Preliminary study of water sources for maintenance and water utilization strategies of *Haloxylon ammodendron* in the arid desert area of northwestern China

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ABSTRACT

Natural vegetation in arid desert areas has been severely affected by uneven spatial-temporal precipitation and underground water distribution. Therefore, it is quite necessary to reserve maintenance water sources and water utilization strategies of natural vegetation. In our experiment, the *Haloxylon ammodendron* was selected to learn about the maintenance water sources and water utilization strategies. The results displayed that *H. ammodendron* could utilize various water sources, in which groundwater (30%)and shallow soil water (average 35%)accounted for very huge proportion to be the most important maintenance water sources *H. ammodendron* does not directly absorb from snowfall, but the application of shallow soil water was stemed from melt snow. The utilization percentage of groundwater is relatively higher in winter (80%) and summer (30%). The utilization percentages of different water sources change with the actual situations of these water sources; Precipitation is also one of main water sources of *H. ammodendron* (respond quickly but not influential). The mainly water of *H. ammodendron* in the study area are as follows: groundwater, shallow soil water formed by snowmelt, medium and large precipitation. Therefore, *H. ammodendron* can make efficient use of water sources in arid desert areas, and transform water sources reasonably under the tremendous variations in water conditions to meet the water requirements.

Keywords oxygen isotope technology; water utilization strategies; *Haloxylon ammodendron*; groundwater; snowmelt; rainfall

INTRODUCTION

The main water sources of plants include groundwater, precipitation and soil water (*Dawson, 1996; Simonin et al., 2014; Sternberg et al., 1987*), and different plants utilize different water sources.

Plants may utilize several water sources simultaneously, or transform water sources when the season changes (*Dawson et al., 1993; Ehleringe et al., 1991*). Among all water sources utilized by plants, one or several key water sources play a key role in the maintenance of the whole growth cycle of plants, which are thus known as water sources for maintenance. Plants cannot survive without maintenance water sources (*Ehleringer et al., 1992; Phillips et al., 2003; Snyder et al., 2000*). Among the several water sources of great importance for plants, some are greatly influenced by environmental conditions, and may easily undergo sharp fluctuations. For example, precipitations often cover uneven spatial-temporal distribution and relatively large inter-annual variations. First, the uncertainty of precipitations increases steeply due to the significant global climatic changes in recent years. Second, more and more groundwater is utilized due to the rapid development of industry and agriculture and large-area farmland cultivation in arid regions, and as a result groundwater tends to decline significantly. Third, rivers in arid regions are more prone to be influenced by industry and agriculture, with the frequency and length of cutoffs increasing year by year. The abovementioned reasons cause unprecedented changes to water sources in arid regions, which influence plants in the fragile desert areas tremendously. However, for vegetation of constructive species in the arid areas, especially in the arid areas of Central Asia, researches regarding water sources and water consumption strategies are insufficient and incomplete. In-depth studies on water sources for maintenance and water utilization strategies will undoubtedly help solve the uneven spatial-temporal precipitation distribution arising from climatic changes and human activities, and restore and rebuild vegetation, especially in the desert regions.

The large-area original halophytes and xerophytes are distributed throughout the alluvial-pluvial fan on the north slope of Mt. Tianshan and the south edge of the Junggar Basin. The above two regions, as typical temperate continental deserts in the hinterland of the Eurasian continent, possess solitary/mixed plant communities with typical desert shrubs and sub-shrubs as the dominant species, e.g. *H. ammodendron*, and are key for the ecological process and ecological security of the arid regions of Central Asia. *H. ammodendron*, as the constructive species here and remnant of the Paleo-Mediterranean flora, is a type of small perennial shrubby tree, and has been listed as a grade-3 national protected endangered plant. *H. ammodendron* is the desert vegetation with the widest distribution in Asian deserts (*Yan et al., 2008*). In the south of the Junggar Basin, water is the most important factor for the growth of *H. ammodendron* (*H. Xu et al., 2006; Yan et* al., 2008). Qualitative research on the water sources for the maintenance of *H. ammodendron* in the study area can help to grasp the dynamic variations of the *H. ammodendron* population. Some scholars have made reports on the water utilization of *H. ammodendron* (Wei et al., 2013; Y et al., 2013; Yang et al.,2013). The issue of water sources for maintenance of *H. ammodendron* is quite complicated. This paper intends to adopt stable isotope technology for the determination and analysis of various water sources, and thoroughly discuss the conditions of main water sources for the maintenance of *H. ammodendron* as well as dynamic seasonal variations of water utilization by *H. ammodendron*, thereby providing a basis for the protection of the *H. ammodendron* population from the perspective of water source.

MATERIALS AND METHODS

Study Area

The study area is situated in Beishawo (N 44.22° 177″, E 87.55° 38.5″, altitude 445 m) in the south of the Junggar Basin, Xinjiang, China. Features of the study area include the following: dendritic dunes in the south-north direction; alternative distribution of dunes and flat grounds; height of most dunes: 3-5 m, main constructive species: *H. ammodendron* and *Haloxylon Persicum*. The climate in the study area is classified as temperate continental desert climate, with hot and dry summers and cold winters, annual precipitation of 60-160 mm, annual evaporation of over 2500 mm, and annual frost-free period of 156 d. Snowfall in winter accounts for more than 1/4 of the annual precipitation. The groundwater level is 5-10 m, which does not vary much when the seasons change. Stable snows in winter, along with snowmelt and rain in spring lead to these two seasons possessing the richest soil water, and they become rich water sources for germination and growth of plants. The study area is distributed with sparse *H. ammodendron* forests, annual plants, ephemeral plants and ephemeroid plants.

Research Methods

Water Source Discrimination Technology

Stable isotope analysis has been widely applied in discrimination of water sources of plants over the past 15 years (Ehleringer et al., 1991; Hondula et al., 2014). Water sources in the xylem of plants may be a mixture of different water sources, and the values of δD and $\delta^{18}O$ are the mixed values of these different water sources. The values of δD and $\delta^{18}O$ of different water sources differ from each other mainly due to the isotope fractionation effects in the physical, chemical, physiological and biochemical actions of these water sources. The principle of the water source discrimination technology is as follows: if there are several water sources, the isotope composition of the water source of plants is the linear mixed value composed of isotopes in all water sources, and the end member isotope linear mixed model (*Dawson et al., 1993; Phillips, 2001*) is hereby established:

$$\delta D_P = \sum_{i=1}^{n} f_i \delta D_i$$

$$\delta^{18}O_P = \sum_{i=1}^{n} f_i \delta^{18}O_i$$

$$I = \sum_{i=1}^{n} f_i$$

where δD_P and $\delta^{18}O_P$ are the values of δD and δ^{18}O in the water sources of plants, respectively; δD_i and $\delta^{18}O_i$ are the values of δD and δ^{18}O in water source I, respectively; and *fi* is the absorption percentage of the water source i by the plants. Through these formulas, we may calculate the values of δD and δ^{18}O in the water sources of plants; after comparison and analysis of the compositions of stable hydrogen and oxygen isotopes, we can obtain the utilization percentages of the water sources used by the plants.

Sampling Method

In the artificial-interference-free natural plot in Beishawo on the edge of the Gurbantunggut Desert, choose three trees of adult *H. ammodendron* with typical representativeness, mark them, and collect samples in important growing seasons. The samples mainly include plants, snowfall, rainfall, groundwater and soil.

Collection of *H. ammodendron* samples: From January 2013 to June 2013, 14 collection times, with three repeated samplings every time. Choose non-green branches with diameter of 10 mm and length of 80 mm. After sampling, scrape the leaves and phloem immediately; keep the xylem parts; prevent pollution to the samples(Phillips et al., 2003); place the samples in polyethylene sampling bottles immediately; seal the sampling bottles with sealing films, and keep the sampling bottles under the temperature of -16℃ until analysis.

Collection of snowfall samples: January 20 and March 2, 2013; choose central snow as the sample on the next day after snowfall; three repeated samplings every time. After sample collection, place the snow in sampling bottles immediately, seal the sampling bottles and store them in the refrigerator.

Collection of rainfall samples: June 22 and June 24, 2013, with both rainfalls exceeding 15 mm; three repeated samplings each time. After sample collection, place the rain water in sampling bottles immediately, seal the sampling bottles and store them in the refrigerator. Meanwhile, collect samples of *H. ammodendron* 1-7 d after rainfall; three repeated samplings every time; place the samples in sampling bottles immediately; seal the sampling bottles and store them in the refrigerator.

Collection of soil samples: April 18, May 18 and June 30, 2013. Choose soils 50 cm away from the marked *H. ammodendron*; drill the ground and collect samples every 20 cm in depth, with five layers the whole drilling depth of 1 m; six repeated samplings for every layer. On June 30, the drilling depth is 2 m; place samples obtained in the three repeated samplings in sampling bottles immediately, seal the sampling bottles and store them in the refrigerator; for the samples obtained in the other three repeated samplings, adopt the drying method for the determination of soil moisture content. There is a groundwater monitoring well near the plot, and the groundwater samples are collected from the monitoring well. Collection of groundwater samples: Once per month; three repeated samplings each time; place the samples in sampling bottles immediately; seal the sampling bottles and store them in the refrigerator.

Water Extraction and Sample Analysis

Adopt the stable isotope mass spectrometer for determination of values of $\delta^{18}O$ in groundwater, rainfall, xylem, and soil water. For samples of soil and *H. ammodendron*, extract the water according to the low-temperature vacuum distillation method (Wang et al.,2013), and determine the values of δD and $\delta^{18}O$ in different water sources. After water reactions in an Isoprime-Pyr OH high-temperature pyrolysis-reduction furnace, conduct online determination of values of $\delta^{18}O$ with an Isoprime mass spectrometer (deviance $<0.5‰$). Calibrate the determination results with the V-SMOW standard. Compare the oxygen isotope compositions in the $\delta^{18}O_{sample}$ with SMOW (standard mean ocean water):

$$\delta^{18}O_{sample} = \left[\frac{R_{sample}}{R_{standard}} - 1 \right] \times 1000$$

where R is the proportional relation between isotopes representing weight ($^{18}O/^{16}O$); and R_{sample} and $R_{standard}$ are the values of the isotope in the samples and the standard value, respectively.

Data Analysis

Use Excel 2003 and SPSS 14.0 for statistical analysis of the data, and draw figures with the origins 8.

RESULTS

Variation Range of Abundance Value of $\delta^{18}O$ in Different Water Sources

There are 11 snowfall samples, with $\delta^{18}O$ abundance value of -19~24‰, and an average value of -21‰. In the experiments, we adopt medium rainfalls with more obvious influence on *H. ammodendron* as the rainfall source; there are 12 rainfall samples, with an $\delta^{18}O$ abundance value of -6~8‰, and an average value of -7.5‰. There are 24 groundwater samples, with relatively stable $\delta^{18}O$ abundance values of -10.6~10.9‰, and an average value of -10.8‰. There are 45 soil water samples; most peak $\delta^{18}O$ abundance value appear in the 40-80 cm section; and the main scope of the $\delta^{18}O$ abundance value is -11.5~17.3‰ (Table 1).

Dynamic Variation of Soil Moisture Content and $\delta^{18}O$ Value

Figs. 2 show that the distributions of soil moisture content and $\delta^{18}O$ value in soils are consistent. The peak value of the soil water contents of the samples obtained on May 18, 2013 mainly appears in the range of 40-100 m, which is consistent with peak value of $\delta^{18}O$ concentrations (Figs. 2). The soil moisture content in the desert varies quickly, dropping from the peak value (May 18) to zero (June 30). There are negative peak values of the $\delta^{18}O$ of the samples, which are closely related with the low isotope value of snowmelt and negative value of $\delta^{18}O$ in the soil sections after snow melting. The $\delta^{18}O$ abundance value in the soil water trends to vary dynamically when the season changes. The main supply source for shallow soil water in the Gurbantunggut Desert is precipitation. The $\delta^{18}O$ values in the soil sections vary significantly due to large differences of $\delta^{18}O$ abundance values between snowfall and rainfall, as well as fractionation arising from intensive evaporation in the Gurbantunggut Desert. According to the variations of soil moisture content in the soil sections, supply sources for about 1 m sections in the desert area are snowfall in winter and rainfall in summer, which are the main supply sources for shallow soil water.

Dynamic Variation of $\delta^{18}O$ Values of *H. ammodendron* and Groundwater

According to Fig. 3, the $\delta^{18}O$ abundance value of groundwater collected from January to June, 2013 is -10.6~10.9%, with small inter-annual variations. This indicates that the underground water source is quite stable, with minimal supply of external waters or insignificant supply effects. The $\delta^{18}O$ abundance values of the *H. ammodendron* samples vary significantly: according to the determination of the $\delta^{18}O$ abundance values of the 73 *H. ammodendron* samples taken from April to June, the dynamic variation range of the water source in the xylem is -9.5~13‰; the $\delta^{18}O$ abundance values in March and April are clearly larger than those in June. Based on the linear analysis of the $\delta^{18}O$ abundance values of the *H. ammodendron* samples in different months, the water sources in the xylem tend to decrease from April to the end of June (R^2=0.69), which shows that the utilization percentages of the water sources by *H. ammodendron* change from April to June.

Response Relationship of *H. ammodendron* with Rainfall

According to Fig. 4, the $\delta^{18}O$ value of the rainfall samples collected on June 22 and 24 is -7~8‰, with an average value of -7.5‰; the average $\delta^{18}O$ value of the groundwater samples is -10.6‰; and the $\delta^{18}O$ value of the *H. ammodendron* samples is -10.8~12.4‰. After the rainfall on June 22, the $\delta^{18}O$ value of the *H. ammodendron* samples does not change significantly; however, on the 4th day after the rainfall (June 25), the $\delta^{18}O$ value in the xylem increases dramatically, reaches a peak (Fig. 4) for 1 d, then decreases gradually. The value reaches a peak again on June 27, then decreases once again, which is clearly related with the values of rainfalls on June 22 and 24 ($P<0.05$). This indicates that although *H. ammodendron* utilizes rainfall, it absorbs rainfall about 2 d after the rainfall, rather than as an immediate response to rainfall. Therefore, rainfall utilization by *H. ammodendron* has a hysteretic nature, and rainfall is one of the water sources utilized by *H. ammodendron*.

Dynamic Variation of Groundwater Utilization Percentage by *H. ammodendron*

The $\delta^{18}O$ values of the different water sources in the desert area are quite different, and the seasonal dynamic variations of the $\delta^{18}O$ values are quite large (Fig 5). If *H. ammodendron* transforms water sources, then the $\delta^{18}O$ values will definitely change. According to the analysis of the samples collected within six months, the $\delta^{18}O$ values in the groundwater samples are relatively stable and within the range of -10.6~10.9‰. The $\delta^{18}O$ values in the xylem of *H. ammodendron* samples are not stable, with extremely evident seasonable differences ($p<0.01$) according to the comparison and analysis of the $\delta^{18}O$ values in the xylem of the *H. ammodendron* samples in the different months. The $\delta^{18}O$ values decrease significantly from winter to summer (R^2=0.69). Based on the end member isotope linear mixed model, *H. ammodendron* can utilize 80% of groundwater at most in winter, with an average utilization percentage of 40%, and 60% groundwater at most in summer, with an average utilization percentage of 30%. This is related to intensive fractionation in the dry season and the utilization of other water sources with high $\delta^{18}O$ values. The largest ground utilization percentage of *H. ammodendron* in the dry and wet seasons is 60-80%, with an average utilization percentage of 30-40%; therefore, groundwater is one of the most important water sources for the maintenance of *H. ammodendron*.

Analysis of Dynamic Variation of $\delta^{18}O$ Values in *H. ammodendron* and Water Sources

The $\delta^{18}O$ abundance values in the xylem are shown in Fig.3. Throughout the entire growing period in 2013, the $\delta^{18}O$ values in the xylem are -8.38~13.5‰; the $\delta^{18}O$ values from January to April are relatively high, slowly decrease from the end of April, and further drop in May (almost in coincidence with the $\delta^{18}O$ values in groundwater). In June, the $\delta^{18}O$ values in the xylem are between the groundwater and shallow soil water. In general, the $\delta^{18}O$ values tend to decrease during the period from April to June (R^2=0.69). The $\delta^{18}O$ values in winter are relatively high, with the possible reason being as follows: *H. ammodendron* is in semi-dormancy, with roots absorbing less water and utilizing more deep soil water and groundwater. The $\delta^{18}O$ values increase slowly from April, with the possible reason being as follows: The snow melting leads to the thawing of the surface soils; the soil moisture content increases; and the roots absorb more water. During this period, the $\delta^{18}O$ values in the xylem are between those in the groundwater and shallow soil water. This indicates that groundwater and shallow soil water are the most important water sources for the maintenance of *H. ammodendron* in spring and summer. During the period from mid-April to mid- and late May, the $\delta^{18}O$ values in the xylem of *H. ammodendron* have the most significant variations, with the possible reason being as follows: The temperature increases in April and all snows in the *H. ammodendron* forest melt; the desert edge has a large temperature difference between day and night, and thus significant alternation of freezing and thawing; the soils in the lower layers are still in the freezing state, and the surface roots have not grown completely; as a result, *H. ammodendron* mainly utilizes deep soil water or groundwater. For the samples collected in May, the $\delta^{18}O$ values in the xylem are stable between the groundwater and shallow soil water.

This indicates that the surface roots of *H. ammodendron* have grown completely, and absorb groundwater and shallow soil water stably with dimorphic roots. Therefore, in spring and summer, the water in the xylem mainly originates from groundwater and shallow soil water (Fig.6); groundwater and shallow soil water are important water sources for the maintenance of *H. ammodendron* in spring and summer.

DISCUSSION

According to researches concerning the dynamic variation of the $\delta^{18}O$ values of *H. ammodendron* in the main growing season, *H. ammodendron* mainly utilizes groundwater and shallow soil water, which are both the most important water sources for *H. ammodendron* and the water sources for the maintenance of *H. ammodendron.* In particular, groundwater accounts for a large percentage in water source utilization during the whole growing season, which is consistent with the water source detection result (*Hui et al., 2008*). However, the conclusions reached by Liyan are different (*Yan et al.,2008*). They, through investigations and researches, found that *H. ammodendron* seldom utilizes groundwater, and precipitation and shallow soil water are the most important water sources for *H. ammodendron*. The difference between the two conclusions may be related to the site conditions, groundwater depth, altitude, topographic relief, plant morphology and size, etc. in the study area. The difference also indirectly indicates the wide ecological amplitude and diversity of water utilization of *H. ammodendron.*

In winter, *H. ammodendron* is in semi-dormancy; the minimal temperature of natural *H. ammodendron* forests is under -30℃; *H. ammodendron* cannot efficiently utilize snowfall and only utilizes a small quantity of frozen shallow soil water. Therefore, snow has a small direct influence on *H. ammodendron*. However, melting of snowfalls, especially extremely large snowfalls, will increase the water content in the shallow soil water, which is one of the most important water sources for dimorphic roots after soil thawing in spring, and plays an important role in the shape building of *H. ammodendron* in the growing season.

Rainfall also has an influence on *H. ammodendron* (*Xu et al., 2006*). Xu hold that *H. ammodendron* can make the best use of the limited and dynamic shallow soil water through the coordination of physiological and individual adaptive mechanisms, thereby maintaining the stable photosynthesis of the leaves. Two of the main mechanisms for adaptation to rainfall variation are strong stomata control and effective shape adjustment. However, through the isotope technology, we found that *H. ammodendron* has an indirect response to rainfall, and the $\delta^{18}O$ values in the xylem increase significantly 2-3 d after the rainfall, which is consistent with research results of other scientists(*Hui et al., 2008; Lin et al., 2013; Pengju et al.,2008; Xu et al., 2006*). Before the rainfall on June 22, the $\delta^{18}O$ values in the groundwater and soil water were almost unchanged; however, after the rainfall, the $\delta^{18}O$ values in the xylem changed. Therefore, we believe that *H. ammodendron* utilizes rainfall. The peak $\delta^{18}O$ value is hysteretic due to the following reason: *H. ammodendron* does not utilize rainfall directly, and the surface roots absorb rainfall indirectly when the rain permeates into the soil. This is somewhat consistent with the opinion of Xu hao(*Xu et al., 2006*)that shallow soil water is a water source for the maintenance of *H. ammodendron*. However, *H. ammodendron* also adjusts its own demands for various water sources through the transformation of water resource utilization percentages, in addition to stomata control and shape adjustment. The response of *H. ammodendron* to rainfall coordinates with its physiological and individual adaptive mechanisms, and transforms water sources appropriately, so as to meet its own demands for water. Li Yan and Xu Hao(*Xu et al., 2006; Yan et al., 2008*), etc., used the artificial rainfall in the same area, and found that, under double rainfall, the root distribution features of adult *H. ammodendron* below 0.5 m are not significantly different from those in natural rainfall; however, the root surface area in 0-0.5 m increase significantly, accounting for about 80% of the total area. Therefore, *H. ammodendron* will absorb and utilize water when there is enough shallow soil water, regardless of whether the shallow soil water is formed by rainfall or permeation of snowmelt. The water source transformation and utilization are consistent with the ecological optimization theory proposed by Eagleason(*Eagleson et al., 1982*).

Due to limitations in time, manpower and technical means, we did not collect samples from the whole soil section in the sampling points, thus it is unknown whether or not the deep soil water is omitted. In addition, in recent years, some scholars have put forward that plants in desert regions can absorb many types of condensation waters(*Jinhua et al., 2004*); further investigation is required to judge if condensation water is also an important water source of *H. ammodendron*. However, based on the previous research achievements, it is clear that shallow soil water, precipitation and groundwater are the most important water sources of *H. ammodendron*. In particular, groundwater is the water source for maintenance of adult *H. ammodendron*, which has been proven by isotope technology.

CONCLUSIONS

The following conclusions are obtained based on this study:

The main water sources for *H. ammodendron* in the south of the Junggar Basin are groundwater and shallow soil water. The water sources for the maintenance of *H. ammodendron* are diversified due to the wide ecological amplitude of *H. ammodendron*.

The water source utilization of *H. ammodendron* has dynamical seasonal variations. *H. ammodendron* utilizes groundwater stably; however, the utilization percentage of groundwater decreases in the rainy season. Medium and large rainfalls are also available to water sources for *H. ammodendron.*

The utilization percentage of shallow soil water fluctuates significantly. In winter, *H. ammodendron* utilizes more groundwater or deep soil water; the utilization percentage of shallow soil water will increase when the temperature and soil moisture content increase.

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ADDITIONAL INFORMATION AND DECLARATIONS

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Author Contributions

‡ the Co-first author，Liu Guojun and Lv Jinling conceived, designed, and performed the experiments, analyzed the data, wrote the paper, prepared figures and/or tables, and reviewed drafts of the paper.

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Table 1 Sample numbers of different water sources, average $\delta^{18}O$ abundance value (with standard deviance) and range in 2013

Sample	Snowfall	Rainfall	*H. ammodendron*	Groundwater	Soil water 40-80 cm
Sample number (n)	11	12	73	24	45
Average value (*M*±*SD*) ‰	-21±2.86	-7.5±2.12	-11.71±1.34	-10.8 (±0.1)	14.5 (±2.85)
Range (‰)	-19~24	-6.8~13.0	-8.38~13.5	-10.6~10.9	-11.5~17.3

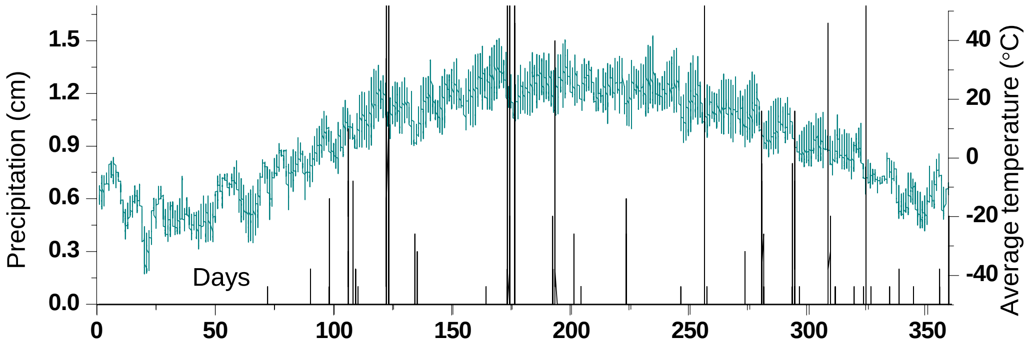

Fig. 1 The variation of temperature and precipitation in the south of the Junggar Basin

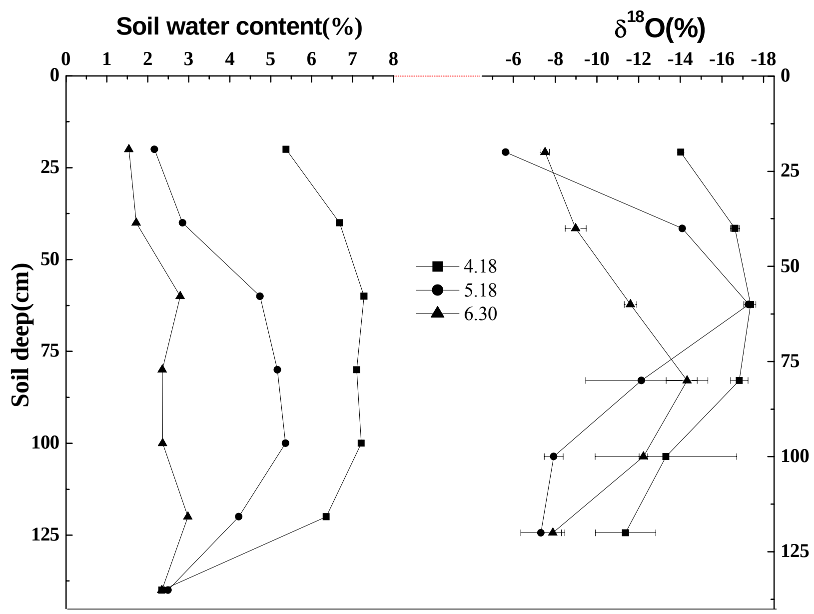

Fig. 2 Variation of soil water and $\delta^{18}O$ content in different phases

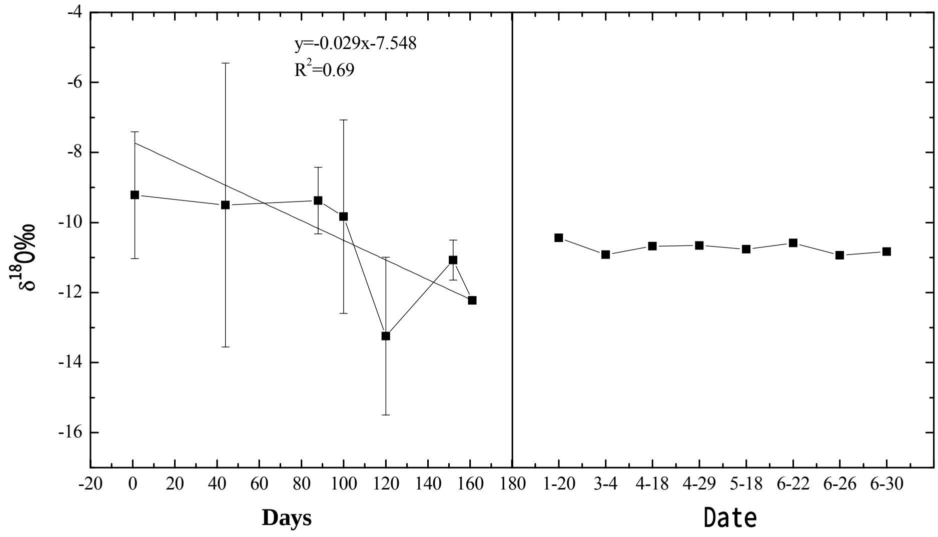

Fig.3 Variation of *H. ammodendron* and groundwater $\delta^{18}O$ linear fitting of *Haloxylon ammodendron* after snow melt

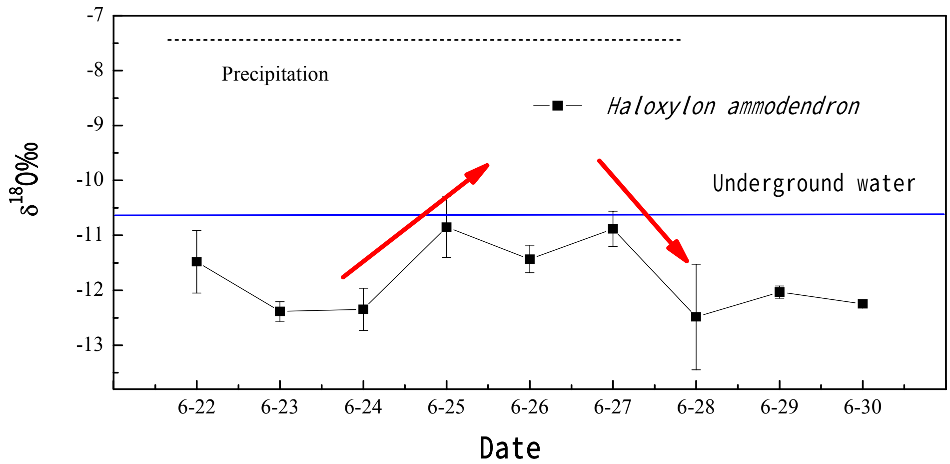

Fig.4 Response of *Haloxylon ammodendron* to moderate rainfall

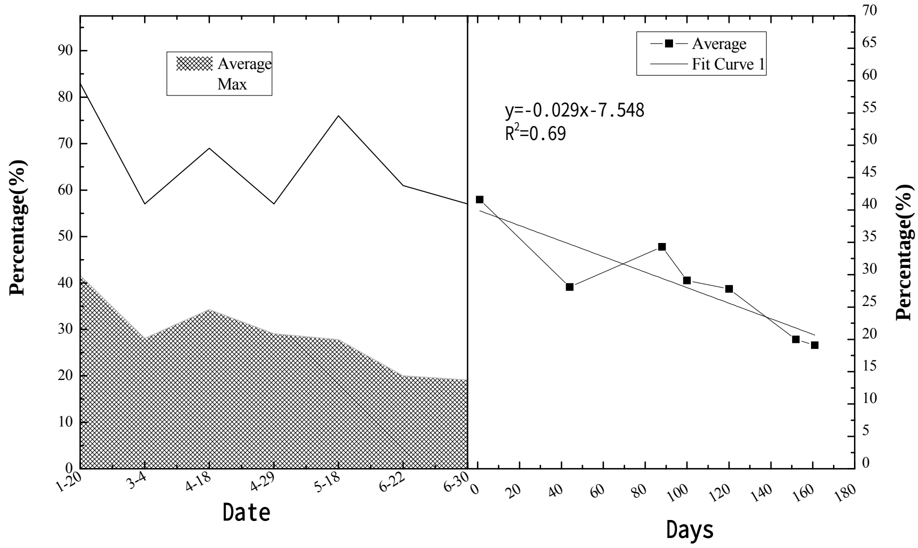

Fig. 5 Percentage change of groundwater for *Haloxylon ammodendron* in main growing season

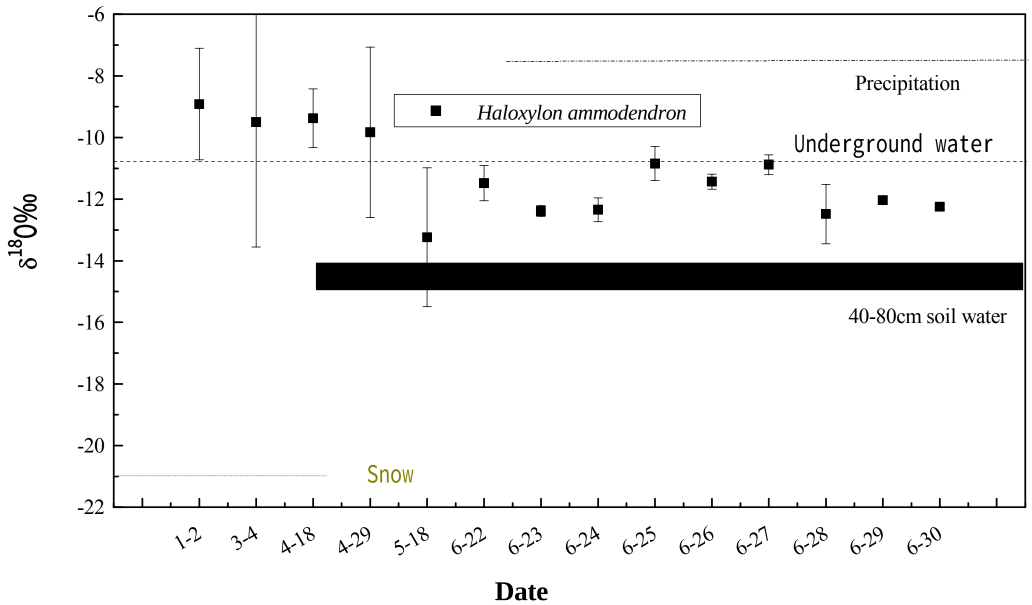

Fig. 6 Range of distribution of different water sources of $\delta^{18}O$