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Plants water status of the shelterbelt along the Tarim Desert Highway

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The plant water consumption and irrigation management are the core issue of the sustainable growing of the Tarim Desert Highway shelterbelt in the hyperaride Taklimakan Desert. The stem sap flow, water status and water consumption of shelterbelt plants were studied, then, the issue of the water save in the process of shelterbelt irrigation management was discussed by measuring the sap flow of shelterbelt plants with a stem sap flow gauge. The stem sap flow exhibited a distinct diurnal course with maximum values between 10:00 and 15:00, and minimum values between 00:00 and 03:00. Generally, sap flow was lower at night than during the day. The daily average stem sap flow of *Calligonum arborescens, Tamarix ramosissima* and *Haloxylon ammodendron* (diameter 1.9—2.0 cm) was 67.2 g·h^{-1}, 77.05 g·h^{-1} and 61.54 g·h^{-1} respectively. The sap flow was influenced by environmental factors, and the solar radiation, wind velocity, temperature and relative humidity were significantly correlative with plant stem sap flow. The annual water consumption of 8-a *Calligonum arborescens, Tamarix ramosissima* and *Haloxylon ammodendron* was 1937.80 kg, 1253.39 kg and 1026.96 kg, while daily average water consumption was 9.69 kg, 6.27 kg and 5.13 kg respectively. Under drip irrigation, soil moisture content of the shelterbelt in different months indicated no obvious fluctuation, and soil moisture was adequate. The predawn and midday plant water potential reflected that the plant water status was in good conditions. There is still some water-saving space if optimizing the present water management, integrating water resources conservation and protection performance.

Tarim, desert highway, shelterbelt, sap flow, water consumption, water status

Typically, arid and semiarid regions are ecologically fragile zones, in the process of comprehensive development of agriculture-forestry-stockbreeding industry and the artificial vegetation building, the problem how to distribute different plant types rationally to realize the aim of ecological and economy benefits combination, the integration of protection performance and development ability, and efficient utilization of resources has not been resolved. The basal problem is to choose and configure plant species in a scientific and rational way; learning the mechanism of physic-ecology and adaptability of water ecology by comparing water use and adaptability of different types of plants[1]. At present, the widespread dilemma of vegetation building is that irrationally increasing forest may be the cause of water use conflict between ecological restoration and other industry. And also, afforesting may be the cause of soil drying which is disadvantageous for vegetation stability. So, it is important for ecological construction and regional development to design and regulate the relationship between vegetation and water[2].

The shelterbelt along the Tarim Desert Highway run-

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ning through the Taklimakan Desert is a great shelterbelts project, the first one in the world built on shifting sands. The desert highway shelterbelt not only safeguards desert highway opening access, but also changes the desert ecosystem original characteristic. Since it was completed, the Tarim desert highway shelterbelt always uses the ground water in drip irrigation. The water consumption of 1.8×10^7 individuals of desert highway shelterbelt plants holds the important share of water loss along the desert highway and even the Tarim basin. But an unblocked desert highway depends on shelterblet protection, and the shelterbelt function implement depends on the water resources support. Therefore, the research on shelterbelt plant's water consumption becomes the foundation of the shelterbelt management and its sustainable existence. The analysis and research of the rule of shelterbelt plant water consumption and needs has the important guiding sense to reasonable matching, to scientific irrigation of existing shelterbelts, to effective implementation of the shelterbelt protection function, and to resolution of the contradictory of water supply and demand. In this paper, the shelterbelt plant's water status and the influence of meteorological factors to the plant water consumption were studied through determinations of the plants water potential, the stem sap flow, and the forest belt soil moisture content under present irrigation pattern, then the possibility of shelterbelt water saving was discussed, all this is important to management of the shelterbelt along the Tarim Desert Highway and to understanding of the desert plants water consumption under irrigation conditions.

1 Site and methods

1.1 Site description

The experiment was conducted at a site in the shelterbelt belt of desert highway near the Taklimakan desert research station of Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (Tazhong Botanical garden, 39°06′N, 83°40′E). This site is situated at the hinterland of Taklimakan Desert, with the annual mean temperature of 12.4℃. In one year the hottest month is July and the monthly mean temperature is 28.2℃; the coldest month is December and mean temperature is –8.1℃. The highest temperature is 45.6℃ and the lowest temperature is –22.2℃. The annual accumulated temperature≥10℃ is 4621.8℃. The frost-free period is 283 d. The annual sunshine hours are 2571.3 h; annual mean precipitation is 36.6 mm, the average relative humidity is 29.4%, and the potential evaporation is 3638.6 mm. Average wind velocity is 2.5 $m\cdot s^{-1}$ and the maximum instantaneous wind velocity is 24.0 $m\cdot s^{-1}$. From April to August is the wind season, the average wind velocity is 3.2 $m\cdot s^{-1}$ and frequently gale. The wind and hot weather is at the same time and the floating dust and sand blowing weather are common. This kind of climate characteristic causes the high temperature and low humidity and the gale low humidity dry-heat wind concurrently, this is extremely disadvantageous to the natural survival of plants and their growth. The ground landscape presents a big compound wind-drift sand ridge, the soil characteristics differ along the landform, the major part is wind-drift sandy soil, the salinity content is 1.26—1.63 $g\cdot kg^{-1}$, the clay soil in the lower level occasionally presents, mixed among the wind sandy soil, and depth generally has 20—60 cm[3,4].

The site in the shelterbelt planted in 1997 was selected, the species included *Calligonum arborescens, Tamarix ramosissima* and *Haloxylon ammodendron*. *Calligonum arborescens* average basal diameter is 3.6±0.19 cm, average height is 268.67±6.3 cm; *Tamarix ramosissima* average basal diameter is 2.4±0.09 cm, average height is 265±8.7 cm; *Haloxylon ammodendron* average basal diameter is 3.9±0.19 cm, average height is 233.7±5.8 cm. The shelterbelt uses drip irrigation, extracting ground water through the water well, the ground water salinity content is 4—5 $g\cdot L^{-1}$. Every year it is irrigated 20 times, every month 3—4 times, each time continually irrigating for 8—10 h, water discharge of one drop is 3.5 $kg\cdot h^{-1}$, one time irrigating water is approximately 35 kg per individual, and irrigation carries on according to the plants growth state.

1.2 Methods

(i) Materials and stem sap flow estimation. Get diameter level distribution through stand investigation first. Then select 3 *Calligonum arborescens* (diameter 1.9, 3.2, 3.6 cm), 3 *Haloxylon ammodendron* (diameter 2.0, 2.8, 3.4 cm) and 2 *Tamarix ramosissima* (diameter 2.0, 3.5 cm) for sap flow estimation, the plants growth is normal and size is moderate.

The stem sap flow is measured by Flow32 system, its principle is heat balance. For the heat balance principle and the instrument installation see refs. [5—7]. In this

paper, the logger recorded the data of sap flow velocity and sap flow accumulation every 15 min from April 11 to October 20, 2005.

(ii) Plant water potential measurements. Plant water potential was measured by plant pressure chamber (PMS. Instrument Co. Model 1000, USA), the predawn and midday water potential of little branch with leaf was measured at 07∶00 and 14∶00 from May to October monthly, one species measured 6 individuals and each individual was repeated three times.

(iii) Meteorological factors and soil moisture content measurements. The meteorological factors were measured at the same time with the sap flow. The meteorological factors were measured by environmental monitoring instrumental (Campell Co.LTD, USA) set up in 2002 by the desert research station. The logger recorded data every 30 min, in this paper, the data including solar radiation, air temperature, air humidity, wind velocity near ground 2 m high were selected to analysis.

The surface 400 cm depth soil moisture content was measured in the middle ten days of May to October monthly by drying weight method and sampled by drills. Each 20 cm layer was sampled.

2 Results

2.1 The stem sap flow characteristics of 3 species of shelterbelt plants

The stem sap flow has an obvious rhythm in day and night influenced by physiological activity and environment factors. When the solar radiation was intense and temperature was higher in daytime, transpiration was higher; when photosynthesis stopped in night, transpiration was lower. Figure 1 is the four days fluctuation curve of stem sap flow of 3 species (the demeter of *Tamarix ramosissima* is 2.0 cm, *Haloxylon ammodendron* is 2.0, *Calligonum arborescens* is 1.9 cm). From Figure 1, the stem sap flow of three plants took obviously periodic fluctuation; the stem sap flow was obviously increasing from 08:00 and at peak in 11∶00—15∶00. Generally, sap flow was fast increasing when the sun rose and peak value was in the morning but not in the midday, so-called "morning peak"[8]. The sap flow was decreasing after 17∶30 and lower during 00∶00—03∶00; it kept 50—70 $g \cdot h^{-1}$ in the night, the 0 point appeared in initial season of April, when growth busy season from May to July, the sap flow kept 60 $g \cdot h^{-1}$; the highest value of sap flow reached up to 1500 $g \cdot h^{-1}$ in July. For different diameter of the same species, it took the same fluctuant trend; the individual of bigger diameter has the higher fluctuations. So diameter and the average stem sap flow had positive correlations[7]. Most studies have indicated that the phenomenon of "transpiration midday stop" existed in the transpiration, in which the transpiration process had two-peak characteristic, but this did not appear in this experiment.

To compare sap flow of three species, the environmental factors must be the same. On the site, soil moisture and meteorological factors were the same, so sap flow of three species could be compared. From Figure 1, for the close diameter, average value of sap flows of *Tamarix ramosissima* was the highest and excessed 32.3% of *Haloxylon ammodendron* and 33.8% of *Calligonum arborescens* in 4 days. Daily average sap flow characteristic value is respectively shown in Tables 1 and 2. The average sap flow density of *Tamarix ramosissima*, *Haloxylon ammodendron* and *Calligonum arborescens* were 25.7 $g \cdot h^{-1} \cdot cm^{-2}$, 15.0 $g \cdot h^{-1} \cdot cm^{-2}$, 24.9 $g \cdot h^{-1} \cdot cm^{-2}$ respectively, *Tamarix ramosissima* and *Calligonum arborescens* were obviously higher than *Haloxylon ammodendron* ($P < 0.01$), there was no obvious difference between *Tamarix ramosissima* and *Calligonum arborescens*. As to the sap flow accumulation and water consumption of 8a same age individuals of 3 species, *Calligonum arborescens* was the first, then *Tamarix ramosissima*, finally *Haloxylon ammodendron.*

2.2 Soil moisture condition and shelterbelt plant water status in forest belt

Under the drip irrigation, soil moisture kept better in the shelterbelt and assured the plants surviving and growth. From Figure 2, soil moisture was stable in different soil layers from May to October, and kept at 8%. At 340 cm, there existed a clay layer having higher moisture capacity, so the soil moisture is always relatively higher. Under the stable and adequate soil moisture, the stem sap flow did not change with soil moisture. In SPAC system, soil is the origin of water rising, under the soil moisture content sufficient condition, inevitably the plant water consumption is also quite high.

The plant water potential in predawn and midday reflected the plant water status in 2 periods, and its the difference of plant water status. Table 3 is plant water potential of 3 species from May to October. We can see that the predawn and midday water potential of

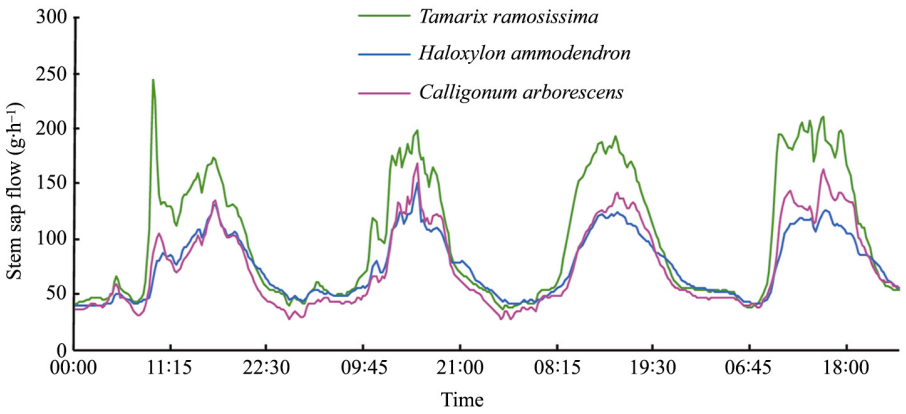


Figure 1 Daily fluctuation of stem sap flow of three species (sunny day, 25—28 June).

Table 1 Daily average sap flow velocity (g/h) and daily water consumption (DWC, g/d) of three species

	C. arborescens		*T. ramosissima*		*H. ammodendron*	
	Sap flow	DWC	Sap flow	DWC	Sap flow	DWC
April	51.59	1238.08	57.53	1380.63	40.96	983.06
May	56.72	1358.21	62.21	1489.05	69.50	1662.52
June	87.23	2101.61	86.83	2083.86	78.04	1872.96
July	101.66	2438.92	110.03	2639.72	74.05	1776.56
August	69.88	1823.32	101.86	2444.72	67.75	1626.02
September	76.01	1677.12	79.84	1914.93	64.53	1547.67
October	26.03	624.69	41.04	978.25	35.94	860.55
Average	67.02	1608.85	77.05	1847.31	61.54	1475.62

Diameters: *T. ramosissima* 2.0 cm, *H. ammodendron* 2.0 cm, *C. arborescens* 1.9 cm.

Table 2 Individuals daily average and maximum value of stem sap flow velocity (SFV)

Species	Diameter (cm)	Daily average SFV ($g \cdot h^{-1}$)	Max value of daily average SFV ($g \cdot h^{-1}$)
C. arborescens	1.9	67.017	129.34
C. arborescens	3.2	202.60	447.35
C. arborescens	3.6	263.60	595.93
H. ammodendron	2.0	61.54	99.74
H. ammodendron	2.8	91.16	208.13
H. ammodendron	3.4	128.46	244.12
T. ramosissima	2.0	77.05	134.46
T. ramosissima	3.5	258.77	430.59

3 species were obviously different, which indicated that the plant water status was better in predawn, but lost more water in midday, causing water potential difference near to 2 MPa. High water potential in the morning indicated that the plant water status gets better recovery through one night absorption, and low water potential indicated plant loses more water through a few hours transpiration later. The night low sap flow also showed that the root absorption activities in the evening had not ended, but met the daytime needs of water loss through the night absorption.

2.3 The relationship between meteorological factors and stem sap flow

In addition to their own eco-physiology characteristics, the plant transpiration was affected by environmental factors also. Under present irrigation, the plant transpiration was mainly affected by meteorological factors because the soil moisture remained at a stable level and these provided a more adequate water supply to plants. Figure 3 is the fluctuation curve of stem sap flow of *Haloxylon ammodendron* and meteorological factors. It reflected the fluctuation trend of stem sap flow and radiation, temperature, wind velocity is very similar; especially the change of radiation and temperature was consistent with that of stem sap flow. Table 4 shows the correlation analysis result of sap flow and several main meteorological factors, and could see that the stems flow had a significant correlation ($\alpha = 0.01$) with solar radiation, air temperature, relative humidity and wind velocity; the stem sap flow had a strong correlation with solar radiation with correlation coefficient of 0.885 and also had a positive correlation with temperature and wind velocity and a negative correlation with relative humidity.

Table 3 The predawn and midday water potential of three species in different months (Unit: MPa)

		May	June	July	August	September
T. ramosissima	predawn	0.77	1.08	0.92	1.33	1.28
	midday	1.92	2.33	2.85	2.60	1.84
H. ammodendron	predawn	1.77	3.14	2.14	2.52	3.18
	midday	3.27	4.24	3.98	4.49	3.99
C. arborescens	predawn	0.61	1.00	0.79	0.90	1.25
	midday	1.18	1.71	1.52	1.72	1.49

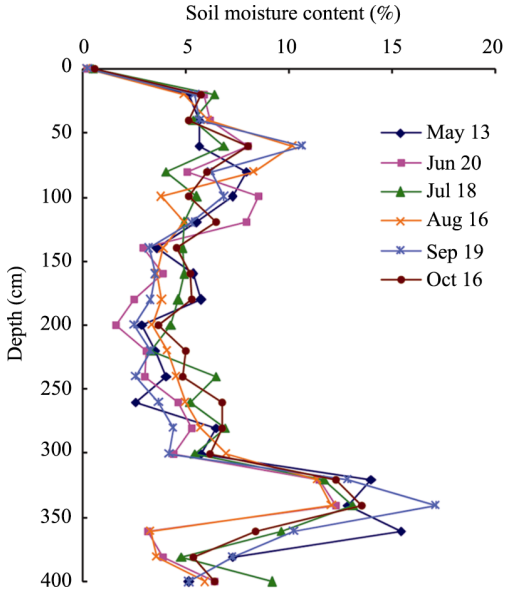


Figure 2 400 cm surface soil moisture in different months.

The regression model between stem sap flow of *Haloxylon ammodendron* and meteorological factors was determinated by multiple regression methods; and the regression model between stem sap flow of *Haloxylon ammodendron* and two meteorological factors was established by stepwise regression methods:

$$S_f = 145.705+0.211X_1-1.07X_2,\ R^2 = 0.905,$$

or the regression model of stem sap flow and solar radiation:

$$S_f = 107.086+0.237X_1,\quad R^2 = 0.885,$$

where S_f is stem sap flow velocity, X_1 is total radiation, and X_2 is relative humidity.

Different result was concluded after analyzing the response of the sap flow of *Tamarix ramosissima* to meteorological factors variation. The correlation coefficient value between stem sap flow of *Tamarix ramosissima* and meteorological factors was followed by radiation, temperature, wind velocity, relative humidity. There was a significant positive correlation between stem sap flow and total radiation, temperature, and wind velocity, the highest correlation coefficient of 0.963 was between sap flow and solar radiation, while there was a negative correlation with relative humidity, and reached signify-

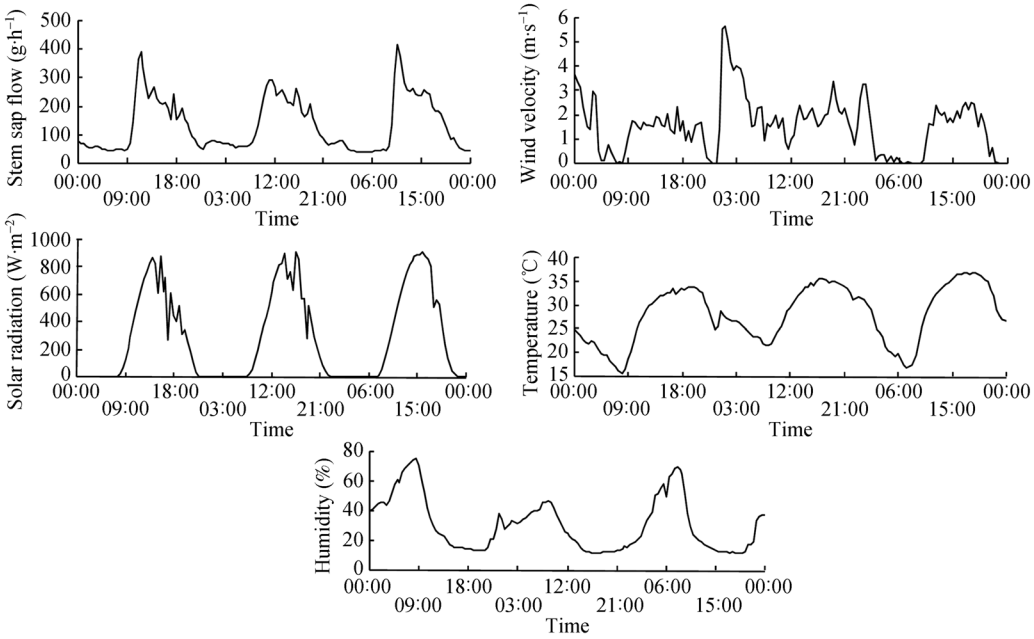


Figure 3 The variation process of stem sap flow and meteorology factors.

Table 4 The correlation between stem sap flow and meteorological factors

	Sap flow ($g \cdot h^{-1}$)	Solar radiation ($W \cdot m^{-2}$)	Temperature (℃)	Wind velocity ($m \cdot s^{-1}$)	Relative humidity (%)
Sap flow	1.000	0.885**	0.686**	–0.577**	0.379**
Solar raiation	0.885**	1.000	0.614**	–0.464**	0.371**
Air temperature	0.686**	0.614**	1.000	–0.944**	0.425**
Wind velocity	–0.577**	–0.464**	–0.944**	1.000	–0.493**
Relative humidity	0.379**	0.371**	0.425**	–0.493**	1.000

** indicates the significant correlation at 0.01 level.

cant level. Based on relative analysis, the model between stem sap flow and several main meteorological factors was established by using multiple line regression. And the model of stem sap flow between total radiation and wind velocity was established by stepwise regression methods also.

$$Y=39.686+0.173X_1+3.833X_2, \quad R^2=0.969,$$

where Y is stem sap flow, X_1 is total radiation, and X_2 is wind velocity.

Variance analysis test showed that the regression equation was significant, so stem sap flow could be predicted by total radiation and wind velocity. Clearly, because of different size in sap flow rate, *Haloxylon ammodendron* and *Tamarix ramosissima* had a different response to meteorological factors. Sap flow of *Tamarix ramosissima* was higher and more influent in wind velocity than that of *Haloxylon ammodendron* which was relatively lower, but more easily influenced by air humidity.

2.4 Water consumption of three species in shelterbelt

Water consumption of 3 species was fluctuated with the growth process. Growth germinated in early April and recessed in October, the water consumption process throughout the growing season was single peaked curve, which was determined by its growth rhythm.

Figure 4 shows the average daily water consumption in different months for 8 individuals. From Figure 4 the largest water consumption period of *Tamarix ramosissima* and *Calligonum arborescens* was July, as to 3.5 cm-diameter *Tamarix ramosissima*, in July the largest water consumption was up to 13 kg. For *Haloxylon ammodendron*, the largest water consumption period was June and August; water consumption in July was slightly lower. Table 5 shows daily water consumption of three species in growth season. In one growing season, the daily water consumption of 3 *Calligonum arborescens*, 2 *Tamarix ramosissima* and 3 *Haloxylon ammodendron* was 4.27 kg, 4.02 kg, 2.24 kg respectively. *Calligonum arborescens* and *Tamarix ramosissima* had higher water consumption, which of *Haloxylon ammodendron* was relatively low. The annual individual water consumption for the 8 years of *Calligonum arborescens*, *Tamarix ramosissima* and *Haloxylon ammodendron* was 1937.80, 1253.39 and 1026.96 kg, and their daily water consumption was 9.69, 6.27 and 5.13 kg respectively.

3 Discussions

(i) Stem sap flow is the water and nutrient flow through stems, the main component is water. It is affected by many factors, and has spatial and temporal variation characteristics. Fredrik summarized the former researches of the relationship between transpiration and stem sap flow in the world, and pointed out that, generally, the day transpiration and water consumption were equal to the total stems flow accumulation[9]. Therefore, in the day scale, stem sap flow accurately reflects individual plant transpiration and water use, so transpiration can be characterized by stem sap flow. The plant transpiration and water status and the impact of environmental factors on transpiration can be directly reflected by learning the stem sap flow and its fluctuation[10,11]. Under any circumstance, the rules of plant transpiration performed low during the nighttime and high during the day. In arid desert zone, these desert plants have larger stems flow, over heat and dry burning can be avoided through a lot of transpiration. At the same time, the desert plant could not restrict water loss by itself under adequate water supplies. The night upward sap flow was partly determined by low water potential of over ground part of the plant which is caused by daily transpiration. According to "transpiration-cohesiontension theory"[12], canopy transpiration during the day was mainly due to stomatal opening to form a leaf-the canopy-the root water potential difference, sunset, stomatal closure, when water potential gradient does not disappear immediately, because the difference of water potential exists, there will be some moisture passively absorbed through trunks and roots into the leaves, a nighttime compensation flow formed, so that the trunk water storage was compensated

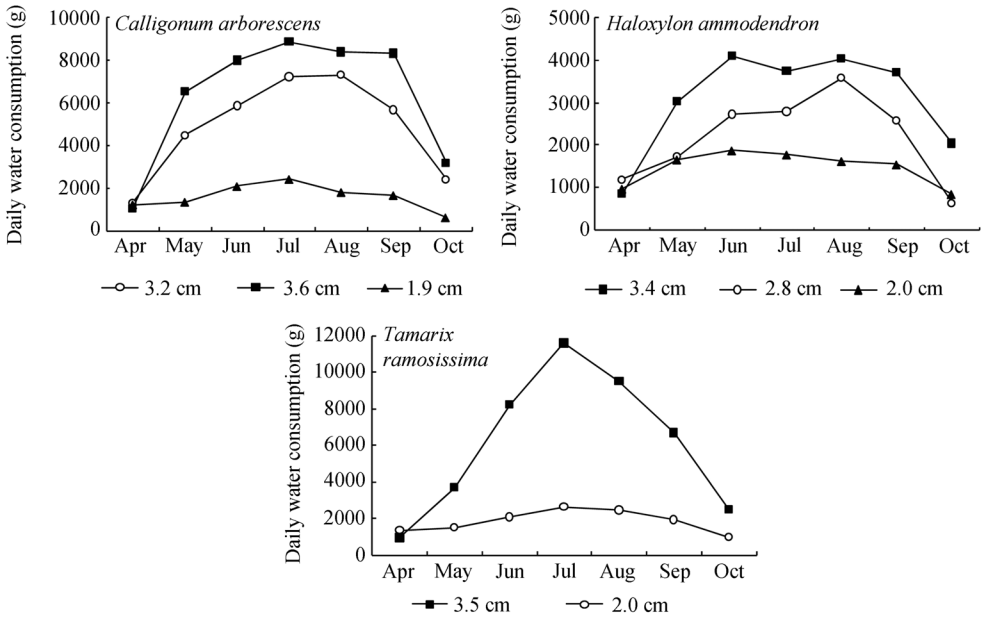


Figure 4 Daily water consumption of 3 species in different months.

Table 5 Daily water consumption (DWC) of three species in growth season

Species	Diameter (cm)	Maximum value of DWC (kg)	Average DWC (kg)
C. arborescens	1.9	3.104	1.61
C. arborescens	3.2	9.527	4.89
C. arborescens	3.6	10.527	6.32
H. ammodendron	2.0	2.393	1.48
H. ammodendron	2.8	4.348	2.18
H. ammodendron	3.4	4.995	3.08
T. ramosissima	2.0	3.227	1.85
T. ramosissima	3.5	13.694	6.19

in the night[13]. Similar results were concluded from the study of *Pinus tabulaeformis*[14]. In hyperarid desert, the water loss during the day cannot be promptly compensated, at night there is still a lower sap flow to supplement the plant's water consumption during the day, and due to high temperatures, air flow and air drying may also be an important reason for night transpiration. Zhang et al. pointed out that the transpiration process of *Haloxylon ammodendron* showed a single-peak curve[15]. But Yang et al.[16] considered that the transpiration process of *Haloxylon ammodendron* showed a double-peak curve. Stems flow is affected by many environmental factors, and sometimes there will be double or multipeak curve, if environmental conditions are relatively stable, for example, in no wind sunny day, stem sap flow fluctuation will not obvious, the transpiration process showed a smooth curve of the single-peak type. From one growing season, daily transpiration process, the long-term trend is the stability of single-peak curve.

(ii) Most studies indicate that solar radiation, wind velocity, temperature and soil moisture are the main factors impacting the sap flow[17−22]. In the hinterland of the Taklimakan Desert, solar radiation, temperature, wind velocity, relative humidity have a strong positive correlation with sap flow, these meteorological factors will influence the plant stem sap flow and water consumption. Sap flow has a significant positive correlation with solar radiation, wind velocity and temperature, and a negative correlation with air humidity, the greatest correlation appeared between sap flow and solar radiation. In the drought desert hinterland, strong solar radiation, high temperature, wind velocity, air drying, these meteorological factors largely affected the plant transpiration, if sufficient water supplied, plant will make full use of existing water resources.

(iii) The plant water consumption was greatly different, with the individual plant water consumption from 10 kg in eastern French *quercus petraea* to 1180 kg in Amazon rain forest upper canopy *euperua purpurea*; 65 species from 35 genus, water consumption of 90% individuals (average height was 21 m) were 10 − 200 kg[23,24]. Zhou et al.[25] compared transpiration water consumption of 9 species seedling and found the sequence of daily transpiration rate followed by *Pinus tabulaeformis*, *Platycladus orientalis*, *Cotinus coggygria*, *Caragana korshinskii kom*, *Ailanthus altissima Swingleh*,

Rhus typhina, *Hippophae rhamnoides*, *Populus tomentosa Carr*., *Lycium chinense Mill*; 5 years *Pinus tabulaeformis* and *Platycladus orientalis* daily water consumption in sunny day were 61.7±9.6 g and 39.8±6.8 g , and 1 year *Populus tomentosa Carr, Ailanthus altissima Swingleh, Rhus typhina and Cotinus coggygria* were 44.8±8.1 g, 53.4±8.8 g, 63.1±14.4 g and 38.4±17.0 g respectively; *Lycium chinense, Hippophae rhamnoides* and *Caragana korshinskii kom* were 18.8±5.6 g, 4.8±1.1 g and 33.1±5.0 g respectively[25]. In the Shiyang River basin, Gansu, the average daily stem sap flow rate of *Tamarix elongata* with 6—7 cm basal diameter was 4.1798 $L \cdot d^{-1}$[26]. In Ejin Oasis of the Heihe River basin, the average daily stem sap flow rate of the basal diameter 4 and 5 cm of 20 a *Tamarix* spp. was 0.37 and 0.62 $L \cdot d^{-1}$[27]. And *Haloxylon ammodendron* in this area, daily water consumption and annual water consumption were 0.3±0.2 mm and 49.4 mm[28]. In the Gurbantunggut Desert, the 2, 3 and 4a *Haloxylon ammodendron* annual water consumption was 33.603, 98.827 and 132.232 kg respectively[29]. In Ejin Oasis, from May to October, the average daily water consumption of *Haloxylon ammodendron* with 5.5 cm basal diameter was 1.87 kg[30]. In this study, water consumption of *Tamarix ramosissima* and *Haloxylon ammodendron* in the shelterbelt was higher than in other place, and cannot compare with that of the *Calligonum arborescens* because there are no more reports for this species. Daily water consumption of 2 *Tamarix ramosissima* was 6.19 and 1.85 kg; 3 *Haloxylon ammodendron* were 3.08, 2.08 and 1.48 kg; and 3 *Calligonum arborescens* were 6.32, 4.89 and 1.61 kg respectively. Obviously, in the arid environment, the plant is not necessarily saving water; these plants have small leaves, developed root systems and some other shape characteristics that adapt to the arid circumstances. Although its drought resistance ability is strong, under the sufficient water supply, it will fully use the water resources, inevitably, the arid environment and more sufficient soil water supply will cause the higher water consumption.

(iv) Although the water potential did not have a direct influence on the physiological metabolism process[31,32], it was one of important indexes and the size to indicating the ability that plant could absorb water from soil or adjacent cells in order to ensure normal physiological activities[33,34]. By analyzing different water potential in different plant species, water potential was different among different species; generally, xerophytes can tolerate more dry circumstances, and appearance of lower water potential[35]. Predawn water potential reflects the plant water restoration, therefore, the plant water deficit can be judged by predawn water potential[36]. Sobrado pointed out that the water potential of the plant suffering water stress was obviously decreasing in the morning[37]. The water potential of 3 species of shelterbelt was higher in the morning, indicating that the plant water gets good restoration in the night and no water deficit appears. However, the lower midday water potential indicated that serious water loss from transpiration happened in daytime and led to the great water potential difference between predawn and midday.

The plant water potential and water consumption indicated that the plant water status was better and, therefore, had no water deficit, conversely, the amount of water restored in the night and lost in daytime, which caused higher water consumption. The good water status indicated that the water supply to the shelterbelt by the present water management was sufficient also.

(v) The main means of plant water loss is transpiration, and this is controlled by soil humidity and meteorological factors[9], soil moisture has great influence on stem sap flow[36—38]. In desert environments, the soil moisture content is very low, in Heihe Oasis, the *Haloxylon ammodendron* stand soil moisture has been lower than 2.0%[28]. In Ejin Oasis, stand soil moisture contents of *Haloxylon ammodendron* and *Tamarix ramosissima* were 0.436% and 0.469%[35]. In the Gurbantunggut Desert, 1—200 cm soil moisture content was <1.0%[29]. In the Wulanbuhe Desert, the survival rate of *Calligonum arborescens* was more than 90% under the circumstance of sand soil moisture content >3%[39]. The present irrigation system of desert highway shelterbelt (irrigation interval is 10 d, irrigation quantity is 1000 $m^3 \cdot ha^{-1}$) can guarantee the plant survive and good growth condition[40]. The 400 cm average soil moisture content under the shelterbelt stabilizes in 8%; this is a water-rich environment for shelterbelt plant. According to present irrigation and soil moisture content, compared with soil moisture under a natural environment, the water supply to the shelterbelt by the present water management is sufficient.

4 Results

In the desert special environmental condition, the shel-

terbelt plant's transpiration has obvious regularity, the transpiration is higher in daytime and lower in the night, however, the low level sap flow is maintained.

According to plant water potential and soil moisture content, the water supply to the shelterbelt by the present water management is sufficient. Compared with other environments, the plant water consumption in the Tarim Desert Highway shelterbelt is higher; and the soil moisture stabilizes at around 8%, this is a water-rich circumstance for shelterbelt plant.

In the arid desert hinterland, the strong solar radiation, high temperature, wind, air drying, these meteorological factors largely affected the plant transpiration. Sap flow has a significant correlation to solar radiation; the stem sap flow can be forecast by using the regression equation for sap flow and other meteorological factors.

The results of one growth season showed that daily water consumption of 2 *Tamarix ramosissima* were 6.19 kg and 1.85 kg; 3 *Haloxylon ammodendron* were 3.08, 2.08 and 1.48 kg; and 3 *Calligonum arborescens* were 6.32, 4.89, 1.61 kg respectively.

The present irrigation management system ensures not only the survival rate but also the plant's blooming growth. Under the present irrigation management system, a large quantity of water was used to maintain the growth of the shelterbelt; according to the plant water consumption, plant water status and soil moisture content, this irrigation management provides adequate water for the plant. Considering the fragile ecological of arid areas, conservation of water resources, improving water use efficiency is the core problem of our concerns. The requirement of improving water use efficiency is combination of shelterbelt performance and rational allocation of water resources. Mainly three drought-resistant desert plants compose the shelterbelt. For desert plants, it has strong ability to adapt to the drought, only a small quantity of water is required to meet their survival needs. But when the environment can provide adequate water, the plants will not refuse; on the contrary, will make full use of available water resources. Therefore, desert plants are not necessarily water-saving, and water-saving just is the passive choice under arid circumstances of the lack of water. As mentioned above, compared to natural conditions, the shelterbelt plants under water-rich conditions, three species have higher water consumption. Superior water conditions are not necessary for the shelterbelt to maintain luxuriant growth. The poor water conditions do not prevent the stability of the shelter forest plants. Therefore, under the present irrigation management there exists the possibility to optimize water-saving space. The following studies of the desert highway shelterbelt should focus on the problem of what is the optimum combination of water resources protection and performance implement.

In the management of the shelterbelt, water conservation and protection performance implement are the basal, optimization of irrigation systems is based on the growth of plants, water status and soil moisture conditions, to achieve the minimum amount use under the protection performance implemented.

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