Comparison of the water consumption levels of four shelterbelt tree species in a typical arid oasis in Northwest China

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Abstract: The shelterbelt is an indispensable barrier to the ecological and economic development of an oasis. Soil moisture, groundwater and irrigation greatly affect the shelterbelt water consumption and development. In this study, the transpiration rate of shelterbelt trees, soil moisture and meteorological data were collected to determine the effects of soil moisture and meteorological factors on the water consumption of different shelterbelt tree species via multivariate statistical methods. The results showed that the water consumption rate was positively correlated with solar radiation, air temperature and precipitation. Moreover, the leaf transpiration rate exhibited the trend of *P. Russkii* Jabl.>*P. alba*>*P. simonii* Carr.>*P. nigracv*, while the average daily water consumption decreased in the order of *P. alba*>*P. Russkii* Jabl.>*P. simonii* Carr.>*P. nigracv*. The average daily water consumption levels of *P. alba, P. Russkii* Jabl., *P. simonii* Carr. and *P. nigracv* were (9.15±0.92) kg/(tree·d), (6.95±1.41) kg/(tree·d), (4.43±1.32) kg/(tree·d), and (1.58±0.18) kg/(tree·d), respectively. Over the growing season, the soil water consumption levels of *P. alba*, *P. Russkii* Jabl., *P. simonii* Carr., and *P. nigracv* in each shelterbelt tree stand reached 674.8, 336.9, 358.1 and 161.7 kg, respectively. More than 96% of the soil moisture lost was provided by the upper 120-cm soil layer. Understanding the influence and contribution of soil water and meteorological factors to shelterbelt water consumption is beneficial for shelterbelt management and protection.

Keywords: water consumption, irrigation management, shelterbelts, soil moisture, climatic factors
DOI: 10.25165/j.ijabe.20241702.8264

Citation: Fu S, Xu B X, Leng Y F, Peng Y X, Tao G G, Li L H. Comparison of the water consumption levels of four shelterbelt tree species in a typical arid oasis in Northwest China. Int J Agric & Biol Eng, 2024; 17(2): 169–176.

1 Introduction

Severe water shortages in arid and semiarid regions in China have triggered regulations limiting the use of irrigation water in desert–oasis agricultural systems[1]. Oases account for only a small proportion of the land surface in Xinjiang, but they are nonetheless important for agriculture and human activity, with more than 95% of the population living in these areas and generating more than 90% of the wealth in this region. The shelterbelt is a protective tool for oases in arid regions, and it can guarantee sustainable oasis development. Shelterbelt degradation processes aggravate wind erosion of soil, cause deterioration in soil physical and chemical properties, reduce the productivity of land, cause high economic losses, and seriously affect the livelihood and living environment of people who live in or near oases in northwestern China[2,3]. However, with water resource shortages in Northwest China, there is an enormous threat to the maintenance and development of shelterbelts[4,5]. Drip irrigation, flood irrigation, and furrow irrigation have been used to manage different functional shelterbelts, and different types of management measures yielded varying impacts on the habitats of shelterbelts[6-8]. In addition, the shelterbelt system has experienced different degrees of decline in terms of management. Therefore, analyzing the water consumption trends of shelterbelts under different management systems and soil moisture are helpful for maintaining and developing oasis shelterbelts.

The transpiration characteristics of trees are affected by the configuration and management modes[9]. *P. Russkii* Jabl., *P. nigracv*, *P. alba* and *Populus simonii Carr* are the four main species of oasis shelterbelt trees in the Manas Oasis. Because of the different characteristics of tree growth and water consumption, the planting positions of different tree species in the oasis and conservation methods are very different. *P. Russkii* Jabl., as the main tree species of the three northern shelterbelts, is cultivated mainly at the junction of desert and farmland areas under drip irrigation because of its higher drought tolerance and rapid growth characteristics. *P. alba* is widely planted on both sides of roads because of its branches and leaves, mainly cultivated under flood irrigation. *P. nigracv* and *Populus simonii Carr* are the main tree species in farmland shelterbelts and are widely used in farmlands; on both sides of

Received date: 2023-03-27 **Accepted date:** 2024-03-06
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irrigation channels and on ridges in fields, furrow irrigation is employed. The functions of each of the tree species in an oasis can include preventing wind and sand erosion, conserving water, changing the microclimate of farmland and facilitating the sustainable development of oasis farmland[10,11]. With climate change intensification, vigorous agricultural development and popularization of water-saving agriculture, the ecological water demand of shelterbelts is difficult to guarantee; thus, withering has occurred in large areas of shelterbelts in oases, causing notable losses in oasis agriculture, ecology or the economy[12]. However, the uncertainty in the water consumption and water storage capacity of different tree species under different management methods restricts the protection and maintenance of protected forest species in oases.

Water is a critical resource for human survival and plant growth. Economic and social development and rapid increases in the human population have resulted in increased water demands and severe water shortages in certain areas, especially in arid and semiarid regions[1,13,14]. With the development of oasis agriculture, drainage and management styles, oasis shelterbelts have declined in recent years[15,16]. In the case of limited water resources in arid oases, oasis expansion and oasis agriculture development, coupled with the application of water-saving facility agriculture and considering the impact of climate change, not only altered the water consumption trend in shelterbelts but also restricted the water resource supply[11,17,18]. Solar radiation, rainfall, air temperature and humidity affect the transpiration rate and water consumption of shelterbelts, and normal shelterbelt development cannot occur without a timely supply of ecological water[5,19,20]. Climate change and frequent agricultural activities have caused an imbalance in the water resource distribution in oases, leading to the crowding out of ecological water resources in shelterbelts[21-23]. The overexploitation of groundwater and popularization of facility agriculture hinder the recharge of shelterbelts by diving evaporation, infiltration and lateral infiltration[24]. Due to the scarcity of effective rainfall, high solar radiation and high temperature in arid regions, irrigation, soil moisture and groundwater are the main water sources of oasis ecosystems[25,26]. As such, the role of shelterbelt water consumption has remained a focus of research. The contribution rate of soil moisture in different soil layers to the water consumption of different shelterbelt species greatly differs seasonally[27]. The active soil layer associated with shelterbelt soil moisture is generally the 0-140 cm layer, while the relatively stable layer also encompasses additional layers[28]. In addition, the scarcity of effective rainfall greatly reduces the soil water supply in shelterbelts. Due to the difference between the supply and demand for ecological water of artificial shelterbelts in an oasis, shelterbelts gradually decline, and the landscape pattern is fragmented, which directly threatens the harmonious development of the agricultural economy in arid oases.

Therefore, in this study, we used field data, including soil water content and leaf transpiration rate data, to examine the effects of different management practices on shelterbelts and provide data for formulating better management practices. The aims of the study were 1) to evaluate the water consumption characteristics of the four main shelterbelt species in the Manas Oasis area; 2) to identify the soil moisture supply characteristics of different protected forest species; 3) to determine the water consumption characteristics of the considered species to guide the design of irrigation management strategies.

2 Materials and methods

2.1 Study sites

This study was conducted in the Manasi Oasis, which is located in the southwestern part of the Junggar Basin in Xinjiang. The famous Tianshan Mountains occur south of this region, and the edge of the Junggar Basin occurs west of this region. The northern part is low, while the southern part is high. Mountains and plains equally share the area. The area is 5156 km^2, the average height is 3022 m, and the glacier area is 608.25 km^2. The main sources of runoff are rainfall and meltwater, of which meltwater accounts for 34.5% of the total runoff[29]. The study area exhibits an arid continental climate, with an average annual temperature of 6.1°C from 1998 to 2014. The annual temperature difference is 44.4°C, and the daily temperature difference is 7.2°C. The accumulated active temperature ≥0°C is 3963°C, and the accumulated active temperature ≥10°C is approximately 3545°C. The annual daily mean sunshine duration is 2749.9 h, and the global radiation is 126.7 kcal/cm^2. The annual mean precipitation is 117.2 mm[30]. During the experimental period from 2012 to 2014, the precipitation and temperature in the basin were consistent with those over the previous 15 years.

This region slopes downward from south to north and tilts from southeast to northwest. The geomorphologic sectors include mountains, flat plains, and deserts. The 1.176×10^3 km^2 central alluvial plain is the major agricultural crop-growing area. *P. alba, P. Russkii* Jabl.*,* *P. simonii* Carr., and *P. nigracv* were planted as protective barriers of oases under different irrigation method[31]. Drip irrigation involves using plastic pipes to send water to crop roots through orifices or droppers, with a diameter of approximately 10 mm (local irrigation). This method is widely used in protecting forests at the junction of deserts and oases. Furrow irrigation is achieved through the excavation of irrigation ditches between crop rows. After irrigation water enters the irrigation ditches from transport or wool ditches, it permeates and moistens the soil in the flow process, which has been widely applied in farmland shelterbelts in oases. Flood irrigation is a relatively extensive irrigation method that does not involve field ditches. Instead, water is poured onto the ground or the soil is moistened under gravity, and this method is widely used in shelterbelts along roads.

2.2 Methods

In this study, four species were selected among the oases, and three trees of each species were sampled at each shelterbelt site. A steady-state porometer (Li-1600) (LI-COR INC, Louisiana, USA) was used to measure leaf transpiration and leaf conductance on clear days (no clouds) during the growing season. A measurement was performed once an hour from 6 am to 8 pm. Leaf conductance and transpiration were measured two days per month. Moreover, the leaf area index and soil water content in the trees were measured. A camera was used to obtain tree photographs, after which the leaf area index could be calculated. The soil water content was measured by soil drying and weighing. A soil auger was used to sample the soil at a depth from 10 to 200 cm, and soil samples were collected at 10 cm depth intervals. Then, the soil was placed in an aluminum specimen box, which was then sealed and transported to the laboratory. All the soil samples were weighed immediately after they were sealed, before transport to the laboratory for analysis. The aluminum specimen boxes were placed in a drying oven, and the temperature was maintained at 120°C for 24 h. The samples were finished and weighed with an analytical balance after cooling. A small weather station was installed next to the shelterbelt to collect air temperature, humidity, solar radiation, rainfall, wind speed, and air pressure data.

Water consumption was calculated by the obtained leaf transpiration, leaf area index, stand area and daylight hour data, as follows:

$$W = T \cdot \mathrm{LAI} \cdot A \cdot t \quad (1)$$

where, W is the water consumption, kg/d; T is the leaf transpiration rate, μg/(cm^2·s); LAI is the leaf area index; A is the tree shadow area, m^2; and t is the leaf transpiration time over one day, s.

All the statistical analyses were performed in SPSS software, version 24.0 (SPSS, Inc, USA). The figures were generated in Origin Pro software, version 8.5 (Origin Lab, Inc, USA).

3 Results

3.1 Leaf transpiration of the 4 species of farmland shelterbelt trees

Four species of trees, namely, *P. simonii* Carr., *P. Russkii* Jabl., *P. alba* and *P. nigracv,* form the main shelterbelt in the Manas Oasis. Each species exhibits unique characteristics and plays a role in the oasis, and they are associated with different irrigation styles. *P. simonii* Carr. is grown in the farmland of the oasis, watered by furrow irrigation. *P. Russkii* Jabl. is cultivated under drip irrigation between the oasis and desert. This species fulfills a protective role by providing oasis wind-proofing and sand fixation functions. The mean tree height is 5.1 m, and the mean DBH (Diameter at Breast Height) is 6.49 cm (Table 1). *P. alba* is planted along roads, with high and broad stems. The average height is approximately 20.38 m, and the crown diameter is 1.40 m, so it provides greater shade. *P. alba* is irrigated by flooding. Most *P. nigracv* plants grow along the irrigation channel in farmland. The average height is greater than that of *P. alba* but with a smaller crown diameter. Thus, the surrounding farmland is covered less, and the consumed water mainly originates from lateral replenishment of farmland and infiltration in ditches. The tree and row spacings were measured by a ruler, after which the floor area could be calculated.

Table 1 Structure of the farmland shelterbelt trees and management style

Tree belt	Height/m	DBH/cm	Crown diameter/m	Coverage/%	Floor area/m^2	Irrigation
P. simonii Carr.	15.78±0.68	18.95±3.00	1.05±0.03	52.45±26.21	2.3	Furrow
P. Russkii Jabl.	5.10±0.96	6.49±2.37	1.30±042	56.00±31.28	4.5	Drip
P. alba	18.33±1.76	20.38±5.67	1.40±0.91	57.69±38.25	2.6	Flooding
P. nigracv	19.88±1.65	30.13±4.83	1.26±0.16	67.18±37.78	2.8	No irrigation

The leaf transpiration rate was measured by a porometer, Li1600 (LI-COR INC, Louisiana, USA) on sunny days, and six leaves of each tree were selected for measurement. The experiment was performed from June 2013 to October 2014. As listed in Table 2, leaf transpiration increased from May to July, and the transpiration level of the four species reached a maximum value in July. Subsequently, the leaf transpiration rate decreased until the end of the growing season. In 2013, *P. alba* exhibited the highest leaf transpiration of the four species in July, with a value of 14.13 μg/(cm^2·s), and the lowest leaf transpiration was observed for P. nigracv in October. In each growing month, the leaf transpiration rate followed the order of *P.* alba>*P.* simonii Carr.>*P.* Russkii Jabl.>*P.* nigracv. In 2014, the highest leaf transpiration rate was observed for P. Russkii Jabl. in July, with a value of 14.2 μg/(cm^2·s). The lowest value was obtained for *P. nigracv* in September, with a value of 1.08 μg/(cm^2·s). The leaf transpiration rate exhibited the order of *P. Russkii* Jabl.>*P. alba*>*P. simonii* Carr.>*P. nigracv*.

Table 2 Mean leaf transpiration rate of the oasis shelterbelt

Year	Tree belt	Mean leaf transpiration rate/μg·cm^{-2} s^{-1}					
		May	Jun.	Jul.	Aug.	Sep.	Oct.
2013	*P. simonii* Carr.	-	8.67	11.20	9.50	6.28	4.26
	P. Russkii Jabl.	-	9.72	12.20	9.63	7.16	5.33
	P. alba	-	8.26	14.13	11.38	7.82	4.63
	P. nigracv	-	5.40	4.67	2.75	2.10	1.30
2014	*P. simonii* Carr.	4.67	9.06	11.63	9.35	4.63	3.39
	P. Russkii Jabl.	11.00	11.32	14.20	9.63	5.72	4.17
	P. alba	5.27	9.65	12.11	12.35	8.53	3.87
	P. nigracv	2.12	4.62	5.13	2.67	1.08	1.15

Note: 8:00-22:00, the sunrise and sunset time in Xinjiang is from 8 am to 22 PM, so this period is selected as the measurement time.

3.2 Water consumption of the four species in the oasis shelterbelt

Leaf area transpiration is an important indicator of forest water consumption. The leaf area index and sunlight availability are also important parameters reflecting forest water consumption. In the northwest, snow and ice begin to melt in March, trees begin to sprout in April, and leaves gradually mature beginning in May. Leaves begin to grow densely in July and August, and they start to wither in September and October. Then, the leaf area index decreases to zero. As shown in Figure 1, the LAI of all four species increased beginning in April, peaked in August, and then declined until October. *P. Russkii* Jabl. exhibited the highest LAI, at 2.6 in August 2013 and 2.3 in August 2014. In 2013, the LAI exhibited the order of *P. Russkii* Jabl.>*P. simonii* Carr.>*P. alba*> *P. nigracv*. In 2014, *P. alba, P. simonii* Carr., and *P. Russkii* Jabl. exhibited similar LAI trends, and the peaks were very similar, at 2.4, 2.2 and 2.3, respectively. In both 2013 and 2014, *P. nigracv* attained a lower LAI in each growing month than that of the other species, and the values peaked in August, at 1.6 and 1.65, respectively.

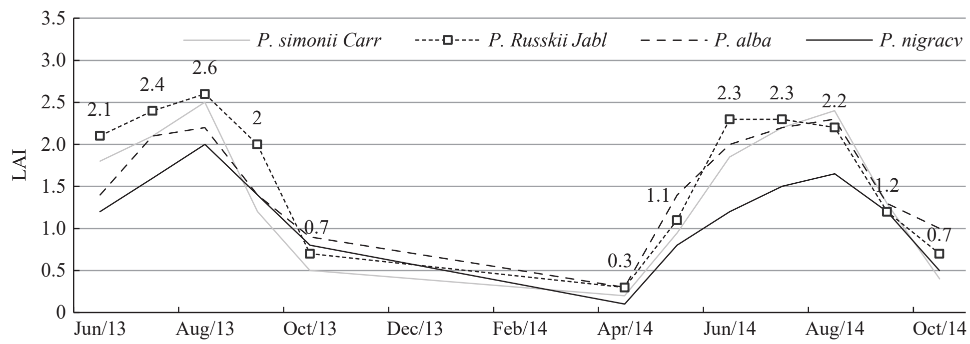


Figure 1 Changes in the leaf area index from 2013 to 2014

At the beginning of the growing season, each tree species exhibited low stand water consumption. In May, the daily water consumption of *P. simonii* Carr. reached approximately 2.0 kg/d, peaked at 12 kg/d in July and August, and sharply declined to its minimum in October (Figure 2). *P. Russkii* Jabl. exhibited higher stand water consumption in May, at 5.8 kg/d in 2013 and 6.1 kg/d in 2014. The value peaked in July, at 16.5 kg/d, after which it declined until the end of the growing season. Among the four species, *P. alba* attained the highest stand water consumption in 2013 and 2014, and the value in August was the highest among the four species, peaking at 19 and 21 kg/d, respectively. In each month, *P. nigracv* exhibited the lowest stand water consumption, and the peak values were 3.9 kg/d in July, 0.9 kg/d at the beginning of the growing month and 0.3 kg/d at the end of the growing month. Notably, the daily water consumption followed the order of *P. alba*>*P. Russkii* Jabl.>*P. simonii* Carr.>*P. nigracv*. The average daily water consumption levels of *P. alba, P. Russkii* Jabl., *P. simonii* Carr. and *P. nigracv* were 9.15±0.92 kg/(tree·d), 6.95±1.41 kg/(tree·d), 4.43±1.32 kg/(tree·d), and 1.58±0.18 kg/(tree·d), respectively. Under sunny and cloudy weather conditions, shelterbelt transpiration and water consumption remained stable and gradually decreased with the growing season continuation and the decreasing soil moisture.

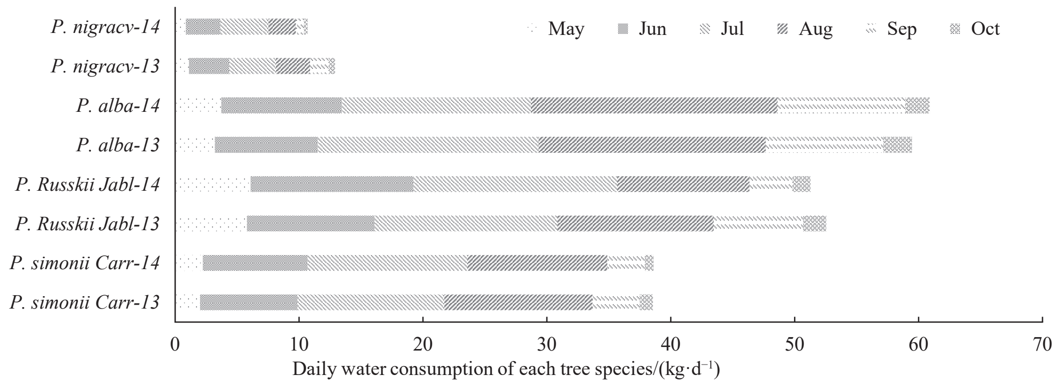


Figure 2 Water consumption of each farmland shelterbelt tree

3.3 Soil water content and stand transpiration in shelterbelts

The soil moisture content not only affects the transpiration rate of leaves but also affects the amount of water consumed. A higher soil moisture content and sufficient sudden moisture availability are beneficial to plant growth and promote plant transpiration. Through soil drying measurements, we obtained the soil moisture content of the different tree species during different growth periods at various depths. The results are shown in Figure 3.

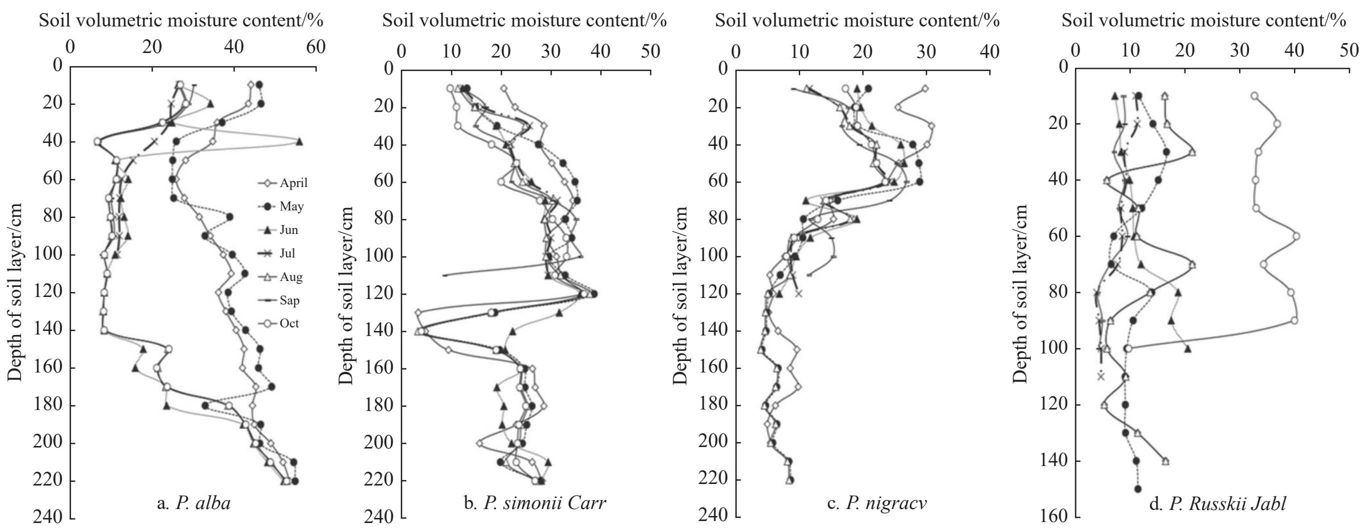


Figure 3 Soil water content during the growing season of the four shelterbelt tree species

During the growing season, at the *P. simonii* Carr. site, the soil water content in the different layers exhibited the following trend: April>May>June>August>September. At depths ranging from 40 to 120 cm, the soil water content was much higher than that in the surface and deep soil layers, at 36% (Figure 4). At the *P. Russkii* Jabl. site, between the sand and farmland areas, the texture is mainly sand-free loam, water retention is relatively poor, and trees are watered by drip irrigation. Throughout the whole growth process, the soil moisture content in each layer was not high but could be maintained at 10%-20%, especially in August and September. When the soil moisture content was less than 10%, the soil water content reached 20%-30% at depths ranging from 60 to 120 cm. The soil water content was much higher in May and July. The soil water content was much higher in October, reaching 30% in the 90 cm soil layer above. At the *P. alba* site, the water content in the soil layer within 2 m varied greatly, whereas the soil water content below 2 m remained relatively stable. From May to June, it sharply decreased to 10% in the 60-140 cm layer. In the deep soil layer, the soil water content remained high, at 46%. *P. nigracv* grows on both sides of an antiseepage channel, and there is almost no irrigation. In April, the soil water content in the surface layer reached 30%, after which it decreased to 10%. The soil water content in the upper 60 cm layer was higher than that in the deep layer. At depths from 100 to 220 cm, the water content decreased to 5%.

The seasonal variation in the soil water content at the different shelterbelt sites under the different irrigation methods was obvious. As shown in Figure 5, the soil water content at the *P. alba* site sharply decreased from the start to the end of the growing season. At the *P. simonii* Carr. site, the soil moisture concentration slowly decreased. Under seasonal irrigation conditions, soil moisture at the *P. Russkii* Jabl. site fluctuated and remained in a state of equilibrium. At the *P. nigracv* site, the seasonal variation in soil moisture was not obvious, and the soil moisture content was maintained at a low level.

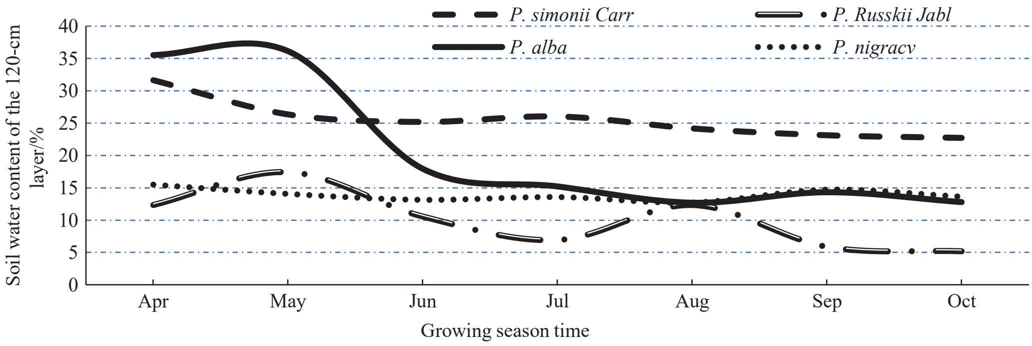


Figure 4 Changes in the soil water content during the growing season

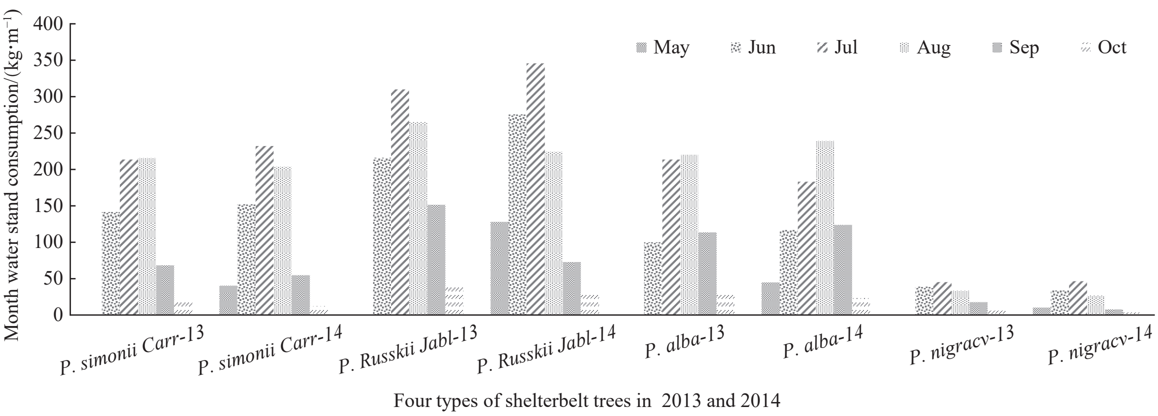


Figure 5 Stand transpiration of the four shelterbelt types

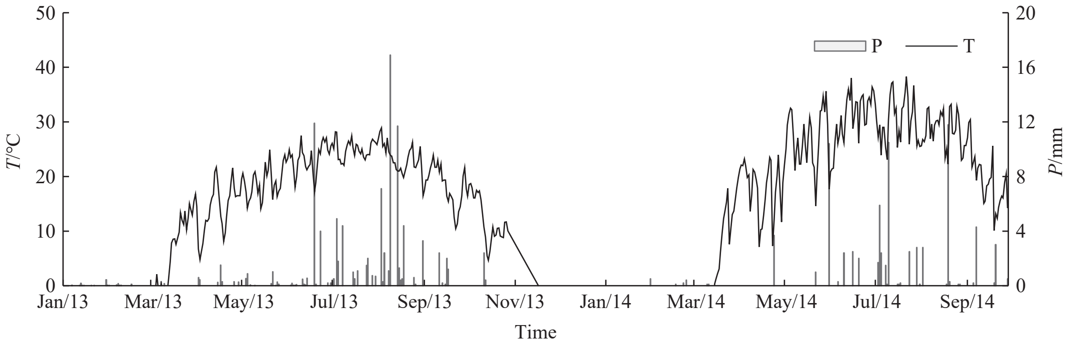
At the beginning of April each year, snow in Xinjiang has melted, the soil is no longer subject to freezing and thawing, and the shelter forest has begun to germinate and grow. Subsequently, tree transpiration increases with increasing leaf area. According to the leaf transpiration rate and leaf area, the water consumption of each shelterbelt tree stand during the growing seasons of 2013 and 2014 is shown in Figure 5. A higher air temperature amplified the shelterbelt transpiration rate. As the growing season progressed, the leaf area index of the shelter forest also increased, leading to an increase in the water consumption of the shelter forest. As shown in Figure 5, the shelterbelt stand consumption during each growing season was much higher in 2014 than in 2013. *P. Russkii* Jabl. is planted at the junction of the desert and oasis areas. The soil is sandy loam and is maintained by drip irrigation. A long-term dropper maintains young forests and moist soil, so the water consumption is relatively high. Especially in approximately July, the average temperature is the highest, the leaf area index reaches 2.4, and the water consumption ranges from 310 to 340 kg/m. *P. nigracv* not only exhibited low leaf transpiration but also the lowest stand transpiration among the shelterbelt species. Without irrigation replenishment, the decrease in groundwater and increase in seepage replenishment on the antiseepage side caused the soil moisture to decrease, eventually yielding a state of stress. Therefore, with the decreasing leaf area index, the leaf surface transpiration rate decreases, and with increasing temperature, the water consumption for transpiration remains low.

4 Discussion

4.1 Effect of meteorological variables on water consumption

Meteorological factors notably affect the growth of forest trees. They can not only restrict the growth of forest trees but also control the activity of leaf stomata, thereby regulating the transpiration and water consumption of forest trees. In addition, drought stress can increase soil evaporation, reduce the replenishment of soil water by plants and limit the growth and water consumption of forest trees. Rainfall during the 2013 and 2014 growing seasons reached 110.0 and 96.0 mm, respectively. The maximum rainfall amounts were 16.9 mm and 10.8 mm in August 2013 and August 2014, respectively. Considering that both the shelter forest canopy interception and evaporation are high at this time, effective precipitation is generally unavailable. Therefore, the water balance method was used to calculate the water consumption during the test phase without considering invalid precipitation data. During the growing seasons of 2013 and 2014, the air temperature increased from April to August and then decreased until the end of the growing season (Figure 6). A lower air temperature and higher precipitation were observed in 2013 than in 2014. The leaf area index and water consumption of the shelterbelts exhibited similar trends, increasing in April and decreasing in August.

Precipitation (P), air temperature (T), relative humidity (RH), solar radiation (Rn) and soil water content (SWC) restrict the water consumption process of shelterbelts. The correlation coefficients between the transpiration rates of *P. simonii* Carr., *P. Russkii* Jabl., *P. alba and P. nigracv* and precipitation were 0.729, 0.609, 0.666 and 0.353, respectively (Table 3), while the correlation coefficients between the transpiration rate and temperature were 0.836, 0.900, 0.739 and 0.636, respectively. All the shelterbelts exhibited positive correlations between water consumption and temperature, precipitation and solar radiation (Table 3). These results indicated that increased precipitation, temperature and solar radiation promoted water consumption of the shelter forest. Therefore, protected forests consume the most water in summer when rainfall, temperature and solar radiation are high. RH was negatively correlated with transpiration of *P. simonii* Carr., *P. Russkii* Jabl., *P. alba* and *P. nigracv*. Therefore, a high RH imposes an inhibitory effect on the shelterbelt water consumption. A high RH reduces the conductance activity of stomata, thereby reducing the transpiration rate of leaves and inhibiting transpiration. The soil water content was negatively correlated with the transpiration rate of *P. simonii* Carr. and *P. alba* and positively correlated with the transpiration rate of *P. Russkii* Jabl. and *P. nigracv*. Under normal circumstances, the soil moisture level is above or below saturation, as determined by the wilting coefficient, and an increase in soil moisture is conducive to plant transpiration and growth. *P. simonii* Carr. and *P. alba* were cultivated under irregular flood irrigation, which caused the soil moisture level to reach saturation, but the water consumption rate did not increase, so there was a negative correlation. However, under drip irrigation conditions, for *P. Russkii* Jabl. and *P. nigracv* grown without mechanical irrigation, with the increase of soil moisture, the transpiration and water consumption are also increased, so there existed a positive correlation, which further shows that these two shelterbelt species exist under a certain soil water stress.



Note: P: Precipitation; T: temperature

Figure 6 Precipitation and temperature variations in 2013 and 2014

Table 3 Spearman correlation analysis of the influencing factors and shelterbelt transpiration rate

Influencing factors	Correlation coefficient with transpiration rate of four shelterbelt species			
	P. simonii Carr.	*P. Russkii* Jabl.	*P. alba*	*P. nigracv*
P	**0.729****	0.609*	0.666*	0.353
T	0.836**	**0.900****	0.739**	0.636*
RH	–0.203	–0.369	–0.110	**–0.442**
Rn	0.711**	**0.852****	0.644*	0.707*
SWC	–0.215	0.065	–0.160	**0.261**

** indicates an extremely significant difference (p<0.01), and * indicates a significant difference (p<0.05).

The increase in effective rainfall promotes the water consumption of shelter forests, while the increase in temperature and solar radiation also accelerates water consumption by transpiration. *P. simonii* Carr. exhibited the highest correlation with precipitation, and *P. Russkii* Jabl. exhibited the highest correlation with temperature change and solar radiation. *P. alba* exhibited the highest correlation with the relative humidity and soil water content. According to the results, although the different environmental factors imposed similar effects on the different shelterbelts, there were differences in the degree of restriction of individual factors on the different shelterbelts.

Regarding the diurnal variation in the transpiration of the shelterbelt trees under the four configurations, transpiration peaked at 12 at noon and declined after 12 at noon because of the high air temperature at noon, and stomata were temporarily closed or reduced to preserve water; thus, vegetation transpiration peaked[32].

4.2 Effect of soil water content on water consumption

Detailed analyses of the soil water and leaf transpiration measurements provided accurate determination of the influences of both climate and soil water content on shelterbelt water consumption. From the beginning to the end of the growing season, the soil water losses in each shelterbelt tree stand were 358.1, 161.7, 674.8 and 336.9 kg for *P. simonii* Carr., *P. nigracv*, *P. alba* and *P. Russkii* Jabl., respectively (Figure 7). More than 96% of soil moisture originated from the soil layer within 2 m. At a depth greater than 2 m, the soil moisture content decreased to close to the wilting coefficient, so the contribution rate was low. For *P. nigracv*, during the whole growing season, 80% of the soil moisture originated from the 60 cm soil layer, and 16% of the soil moisture originated from the 60-120 cm soil layer. The shelterbelt water consumption was similar to that of irrigated maize, with the water consumption and water storage layers mainly comprising the middle and upper layers of root growth, respectively. The thickness of the water consumption layer of maize is approximately 100 cm, while that of the shelterbelt reaches 200 cm[33].

As the growing season progresses, not only do the solar radiation, temperature and relative humidity fluctuate but also the leaf area index, leaf transpiration rate, and water consumption of the shelter forest. Plant growth, leaf area changes, and leaf transpiration rates also fluctuated. The soil moisture content is a restricting factor. Sufficient soil water promotes the growth of shelter forests and increases transpiration water consumption. A reduction in soil water not only reduces the transpiration water consumption of shelterbelts but also limits the growth of shelter forests and produces a coercive effect, thereby restricting the development of shelter forests.

From April to October, the soil water content at the *P. simonii Carr* and *P. alba* sites exhibited a continuous downward trend. Both sites were irrigated by flooding, and at the beginning of the growing season, pressurized irrigation was conducted, followed by flood irrigation during the drier period. Due to irregular maintenance, irrigation was performed two or three times during the growing season. Therefore, in April and May, the soil moisture content is high, but the water consumption rate and water consumption of the shelter forest gradually increase. As leaves grow, the leaf area index increases, and the water consumption rate and water consumption gradually increase. The soil moisture content also continues to decline. *P. Russkii* Jabl. was irrigated by regular drip irrigation, and drip irrigation was performed once a month. Because the soil at the junction of the oasis and desert is mainly sandy loam, the soil moisture content is not high. Under the premise that the water content is guaranteed, the transpiration rate and water consumption of *P. Russkii* Jabl. remained high. The soil water content at the *P. nigracv* site was higher than that at the *P. Russkii* Jabl. site, but the water consumption was lower. Because the soil at the *P. nigracv* site is brown loam, the soil moisture content indicates a state of stress, so the transpiration water consumption remains very low. In the absence of irrigation and lateral infiltration, the soil moisture content is maintained at approximately 15% throughout the growing season.

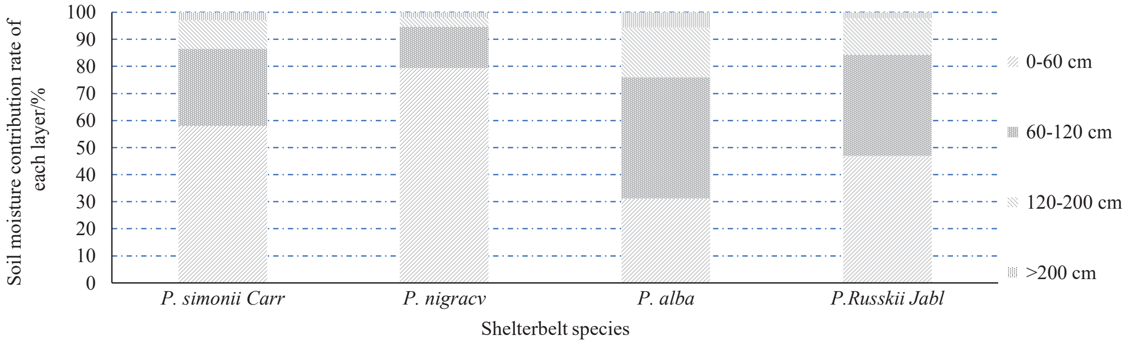


Figure 7 Soil water contribution of each layer at the different shelterbelt sites

Flood and furrow irrigation can instantaneously increase the soil moisture content, but these changes do not persist. During the two or three flood irrigation events in the growing seasons of *P. simonii* Carr. *a*nd *P. alba*, the soil moisture content almost returned to the state before irrigation within three days[34]. As the growing season progressed, water consumption and leaf transpiration peaked in July and June, respectively, and the soil water at the shelterbelt site sharply decreased. As indicated in Table 3, the soil water content was negatively correlated with tree transpiration in the flood irrigation shelterbelt and positively correlated with transpiration at the drip irrigation and non-irrigation sites. Flooding irrigation can sharply increase the soil water content, but under drought conditions, a high soil water content causes an increase in the transpiration and evaporation rates. Ultimately, the soil water content quickly decreases after irrigation (Figure 4). Before the implementation of drip irrigation, the supply of water to the shelterbelt around the farmland depends on water leakage from the irrigation canal system. However, after the comprehensive promotion of water-saving facility agriculture, most canal systems were abandoned or covered with impervious film, and shelterbelts were rarely irrigated, with an irrigation frequency of 2-3 times a year. Water-saving irrigation technology is fully adopted in the windproof sand forests outside oases, and irrigation water is limited. Coupled with the high temperature, high evaporation and poor water retention of sandy soil, drip irrigation water can hardly reach deep root parts, so the irrigation efficiency is low, and the water conditions of the forest belt are poor[35]. Therefore, at the *P. Russkii* Jabl. site, although the soil moisture content fluctuated before and after irrigation, it remained low, while at the *P. nigracv* site, a constant low soil moisture content was maintained, with no irrigation.

5 Conclusions

The results of this study showed that there were certain similarities and differences in water consumption among *P. Russkii Jabl*, *P. nigracv*, *P. alba* and *Populus simonii Carr*. The water consumption of all four tree species exhibited an obvious circadian rhythm and was positively correlated with solar radiation, air temperature and precipitation. However, it was negatively related to the air relative humidity. The leaf transpiration rate exhibited the following trend: *P. Russkii* Jabl.>*P. alba*>*P. simonii* Carr.>*P. nigracv*. Moreover, the average daily water consumption decreased in the order of *P. alba*>*P. Russkii* Jabl.>*P. simonii* Carr.>*P. nigracv*. The average daily water consumption levels of *P. alba*, *P. Russkii* Jabl., *P. simonii* Carr. and *P. nigracv* were 9.15±0.92 kg/(tree·d), 6.95±1.41 kg/(tree·d), 4.43±1.32 kg/(tree·d), and 1.58±0.18 kg/(tree·d), respectively. Over the growing season, the soil water consumption levels of *P. alba, P. Russkii* Jabl., *P. simonii* Carr., and *P. nigracv* in each shelterbelt tree stand were 674.8, 336.9, 358.1 and 161.7 kg, respectively. More than 96% of the soil moisture loss was provided by the 0-120 cm soil layer. At a depth greater than 2 m, the soil moisture content decreased to close to the wilting coefficient, so the contribution rate was low. By distinguishing the water consumption characteristics of different conservation shelterbelts and the water contribution rates of different soil layers, irrigation management of shelterbelts can be improved, and the drought resistance of shelterbelts can be enhanced by characterizing the meteorological factors and water consumption of shelterbelts.

Acknowledgements

This study was financially supported by the National Science Foundation (Grant No.42361003); the Opening Foundation of Xinjiang Key Laboratory of Water Cycle and Utilization in Arid Zone, the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (Grant No.XJYS0907-2023-22); Research Team of International Price Analysis and Prediction of Bulk Commodities, Jiangxi University of Finance and Economics; and the Postdoctoral Science Foundation of China (Grant No. 2017M612161).

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