‰ – -27.28‰) of *S. psammophila* in Gonghe Basin is similar to its original distribution area (-26.75‰ – -28.68‰ , Wushen Banner, Ordos City) [34], which means that this shrub has adapted to the semi-arid climate in Gonghe Basin.

2.5. Conclusion

The water use strategy of four dominant desert shrubs was adapted to the semi-arid climate in Gonghe Basin. They used different water sources depending on their availability in different seasons, including shallow soil water recharged by rain, deep soil water recharged by ground water or ground water. They could use shallow soil water after rain in spring and summer. When shallow soil water was depleted, they turned to use deep soil water or ground water. The reliance of ground water was different for four shrubs in two habitats. Two shrubs in *Caragana* mainly depend on soil water and did not depend on ground water on sand dunes. *C. intermedia* barely used ground water, whereas *C. korshinskii* only used ground water in spring, which accounted for 12.9% of its total water source. Two shrubs in *Salix* used ground water as an important stable water source on interdune. *S. psammophila* always used ground water in the growing season, which accounted for 13.1–16.1% of its total water source; whereas *S. cheilophila* used ground water in spring and summer, which accounted for 22.6% and 15.6% of its total water source. Moreover, both of four shrubs increased long-term WUE in drought spring. Two shrubs in *Caragana* had similar WUE in the growing season. However, the WUE of *S. psammophila* was always higher than *S. cheilophila*, which means that the former might had more adaptability in Gonghe Basin.

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Author details

Yajuan Zhu*

Address all correspondence to: zhuyj@caf.ac.cn

Institute of Desertification Studies, Chinese Academy of Forestry, Beijing, China

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