Effects of drought stress on water consumption of poplar trees in an oasis shelterbelt of the Northwest China

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Abstract: The shelterbelt is an indispensable component of the oasis ecological system. However, drought stress can cause a large-scale decline in oasis shelterbelts. In this study, meteorological data, sapflow and soil moisture were measured to analyze the effect of drought stress on the water consumption of the oasis shelterbelt in the northwest China. Results showed that the most critical factor affecting the water consumption of an oasis shelterbelt is solar radiation, followed by relative humidity, temperature and precipitation, while the weakest factor is rainfall. Water consumption increases with solar radiation and air temperature rising, decreases with relative humidity increasing. A power index relationship between *Poplar* water consumption (*Tr*) and soil volumetric moisture content (*SW*) was found, which is expressed as follows: $Tr=11.52/[1+e^{(-0.609SW+13.17)}]$. Meteorological and soil drought stress severely restrict oasis shelterbelt water consumption. An improved understanding of the relationship between water consumption and drought stress in oasis shelterbelts would be beneficial for irrigation managements.

Keywords: oasis shelterbelt, water consumption, irrigation management, drought stress
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1 Introduction

Oasis shelterbelts play an important role in the oasis ecosystem, are plantation forest ecosystems that are designed to prevent natural disasters, improve climate and soil moisture conditions, create an environment conducive to crop growth, ensure high and stable yields in agriculture and animal husbandry, and contribute in a variety of ways to maintaining or increasing human living standards. Oasis shelterbelts have a significant effect on oasis microclimates and the stability of agricultural production, and Oasis represent important maintenance barriers for agricultural ecological security in oasis in China’s arid regions. They improve the climate conditions near the ground, reduce or eliminate damage caused by wind and sand, promote the restoration of vegetation, and improve oasis productivity. On the edge of the oasis, there is a large-scale basic windbreak, a sand-control shelterbelt, and a sand-enclosing belt[1,2]. Climate change, environmental deterioration, and shelterbelt decline have become challenging issues worldwide[3]. Because of the rapid development of agriculture, oasis shelterbelt resources have been drastically reduced. Soil erosion, water resource depletion and environmental degradation have become more serious. One effective means to address such problems is to construct oasis shelterbelts. In fact, many countries have successively carried out the large-scale construction of oasis shelterbelts, and China is the largest country to create such oasis shelterbelts[3]. There is a substantial amount of scientific research on the protective effects of oasis shelterbelts, and many scientific research achievements have played an active role in agricultural production practices.

The soil-plant-atmosphere-continuum is a complex interaction system in arid-area oasis. Such areas frequently experience insufficient precipitation, and irrigation water and shallow groundwater reserves are inadequate to recharge the soil water, which is the main source of water for plants. At present, there has been a significant decline in oasis shelterbelts[4], for which there are many reasons. First, the amount of irrigation water available for shelterbelts has been limited by the increasing area of arable agricultural land in recent years[5,6]. Second, the shallow groundwater supply capacity has been weakened by overdrawing groundwater. Third, significant climate change has restricted shelterbelt construction[7].

This study investigates the water consumption patterns of an oasis shelterbelt to determine the water consumption of the shelterbelt under different water stress and meteorological conditions. In addition, a method is developed to calculate water consumption in oasis shelterbelts. Finally, we provide a strong scientific management basis and a reasonable irrigation management model for oasis shelterbelt protection. Understanding the water consumption mechanism of the oasis shelterbelt should benefit the socially sustainable economic development of oases and contribute to the stable development of the oasis ecology.

2 Materials and methods

2.1 Study site

The experimental site is located in the oasis shelterbelt of Shihezi irrigation test field (44.27°N, 85.94°E), Manas oasis in Xinjiang, China. The annual precipitation in the lowland and hilly

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areas is 344-428 mm. Precipitation in the piedmont plain is 197 mm, and annual precipitation in the dry delta near the edge of the desert is 108 mm. The average annual evaporation at the study site is 1500-2100 mm[8]. Manas accounts for 18.31% of the total cotton planting area in Xinjiang[9,10].

2.2 Data collection and analysis

In the oasis, three trees with different diameter at breast height (DBHs) with good growth in the oasis shelterbelt were selected to study. The tape measure was used to measure the perimeter of the tree and then converted it to DBH. A growth cone was used to collect core material and sapwood of the sample trees in the forest. Then measure the sapwood radius, core material radius and tree breast diameter by Vernier caliper. Leaf area index was measured by LAI2000. Soil moisture probes were installed from 0 to 120 cm to collect soil moisture data. To determine the factors that affect oasis shelterbelt growth regulation in the oasis, sapflow and soil moisture were measured from May to October. TDP probe instrument was used to measure the sapflow of the sample trees. The data collection was set to record in each 20 min (synchronized with the meteorological data record). Meteorological data was collected from Shihezi weather station. Solar radiation, temperature, precipitant, relative humidity and wind speed data were collected. The monthly sapflow and water consumption were calculated by each month averaged. Statistical analysis and mapping of the experimental data were performed using Microsoft Excel, Origin and SPSS statistical software.

3 Results and discussion

3.1 Intraday changes in the poplar sapflow rate

The leaf area index of the studied poplars increased from May, peaked in June, slightly decreased from July to August, and reached the late growth stage from September to October, when the leaf area index rapidly decreased. July and August have similar sapflow peak and change characteristics, and the sapflow decreased rapidly since October. Typical days from the beginning to the end of the growth period were chosen to describe the variation in the poplar sapflow rate at different DBHs for different growth periods. Figure 1 is a comparative analysis of daily changes in sapflow rates of poplars based on DBH for different growth seasons. Changes in the sapflow of poplars with different diameters at breast height show the same fluctuation pattern. The diurnal flow variations in May, June and September are of the unimodal type, while in July, there are two peaks. For a poplar with a breast diameter of 20.6 cm, the sapflow peaks at 11:00 and 17:00 were 1.1×10^{-3} cm/s and 1.2×10^{-3} cm/s, respectively. From May to September, the daily sapflow rate showed a trend of increase, peak, and decrease. As shown by the 25.1 cm diameter tree, the flow was regular, with one peak in May, June, July and September (1.2×10^{-3} cm/s, 2.5×10^{-3} cm/s, 1.5×10^{-3} cm/s, and 1.25×10^{-3} cm/s, respectively). As the growing season progressed, night-time sapflow gradually increased from July to September, the inter-day flow gradually decreased, and the proportion of night-time sapflow increased with the growing time. The production of night-time flow is generally believed to be due to the water potential difference between canopy, trunk and root[11]. Stomatal closure occurs after sunset, and the water potential difference generated at this time does not immediately disappear due to poor water potential. At a certain time during the night, soil enters the trunk through the roots to compensate for a lack of water in the trunk. This restoration of the water balance in the plant resulted in a night-time sapflow. In certain trees, the amount of night-time replenishment reached 7.22% of the water evapotranspiration[12].

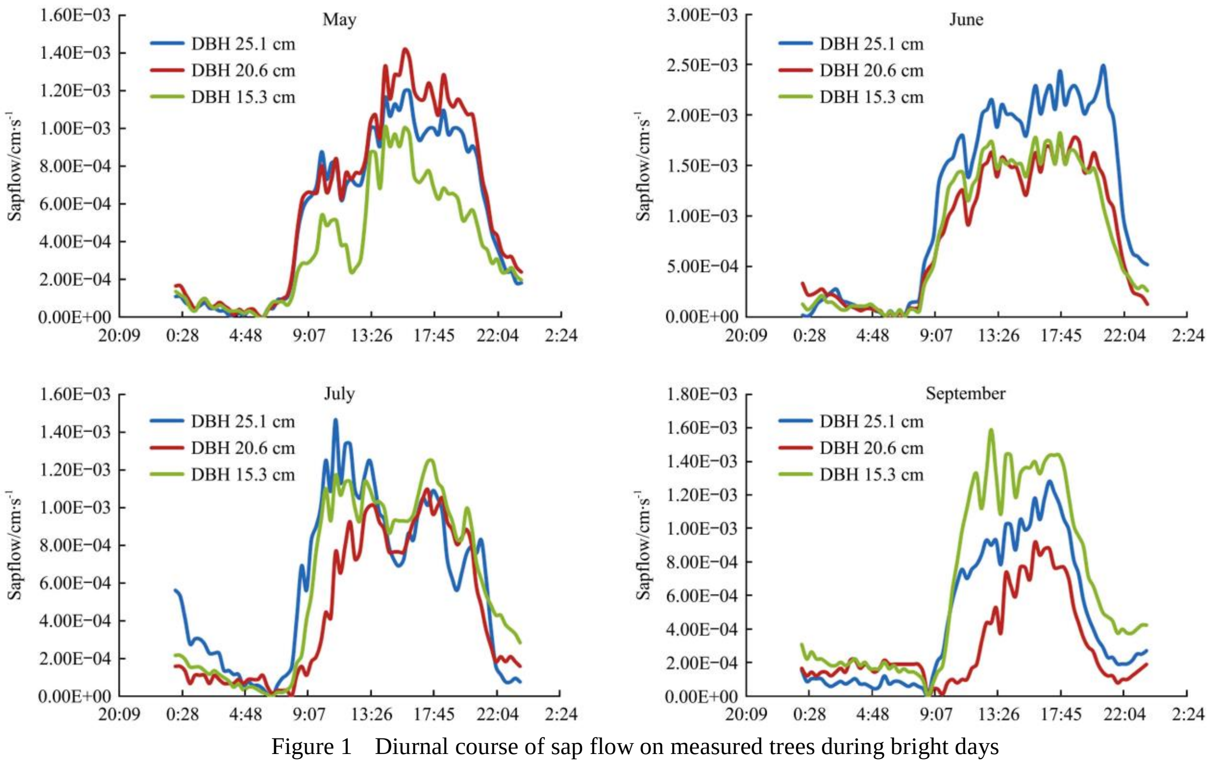


Figure 1 Diurnal course of sap flow on measured trees during bright days

In May, the soil moisture condition was adequate, and sapflow at each DBH exhibited unimodality. The highest sapflow rate was observed in a tree with a DBH of 20.6 cm (1.54×10^{-3} cm/s), followed by in a tree with a DBH of 25.1 cm (1.23×10^{-3} cm/s). In June, the poplars were in an energetic growth period. The leaf area index was greater than 1 and reached the maximum value. At the same time, the sapflow rate of the tree with the largest DBH was the highest, and there was little change in sapflow in the 20.6 cm and 15.3 cm DBH trees. In July, the same trend as in June was observed. The tree with the largest DBH exhibited the highest sapflow density, and there were small differences in sapflow among trees with different DBHs. At the end of the growth period in September, the maximum sapflow rate was observed in the 15.3 cm DBH poplar, followed by the 25.1 cm DBH poplar. During the entire growing season, the diurnal variation of the sapflow rate showed a typical single- or double-peak curve, and there was weak night-time flow throughout the growing season. As the growing season progressed, soil moisture decreased, and night-time flow appeared to become gradually more apparent.

3.2 Seasonal changes in poplar sapflow rate

Figure 2 shows the average daily sapflow of poplars with different DBHs in the oasis shelterbelt. Sapflow varies with a changing leaf area index. In May, the sapflow increased and then entered a continuously decreasing period. In middle and late June, the sapflow rate increased quickly and entered a period of sustained decrease. In late July, the sapflow showed a slight increase, and in August and September, the sapflow rate changed little in the late growing season. The changes in sapflow rate, leaf area index and soil water content maintained the same trend. This outcome indicates that soil moisture and leaf area index played important regulatory roles in water consumption in the oasis shelterbelt. The stem sapflow rate was also closely related to the leaf area index[13]. The leaf area index of the studied poplars increased beginning in May, peaked in July and gradually decreased over the later growth period.

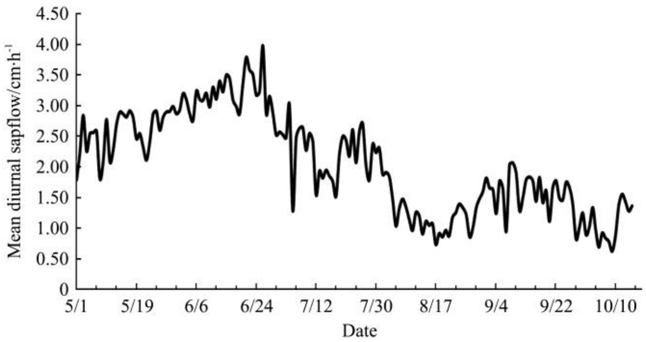


Figure 2 Mean diurnal sapflow velocity on a sapwood-area basis (SFD, cm/h) for different DBH populus trees during the growing season

Considering the 25.1 cm poplar as an example, when soil moisture was sufficient in early May, the leaf area index gradually increased, and the average daily flow rate was 3.6 cm/h. With a decrease in soil moisture and leaf area index, the sapflow rate decreased to 0.79 cm/h. After deficit irrigation, the poplar sapflow rate quickly rebounded to 2.39 cm/h. After full irrigation, the flow rate reached 4.61 cm/h. From July to September, the sapflow rate and soil moisture continuously decreased. During the entire growing season, the average daily sapflow rate of the poplars showed an alternating process according to DBH. When water was abundant, a higher sapflow rate appeared in the larger DBH poplars, and the soil water deficit was more severe. In contrast, the performance was reversed in the smaller DBH poplars. There was no significant correlation between sapflow and DBH. However, a significant correlation was found between sapflow and soil moisture. Therefore, soil moisture and leaf area index play more important roles in the poplar sapflow rate.

3.3 Water consumption characteristics of an oasis shelterbelt

Although the sapflow rate of poplar sapwood in the oasis shelterbelt did not change significantly with tree diameter, there was an overall change in the leaf area index over the entire growth season (Figure 2), and the seasonal water consumption of the studied poplars exhibited the same trend (Figure 3). The poplar water consumption was directly proportional to DBH, and the larger that the DBH was, the stronger the seasonal variability in water consumption was (Figure 3). After watering in mid-June, the water consumption of the 25.1 cm and 20.6 cm DBH poplars increased significantly, while the transpiration water consumption of the DBH 15.3 cm poplar remained steady. The canopy area of the poplars in the oasis shelterbelt increased with increasing DBH, and their leaf area was proportional to their DBH. Under the same climatic conditions, when the soil water condition is sufficient, the transpiration water consumption inevitably increases substantially. When the DBH is small, the leaf area is also small, therefore, it exhibited little response to soil moisture changes.

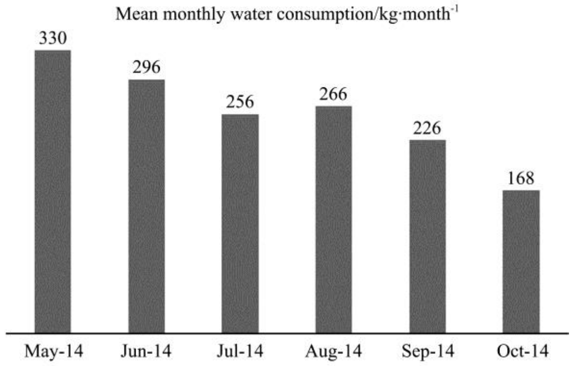


Figure 3 Mean monthly tree water consumption in the oasis shelterbelt

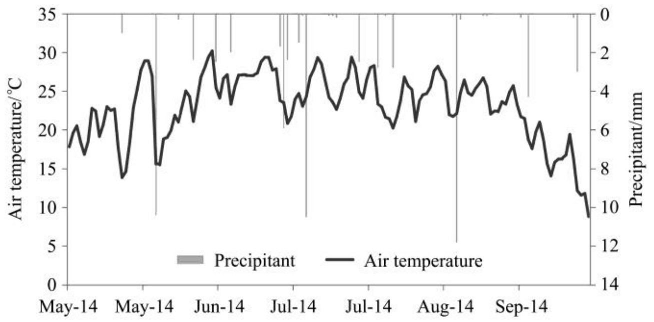
The water consumption of the shelterbelt poplars varies substantially with each day and according to month, season and year (Figure 3). Throughout the growing season, the highest single-day water consumption was 29 kg/d by the DHB 25.1 cm poplar after strong irrigation in June, while the lowest appeared in the DHB 15.3 cm poplar in late October (2.57 kg/d). In the oasis shelterbelt, monthly water consumption was 330 kg/month in May. It decreased to 168 kg/month from June to October. During the entire growing season, the air temperature increased from May to July and decreased from July to October. The oasis shelterbelt water consumption was consistent with the air temperature change. As shown in Figure 3 and Figure 4, the sapflow rate and transpiration water consumption increased with increasing air temperature, while the increase in precipitation did not have an obvious effect on transpiration water consumption (Figure 4a). An air temperature increase will promote stomata activity. When the temperature is at an extreme value, the stomatal activity will increase with the temperature increase. Then, the high transpiration rate of the leaves will increase water consumption. A rainfall increase inevitably increases the relative air humidity, which results in a corresponding closure of the stomata and a tendency to decrease the transpiration of the foliage. Therefore, air temperature and precipitation showed different correlations with poplar water consumption in the oasis shelterbelt.

3.4 Water consumption characteristics of an oasis shelterbelt

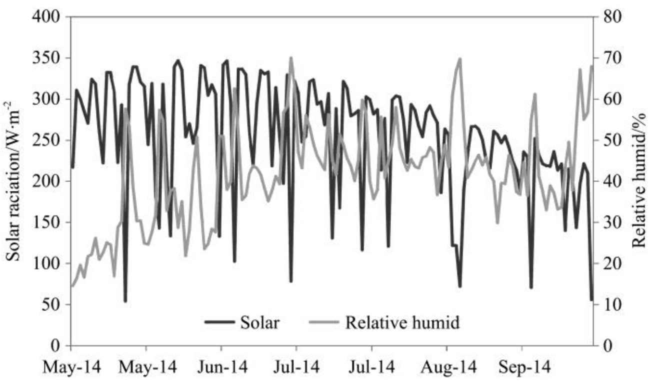
3.4.1 Effect of meteorological factors on oasis shelterbelt water consumption

Air drought stress refers to the phenomenon that plants lack water due to special meteorological reasons such as excessively high atmospheric temperature, low relative humidity, and dry hot wind. Atmospheric drought restricts the growth and transpiration of forest trees[14,15].

Due to the rhythmic changes of the external environmental conditions and stomatal movement, the water consumption of the poplars changed regularly. Environmental factors affected the transpiration rate of the poplar leaves, and they affected shelterbelt water consumption in various ways. Daily changes in environmental factors (e.g., air temperature, relative humidity, effective radiation, and precipitation) are shown in Figure 4. Air temperature exhibited the same change trend as shelterbelt water consumption. It increased in May, maintained a peak in June and then decreased until September (Figure 2 and Figure 3). During the growing season, precipitation heavier than 5 mm occurred only four times, with two occurrences in July of 6 mm and 11 mm (Figure 4a). Relative humidity gradually increased as the growing season progressed, while solar radiation showed the opposite pattern (Figure 4b). In the absence of irrigation, the transpiration water consumption of the oasis shelterbelt poplars increased with increasing temperature and solar radiation and decreased with increasing relative humidity.



a.



b.

Figure 4 Environmental conditions during the growing season

Temperature, solar radiation, air humidity and precipitation affected the sapflow rate and the water consumption of the poplars in the oasis shelterbelt. According to a correlation analysis of water consumption and the daily environmental factors on non-irrigation days (Table 1), there was a significant positive correlation between water consumption and solar radiation, the correlation coefficient was 0.75 ($p=0.01$). Water consumption exhibited a negative correlation with precipitation and relative humidity, the correlation coefficients were –0.19 and –0.42, respectively ($p=0.01$). There was a positive correlation between temperature and water consumption (the correlation coefficient reached 0.53, $p=0.01$). The correlation analysis revealed that the transpiration water consumption of the oasis shelterbelt poplars increased with increasing solar radiation, temperature and wind speed. It decreased with decreasing air relative humidity and increasing precipitation. Solar radiation, temperature and wind speed promoted poplar transpiration and accelerated sapflow, while the relative humidity of the air had an inhibitory effect.

Table 1 Pearson correlation matrix for meteorological factors and tree water use of the oasis shelterbelt

	Tr	*T*	*RH*	*Pr*	*SR*
Tr	1				
T	0.53**	1			
RH	–0.42**	0.31	1		
Pr	–0.19**	–0.12	0.42**	1	
SR	0.75**	0.32**	–0.30**	–0.12	1

Note: * Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed). *Tr*: Transpiration; *T*: Temperature; *RH*: Relative humidity; *Pr*: Precipitation; *SR*: Solar radiation.

In a multiple linear regression analysis, the relationship between transpiration (*Tr*) and temperature (*T*), relative humidity (*RH*), precipitation (*Pr*), and solar radiation (*SR*) was as expressed in the following equation:

$$Tr=0.041T-0.026RH-0.147Pr+0.031SR+3.22,\ R^2=0.91 \quad (1)$$

The equation is good for simulating transpiration and water consumption in the oasis shelterbelt and achieved a high R^2 value. The regression analysis also revealed that precipitation and air relative humidity were negatively correlated with transpiration and water consumption in the oasis shelterbelt.

3.4.2 Effect of soil moisture on oasis shelterbelt water consumption

Soil water drought refers to the drought caused by soil moisture that cannot meet the needs of plant roots for absorption and normal transpiration[16,17]. Soil moisture is an important factor that affects the transpiration of trees, particularly in an arid-area oasis environment. Soil water content plays an important role in controlling stomata activity and transpiration. The stomata are the primary means to control leaf transpiration and tree water consumption. When there is soil water stress in the area, it causes stomatal closure, which drastically decreases the transpiration rate. The order of water consumption at different levels of soil water stress in the oasis shelterbelt is adequate water > moderate drought > severe drought. The highest water use efficiency is under moderate drought, and the lowest is under severe drought. The water consumption of poplars under suitable moisture conditions is significantly higher than during moderate and severe droughts. Water use during the day varies significantly with the duration of poplar growth and with soil moisture[18]. When the soil water supply is sufficient, the transpiration of poplars is primarily determined by their physiological and biological characteristics and external weather factors. When the soil water supply is insufficient, the transpiration is largely affected by soil moisture content[19,20]. Li-1600 is typically used to measure stomatal conductance and to determine the transpiration rate of forest trees under different soil moisture conditions. The relationship between transpiration rate and soil water content is expressed by the following equation: $y=ax^3+bx^2+cx+d$ (y: transpiration; x: soil water)[21,22]. It can be observed that the transpiration water consumption increases with increasing soil moisture. In this study, a linear regression was performed on the soil water content in the 0-120 cm layer and transpiration. The results show a close relationship between soil moisture and transpiration water consumption (Figure 5). A power index relationship exists between the transpiration water consumption and the 120 cm soil volume moisture content and is expressed as follows: $Tr=11.52/[1+e^{(-0.609SW+13.17)}]$, ($R^2$=0.91), (*Tr*: daily transpiration water consumption, kg/d; *SW*: volumetric moisture content of soil in the 120 cm layer, cm^3/cm^3).

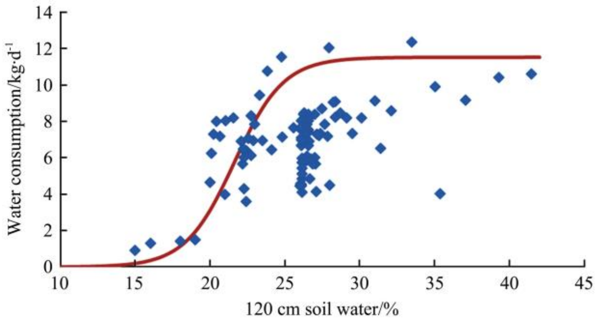


Figure 5 Relationship between the transpiration of the oasis shelterbelt and soil moisture in the root profile

Many factors influence the transpiration water consumption of a oasis shelterbelt. For example, tree species, physiological characteristics of the oasis shelterbelt and environmental factors result in sapflow rate variation in oasis shelterbelt poplars[23]. Under normal conditions, transpiration decreases with increasing soil drought stress. When heavy drought stress occurs, water consumption can be reduced to 11.7% of normal water conditions, while other conditions can decrease it to 6.6% of normal[24]. Meteorological conditions and soil water are important factors for plant water consumption[25], and many experimental studies on precipitation have shown that precipitation is an important factor for plant water consumption[26]. Precipitation can change the surrounding environment of the trees and the soil's drought index, thereby affecting stomata activity and regulating forest tree water consumption by controlling transpiration and water consumption through the opening and closing of the stomata[27]. In arid environments, stomatal conductance decreases with decreasing hydraulic conductivity[28]. In addition, groundwater is a key factor that affects the sapflow of wood and sapwood as well as transpiration water consumption[29]. Recent research on the supply of groundwater to plants has primarily focused on the shallow water of riparian forests in arid areas[30]. Certain scholars have used models to simulate the response of groundwater to water consumption in valley forests in arid areas[31]. Studies have shown that the flow density of forest trees increases with an increase in groundwater level[32], and other investigations have found that sapflow is not related to groundwater level but to the biomass of forest trees and decreases when the available groundwater decreases[33].

4 Conclusions

The oasis shelterbelt is an important component of oasis agriculture and oasis ecology. Air drought stress and soil water drought stress restrict oasis shelterbelt management and development. The sapflow rate of poplars, which represent the main species in oasis shelterbelts, is closely related to leaf area index, soil moisture and meteorological factors. The most important factor that affects the water consumption of oasis shelterbelts in oases is solar radiation, followed by relative humidity, temperature, and wind speed, while the weakest factor that affects this consumption is precipitation. Water stress has a power exponent relation to the water consumption of oasis shelterbelts in arid areas. When the soil moisture content is less than 20% (i.e., drought stress), the shelterbelt water consumption drastically decreases. The meteorological elements and drought stress caused by inadequate soil moisture significantly restrict the water consumption of oasis shelterbelts in oases. The analysis and study of the influence factors and the relationship between the transpiration water consumption of poplars in oasis shelterbelts and drought stress can assist in the implementation of irrigation management measures for oasis shelterbelts and provide a theoretical basis for the protection of oasis ecosystems.

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