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Relating Water Use to Tree Vitality of *Populus euphratica* Oliv. in the Lower Tarim River, NW China

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Received: 4 June 2017; Accepted: 17 August 2017; Published: 19 August 2017

Abstract: This study aimed to compare the hydraulic characteristics of different vitalities of *Populus euphratica* to reveal the differences in their water use strategies and water consumption to provide useful data to scale water use of riparian poplar forests in the lower reaches of the Tarim River, Northwestern China. Our results showed that the sapwood area of *P. euphratica* could be estimated based on its correlation with tree biometric parameters. The sapwood area of vital poplars tended to be larger than the senesced poplar despite both having the same diameter at breast height. This indicates that poplar vitality should be taken into account when estimating its sapwood area. Therefore, we established two different sapwood area estimation models for vital and senesced poplar (sapwood area = 1.452 × DBH$^{1.553}$, R^2 = 0.891; sapwood area = 0.915 × DBH$^{1.618}$, R^2 = 0.718; DBH: diameter at breast height). The sap flow process of vital and senesced poplar had certain differences and similarities; the average diurnal sap flow velocity and water consumption of vital poplar were 15.85 cm/h and 45.95 L, respectively; for the senesced poplar, it was 9.64 cm/h and 18.17 L, respectively, which were smaller than that of vital poplars. The influence of environmental factors on the sap flow velocity of two different *P. euphratica* was similar; the sap flow of both vital and senesced poplar had positive correlation with air temperature (R^2 = 0.800 and 0.851), solar radiation (R^2 = 0.732 and 0.778), vapor pressure deficit (R^2 = 0.508 and 0.643) and groundwater depth (R^2 = 0.301 and 0.171), while negative correlation with air humidity (R^2 = −0.313 and −0.478).

Keywords: *Populus euphratica*; tree vitality; sapwood area; water consumption; environmental factors

1. Introduction

Heterogeneous environmental conditions influence the hydraulic characteristics of vegetation. Water availability is one of the most important factors influencing the growth and development of plants [1]. Related studies have indicated that the structure of the plant hydraulic system has the potential to limit water flow through its body, thus restricting its water balance, and eventually its growth [2]. Therefore, studying the differences in the hydraulic characteristics of plants of different vitality may help us understand the influence of water availability on tree growth.

The Tarim River, located along the northern rim of the Taklamakan Desert in the Xinjiang Uighur Autonomous Region, Northwestern China. It is one of the longest inland water ways in the world along with the Volga, Syr Darya, Amu Darya, and the Ural [3–6]. The riparian forests at the Tarim are an important ecosystem which plays a key role in maintaining the structure, function and stability of the arid ecosystem [7,8].

Populus euphratica Oliv. is a rare, ancient, and endangered tree species which forms the floodplain forest ecosystem in inland river basins in central Asian arid regions [9,10]. Given its high capacity against environmental stressors, e.g., saline, high temperature, drought and sand storms, it plays an irreplaceable function in these areas [11–14]. However, due to the irrational water allocation along the upper and middle reaches of the Tarim River, the lower reaches (ca. 320 km) has been cut off since 1970. This has resulted in a decrease in the groundwater level along the lower Tarim [4,15,16], and the eventual degradation of the riparian ecosystem [6,12,17,18]. Since 2000, the Ecological Water Diversion to the lower Tarim River was started to restore the degraded ecosystem of this region, and a number of studies have shown that the riparian forest has demonstrated a positive response to the water diversion [12,13,19,20].

However, in terms of water shortage in this region, the insurance of long-term water transferring and the virtuous cycle of ecological environment depends on the rational and efficient usage of limited water resources, which includes the scientific allocation of water for irrigated agriculture, nature and ecosystem conservation, as well as for industry, oasis settlements and human well-being [4,21–24]. Therefore, it is important to estimate the water use of riparian forests in the lower Tarim River for providing scientific reference to the water management authorities. Different upscaling methods have been reported for estimating the water use of poplar forests [25–27]; however, these methods did not consider the vitality of poplar trees.

The objectives of this study were to assess and compare the hydraulic characteristics of *Populus euphratica* of different vitalities by monitoring the diurnal changes of its sap flow during hot sunny days, measuring and estimating the area of water conducting tissue, as well as analyzing the correlation between sap flow velocity and environmental factors. These experiments were carried out on poplar trees of different vitalities growing at two sites with different groundwater conditions. There is evidence from the literature that the sapwood area of the poplar tree can be estimated based on the correlation between the sapwood area and tree biometric parameters [25,27]; furthermore, the water consumption of poplar trees at stand level could be obtained by upscaling methods based on the sap flow measurement of sample trees [26,28], but little information is available regarding the water consumption of poplar trees at different vitalities. This knowledge is of particular importance when estimating whole tree water usage in this region more accurately.

2. Materials and Methods

2.1. Study Area

The study area was located at the lower reaches of the Tarim River (Arghan, 40°08′50″ N, 88°21′28″ E), between the Taklamakan and Kuruktagh Deserts in the southern part of the Xinjiang Uighur Autonomous Region, Northwestern China (Figure 1). The region is within an extremely arid warm temperate zone, with an annual precipitation from 17 to 42 mm and a potential evaporation of approximately 2500–3000 mm [4,11,17], rendering this area one of the most hyper arid places in the world [10,27,29]. The average groundwater depth beside the riverbank is low, thus can only support vegetation types with a higher drought resistance [29,30]. Therefore, desert riparian vegetation has a relatively simple structure along the river. The main tree species are *Populus euphratica* Oliv., *Elaeagnus angustifolia* L; and the main shrubs are *Tamarix hispida* Willd., *Tamarix elongata* Ledeb., *Tamarix ramosissima* Ledeb., *Halimodendron halodendron* (Pall.) Voss., *Lycium ruthenicum* Murr., *Karelinia caspica* (Pall.) Less., *Hexinia polydichotoma* (Ostent.) H.L., *Inula salsoloides* (Turcz.) Ostrnf., *Phragmites communis*, *Poacynum hendersonii* (Hook. F.) Woodson., *Halostachys caspica* (M.B.) C.A. Mey., *Alhagi sparsifolia* (B.Keller et Shap.) Shap. and *Glycyrrhiza inflate* Bat. [10–12,16].

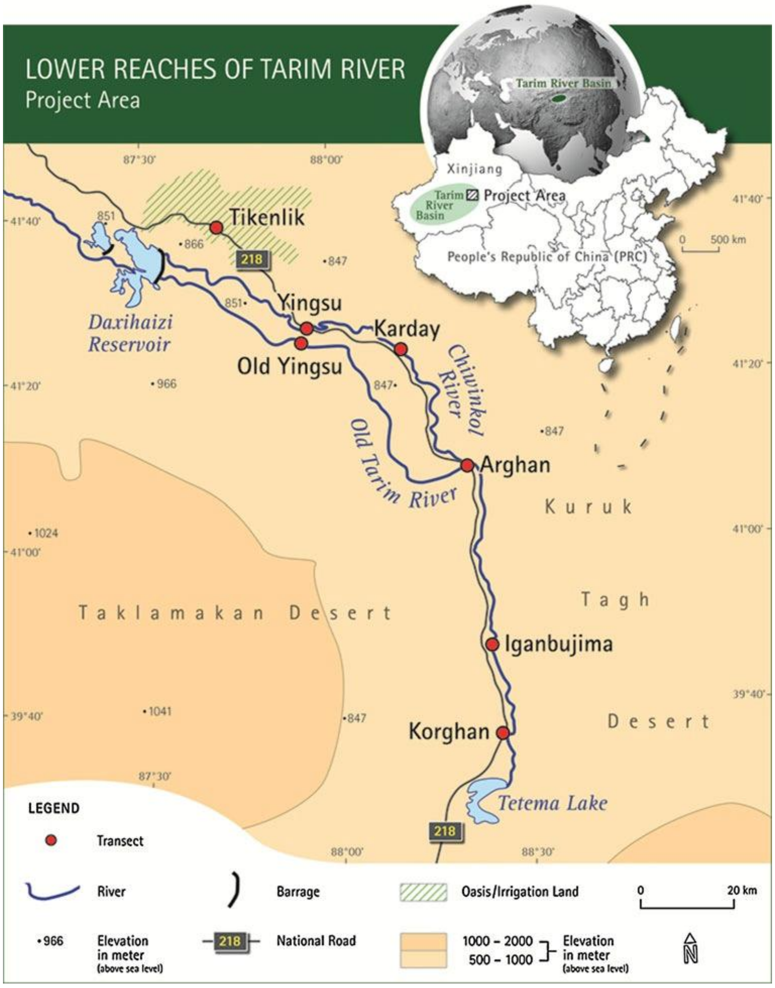


Figure 1. The lower reaches of the Tarim River and the study area Arghan [10].

2.2. Sample Selection and Measurement

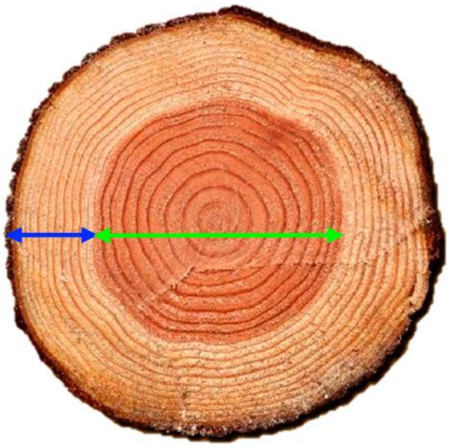
Based on the vitality classification criteria of Halik et al. [12] and Aishan et al. [20], *Populus euphratica* of different vitality status were chosen. Vital poplar sample trees were located at 40°08′44″ N, 88°20′59″ E; senesced poplar trees were located at 40°08′07″ N, 88°21′44″ E. Three sample trees were selected from each plot to run sap flow measurements. Sapwood samples were taken from 91 vital *P. euphratica* and 78 senesced *P. euphratica* using an increment borer, in addition, their biometric parameters (DBH: Diameter at breast height, CD: Crown diameter and TH: Tree height) were measured to run modeling analysis for estimating the sapwood area and model validation. Table 1 shows a summary of the statistics of the poplar trees used for sapwood sampling.

Table 1. Summary statistics of poplar trees with vital and senesced growth status.

Tree Parameters	DBH (cm)		TH (m)		CD (m)		Sapwood Area (cm^2)	
Vitality Status	**Vital**	**Senesced**	**Vital**	**Senesced**	**Vital**	**Senesced**	**Vital**	**Senesced**
Number of samples	91	78	91	78	91	78	91	78
Average	21.5	21.2	8.3	6.5	4.9	4.4	175.6	130.8
Max	53.1	35.4	13.0	10.0	8.5	7.2	822.5	332.6
Min	7.4	9.0	2.6	2.9	2.0	1.8	18.4	18.2

Note: DBH = diameter at breast height, TH = tree height, CD = crown diameter.

To calculate the sapwood area of the poplar stem, we assumed that the tree stem was circular, that the sapwood and the inner wood areas were in the shape of concentric circles, and the outer circle represented the sapwood area (Figure 2a). The sapwood of *P. euphratica* is easy to differentiate from the inner wood when the sample is fresh (Figure 2b), and can usually be observed with the naked eye.



(**a**)

(**b**)

Figure 2. Sapwood and inner wood of the tree stem where (**a**) the blue colored part is the sapwood, and the green colored part is the inner wood; (**b**) the white area on the left is the sapwood, the dark area on the right is inner wood of *P. euphratica*.

The following equation is for calculating the sapwood area:

$$\text{sapwood area} = \pi \times \frac{\mathrm{d}}{2}^{2} - \pi \times \left(\frac{\mathrm{d}}{2} - \text{sapwood depth}\right)^{2} \tag{1}$$

where π is the mathematical constant (3.14), and d is the diameter of tree at breast height.

2.3. Sap Flow Measurement

A SFM1 sap flow meter (ICT, Armidale, NSW, Australia) that utilized the heat ratio method (HRM) was used to record heat pulse velocity (*Vh*) at 15 min intervals for the period from 1 to 10 September 2015. The installation and sensor design were identical to descriptions provided in Pfautsch et al. [31] and Keyimu et al. [32].

2.4. Meteorological Data

Meteorological parameters, such as R_s (solar radiation), T_a (air temperature), *RH* (air humidity) were collected from the corresponding sensors (Watchdog 2000, Spectrum Co. Ltd., Selmer, TN, USA). The parameters were recorded at 1 h intervals; data read out was completed using Spec ware software. Vapor pressure deficit (*VPD*) was calculated using the following equation [33]:

$$VPD = \left(1 - \frac{RH}{100}\right) \times ea^{*} \tag{2}$$

where *RH* is air humidity, *ea** is vapor pressure. *ea** is obtained using the following equation [34]:

$$ea^{*} = a \times EXP^{\left(b \times \frac{Ta}{Ta+c}\right)} \tag{3}$$

where *Ta* is air temperature, and the values of parameters *a*, *b*, and *c* are 0.611 kPa, 17.502, and 237.3 °C, respectively.

2.5. Groundwater Data

The groundwater depth (*GWD*) measurement was carried out simultaneously with sap flow measurement using a Diver data logger (Schlumberger Limited, Paris, France) at two different sites. Logger installation, sensor design and measurement principles were provided in detail in Keilholz et al. [24,35].

2.6. Data Processing

A sap flow tool (ICT International, Armidale, NSW, Australia) was utilized to process the raw sap flow data, calculate the sap flow velocity, and water consumption. The number of trees and their biometric parameters data as well as sapwood area calculation were processed by Microsoft Excel 2015 software. Sapwood area estimation models for both vital and senesced *P. euphratica* were created by selecting the sapwood area as a dependent variable, and DBH, crown diameter, and tree height as the independent variables. Regression models between sap flow and meteorological parameters were established by selecting the *VPD*, *RH*, *Ta*, *Rs*, and *GWD* as the independent variables and sap flow rate as the dependent variable. Modeling analysis was carried out using the SPSS statistical tool 20.0 (IBM, Armonk, NY, USA). Paired *t*-test was conducted for validating the sapwood area estimation model at $p \leq 0.05$ significance level. All plotting was carried out on Microsoft Excel 2015.

3. Results

3.1. Sapwood Area of P. euphratica with Different Vitality

In the first plot, the results showed that DBH and sapwood area could be modeled at higher R^2 when compared to other biometric parameters (Figure 3), $R^2 = 0.901$, $n = 48$. In the meantime, the sapwood area of the rest of the trees was measured. The *t*-test result showed that there was no significant difference between the model's estimated value and the measured value ($n = 43$) of the sapwood area ($p > 0.05$) (Figure 4). Therefore, the estimation value of power function model was reliable, and could be used for estimating the sapwood area.

However, the performance result of the first model (which was established based on the biometric parameters of vital poplars) was not reliable when it was used to estimate the sapwood area of senesced poplars (Figure 5). As the estimated sapwood area tended to be larger than the measured sapwood area, the mean value of the model based estimated sapwood area and measured sapwood area were 166.04 cm^2 and 134.05 cm^2, respectively. Therefore, another model was established using similar growth parameters of senesced poplars (Figure 6), $R^2 = 0.718$, ($n = 40$), the model validation result was reliable ($p > 0.05$) (Figure 7) ($n = 38$).

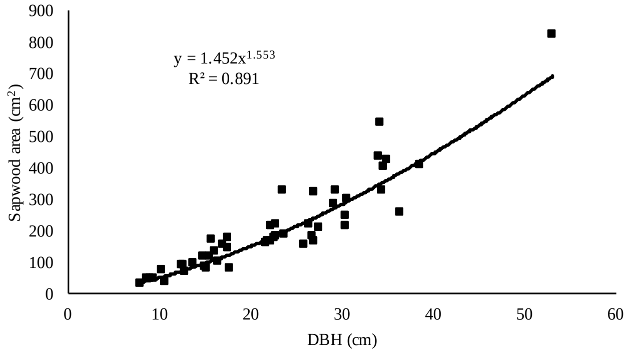


Figure 3. Sapwood area estimation model for the vital poplars.

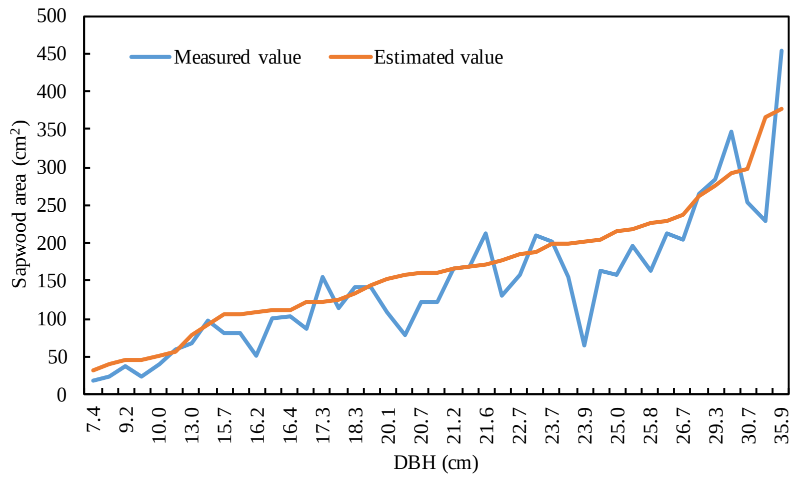


Figure 4. Validation result of the sapwood area estimation model of vital poplars.

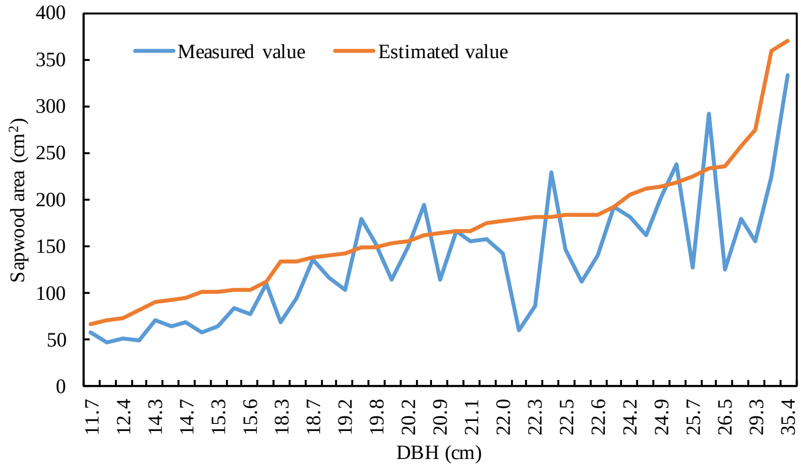


Figure 5. Validation result of the sapwood area estimation model.

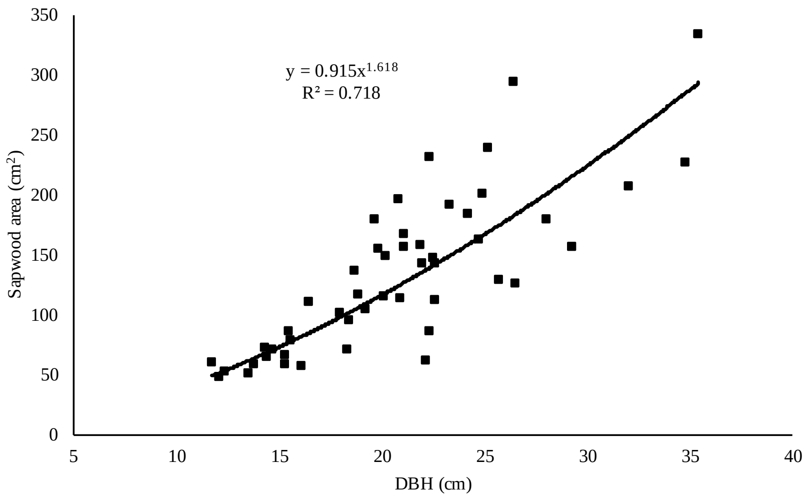


Figure 6. Senesced poplar sapwood area estimation model.

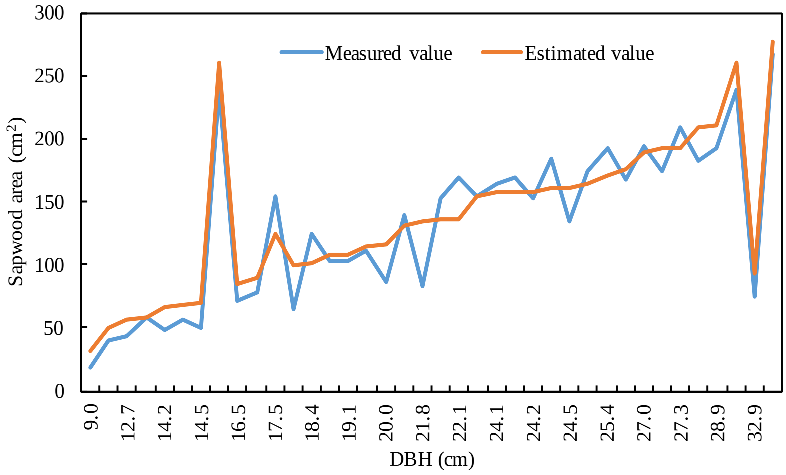


Figure 7. Validation result senesced poplar sapwood area estimation model.

3.2. Sap Flow Characteristics of *P. euphratica* with Different Vitality

There were certain similarities of sap flow variation between poplar trees of different vitality. Both vital and senesced poplars showed a pronounced diurnal sap flow process, all had peak variation features (Figure 8); and during the night the sap flow remained active, but at lower rate.

However, heterogeneous characteristics of sap flow variation also existed between the vital and senesced poplars. This was manifested from aspects of average sap flow velocity, daily consumed water amount, and increasing and decreasing time points of sap flow. The average sap flow velocity of vital poplars throughout the whole measurement period was 15.85 cm/h, which was higher than the average sap flow velocity of senesced poplar at 9.64 cm/h. The average daily consumed water amounts of vital and senesced poplars were 45.95 L and 18.17 L, respectively (Figure 9). Sap flow velocity of both vital and senesced poplars started to rise from 7:00 a.m., whereas the sap flow of senesced poplars reached its higher value of 13.69 cm/h at 10:00 a.m. and vital poplars reached its higher sap flow 25.68 cm/h at 12:00 p.m., after the midday depression appeared. From 17:00 p.m. onwards, the sap flow velocity of senesced poplars began to decrease, which was 2 h earlier than vital poplars.

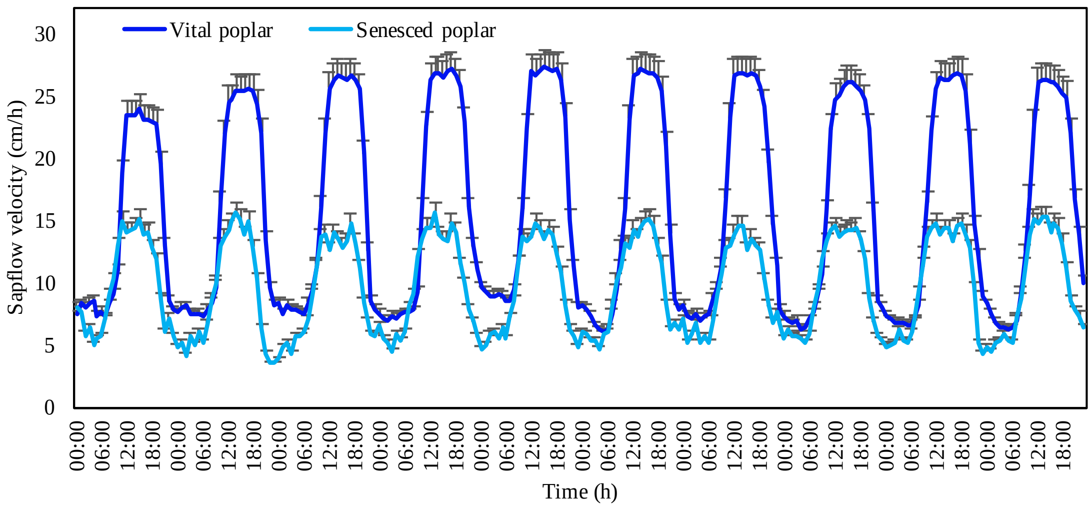


Figure 8. Diurnal sap flow variation of *P. euphratica* within different vitalities.

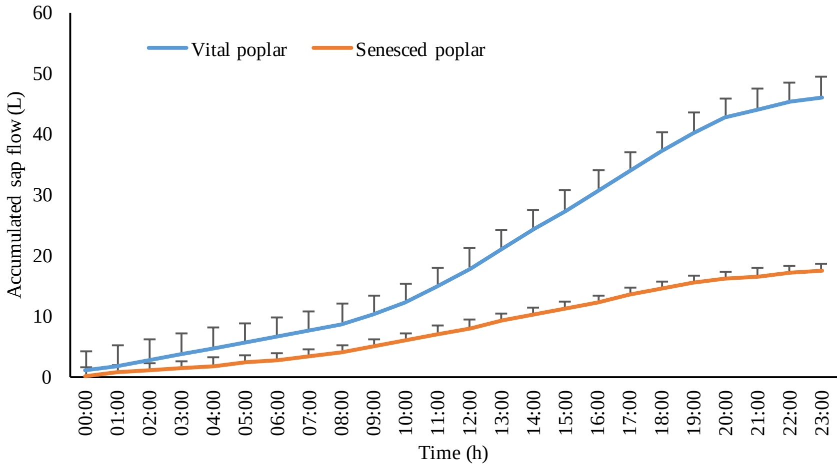


Figure 9. Accumulated sap flow of vital and senesced poplar trees.

3.3. Relationship between Sap Flow of Different Vitality P. euphratica and Meteorological Factor

The sap flow variation feature of vegetation was closely related to changing environmental factors during the measurement period [36]. While conducting sap flow measurements on the sample trees, environmental factors were recorded simultaneously (Figure 10). The result of the non-parametric Spearman correlation analysis between sap flow velocity and environmental factors showed that the diurnal variation of sap flow velocity of both vital and senesced poplar was significantly related to *VPD*, T_a, *RH*, R_s and groundwater depth. It was negatively related to *RH*, and positively related to other meteorological factors (Table 2). The influence of meteorological factors on the sap flow rate of vital poplars was in the order of: T_a (0.800) > R_s (0.732) > *VPD* (0.508) > *RH* (−0.313) > *GWD* (0.301). For the senesced poplars, it was in the same order of: T_a (0.851) > R_s (0.778) > *VPD* (0.643) > *RH* (−0.478) > *GWD* (0.171).

Table 2. Spearman correlation between sap flow velocity and environmental factors.

Environmental Factors	T_a (°C)	R_s (w/m^2)	*RH* (%)	*VPD*	*GWD* (m)
Sap flow velocity of vital poplar	0.800 **	0.732 **	−0.313 **	0.508 **	0.301 **
p-value	<0.01	<0.01	<0.01	<0.01	<0.01
Sap flow velocity of senesced poplar	0.851 **	0.778 **	−0.478 **	0.643 **	0.171 **
p-value	<0.01	<0.01	<0.01	<0.01	<0.01

Note: ** Significant at 0.05 level.

The multiple regression equations showed that the main influencing factors on the sap flow rate of vital and senesced poplars were almost similar in the order of *Ta*, *Rs*, and *GWD* (Table 3). The regression coefficients of the equations were tested, and the significant error probability of the respective variables was <0.01, indicating that our regression equation revealed the interrelation between environmental factors and sap flow rate.

Table 3. Relationship models between sap flow velocity and environmental factors.

Sap Flow Velocity	Regression Model	Validation Results
Sap flow velocity of vital poplar	$Fv = -50.903 + 1.960\ Ta + 0.011\ R_s - 2.759\ VPD + 5.377\ GWD$	$R^2 = 0.720$, $F = 150.995$, $n = 240$
Sap flow velocity of senesced poplar	$Fv = -2.853 + 0.746\ Ta + 0.005\ R_s + 0.992\ GWD$	$R^2 = 0.770$, $F = 263.218$, $n = 240$

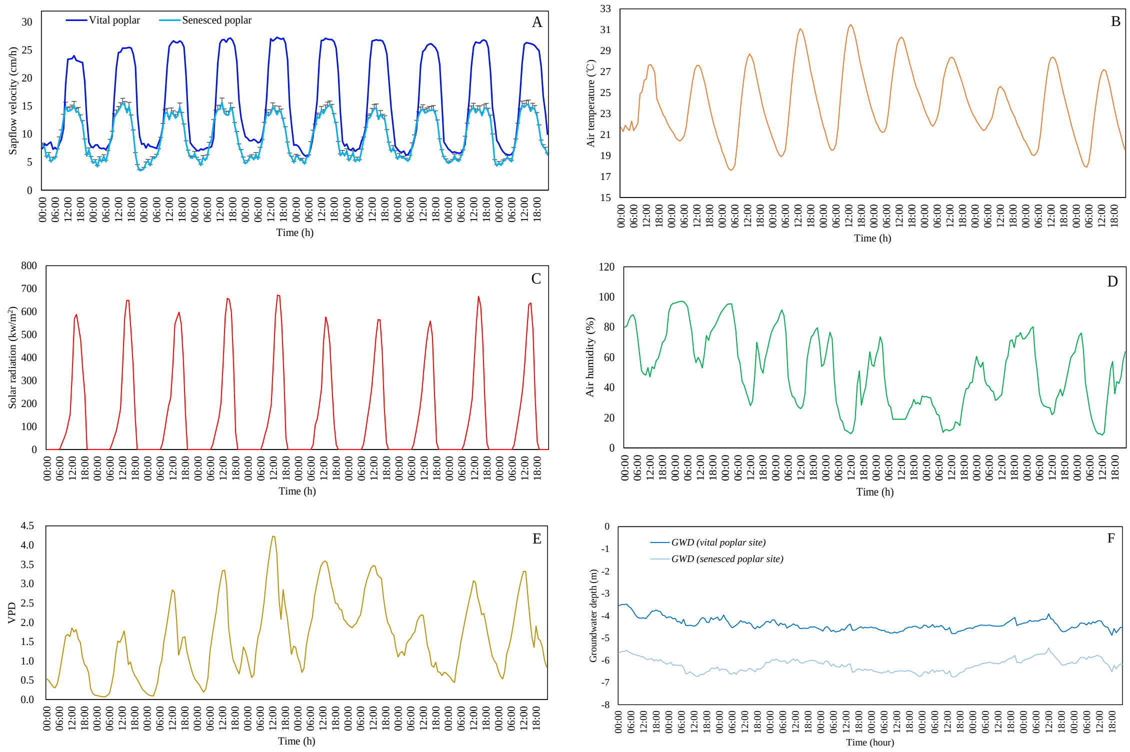


Figure 10. Diurnal variation of sap flow velocity of *P. euphratica* with different vitality and environmental factors. (**A**): Diurnal variation of sap flow velocity of different vitality poplars, (**B**): Diurnal variation of air temperature, (**C**): Diurnal variation of solar radiation, (**D**): Diurnal variation of air humidity, (**E**): Diurnal variation of vapor pressure deficit (VPD), (**F**): Diurnal variation of groundwater depth.

4. Discussion

A comparison analysis of the hydraulic characteristics of different plant species, the different individual of the same species (at different vitality), and the same species in heterogeneous environmental conditions should be based on their simultaneous observation and measurement; otherwise it does not make sense.

Sapwood is the water-conducting tissue [37–39], and direct correlation manifested between the sapwood area and water consumption of trees [27,40,41]. Estimation of the sapwood area of a tree stand is commonly achieved based on the correlation between growth parameters of the tree (e.g., diameter at breast height, crown size, biomass, leaf area index) and the sapwood area. Hatton and Vertessy's study showed that the area of xylem conducting tissue, DBH, and tree basal area were efficient upscaling parameters [42,43]. However, there are differences of sapwood width and sapwood area among different tree species, even among different individuals of the same tree species, which is influenced by the tree growth status [44,45], site condition [46,47], and tree genetic traits [48,49]. Therefore, heterogeneous environmental conditions and the growth status of trees require different sapwood area estimation models, this support the findings in our study.

The diurnal sap flow variation feature of vital and senesced poplars in this study was similar as both showed obvious circadian rhythms; however, there were differences in the increasing and decreasing time points, as well as the average, maximum, and minimum value of sap flow. Average sap flow velocity of vital poplars was almost twice that of the senesced poplar. Sap flow of vital poplar started to decrease from 19:00 p.m., which was 2 h later than the senesced poplar, which may have been decided by the physiological and morphological status of the tree itself. Hörtensteiner's study showed that chlorophyll content in tree leaves decreased when the tree leaves were senesced [50]; furthermore, Christ et al. found that water shortage also induced decreasing chlorophyll in tree leaves [51], however, the lower chlorophyll content in tree leaves weakened the photosynthetic activity of tree leaves, which eventually reduced transpiration. Bucci et al. and Chave et al. presented studies that showed that lower water availability increased the density of sapwood and lowered the water transport capacity in trees [52,53]. The average sap flow velocity during the day was higher than at night. Although the sap flow process was weaker at night, it remained active. This was probably to refill the water loss during the day to keep its water balance [54], which corresponded to the research results of Zhang et al. [55,56], Si et al. [57], and Yu et al. [58].

Water is the most influencing factor to the survival, distribution and development of vegetation in hyper arid regions [59]. The root system is the main organ of the plant to absorb water from the ground, therefore, its morphology and distribution impacts the growth of vegetation. Feng et al. showed that *P. euphratica* had a highly developed root system, and its root density decreased with increasing distance from the ground [60], therefore, when the groundwater table was lower, the plant water uptake through its root would be restricted to some degree, and the amount of water transported by vegetation decreased. In contrast, a higher groundwater table enabled vegetation to uptake more water. Our findings on the difference of sap flow velocity and diurnal water consumption between two different measurement sites with heterogeneous groundwater depth corresponded with the research results of Ma et al. [61], Zhao et al. [62], and Shen et al. [63].

As demonstrated in our study, the groundwater depth was positively related to the sap flow velocity of both vital (R^2 = 0.301) and senesced (R^2 = 0.171) poplars. When the sap flow velocity increased, the groundwater depth also increased, which was due to the water uptake by poplar trees. The correlation of sap flow velocity and groundwater depth in the vital poplars distributed plot was larger than that of the senesced poplar plot, which indicates that the groundwater availability strengthened the influence on the water uptake of poplars.

Many studies have shown that *Rs*, *RH*, *Ta*, and *GWD* are the most influencing external factors on the water consumption of trees [40–42,56,64]. Solar radiation affects the photosynthetic and transpiration activities of vegetation; it is the energy required to activate photosynthesis. Air temperature rises with the strengthening of solar radiation. When the leaf temperature is higher, plants decrease its temperature through increasing its transpiration rate. Leaf stomatal resistance increases when the air temperature reaches 32 °C, next, the stomata conductance and water potential decreases, which reduces the transpiration rate [65]. Air humidity changes the *VPD* between the plant, leaf, and atmosphere. When the air humidity is low, the difference in vapor pressure between the leaf and atmosphere is higher, which accelerates the transpiration rate. In contrast, when the air humidity is higher, the transpiration rate is lower.

5. Conclusions

As reported in the relevant literature, the results of our study further showed that DBH and the sapwood area of poplars were closely related to each other; therefore, DBH could be used to estimate the sapwood area by establishing statistical models. However, the sapwood area of vital poplars tended to be larger than the senesced poplars, therefore, the vitality of the poplars should be taken into account when estimating the sapwood area. There were certain similarities and differences between the sap flow processes of vital and senesced poplars; sap flow velocity and diurnal water consumption of vital poplars was larger than that of the senesced poplars. However, the influence of environmental factors on sap flow was similar; sap flow of both vital and senesced poplars had a positive correlation with air temperature, solar radiation, vapor pressure deficit, groundwater depth, and negative correlation with air humidity. Our results demonstrated that the hydraulic characteristics of two different vitalities of poplar were not the same, and that when analyzing the water usage strategy and estimating the water consumption of poplar forests, these two kinds of trees should be treated differently.

Acknowledgments: This research work was supported by the German Volkswagen Foundation within the framework of EcoCAR project (Az.: 88497), National Natural Science Foundation of China (Grant No: 31360200), and "Sino-German interdisciplinary joint training of innovative talents for ecological restoration of floodplain" funded by China Scholarship Council (Grant No. 201505990312). We thank the Forestry Department of Qarkilik (Ruoqiang), especially Askar and Sadik from Arghan Forestry Station for their support during our field work. We also would like to express our gratitude to Zhang Ximing (CAS), Atawulla Muyibul for supervising and supporting our sap flow equipment installation, and to our team memmbers Gulipiya Wumaier, Kailibinuer Nuermaimaiti and Maidina Muhetaer (Xinjiang University) for their assistance during the field work. Finally, we thank the editors and anonymous reviewers who helped to improve the manuscript.

Author Contributions: The manuscript was mainly written by Maierdang Keyimu with support from Ümüt Halik. Ümüt Halik and Maierdang Keyimu conceived of and designed the overall concept for the research; Ümüt Halik and Aihemaitijiang Rouzi are responsible for manuscript modification. Data were collected and sorted by Maierdang Keyimu, Aihemaitijiang Rouzi.

Conflicts of Interest: The authors declare that they have no conflict of interest.

References

1. Lemoine, D.; Peltier, J.P.; Marigo, G. Comparative studies of the water relations and the hydraulic characteristics in *Fraxinus excelsior*, *Acer pseudoplatanus* and *A. opalus* trees under soil water contrasted conditions. *Ann. For. Sci.* **2001**, *58*, 723–731. [CrossRef]
2. Tyree, M.T.; Ewers, F.W. The hydraulic architecture of trees and other woody plants. *New Phytol.* **1991**, *119*, 345–360. [CrossRef]
3. Hai, Y.; Wai, L.; Hoppe, T.; Thevs, N. Half a century of environmental change in the Tarim River Valley—An outline of cause and remedies. In *Watershed and Floodplain Management along the Tarim River in China's Arid Northwest*; Hoppe, T., Kleinschmit, B., Roberts, B., Thevs, N., Halik, U., Eds.; Shaker Press: Aachen, Germany, 2006; pp. 39–76.
4. Chen, Y.; Chen, Y.; Xu, C.; Ye, Z.; Li, Z.; Zhu, C.; Ma, X. Effects of ecological water conveyance on groundwater dynamics and riparian vegetation in the lower reaches of Tarim River, China. *Hydrol. Process.* **2010**, *24*, 170–177. [CrossRef]
5. Zhou, H.; Zhang, X.; Xu, H.; Ling, H.; Yu, P. Influences of climate change and human activities on Tarim River runoffs in China over the past half century. *Environ. Earth Sci.* **2012**, *67*, 231–241. [CrossRef]
6. Ling, H.; Zhang, P.; Xu, H.; Zhao, X. How to regenerate and protect desert riparian *Populus euphratica* forest in arid areas. *Sci. Rep.* **2015**, *5*, 15418. [CrossRef] [PubMed]
7. Thevs, N.; Buras, A.; Zerbe, S.; Kühnel, E.; Abdusalih, N.; Ovezberdiyeva, A. Structure and wood biomass of near-natural floodplain forests along the Central Asian rivers Tarim and Amu Darya. *Forestry* **2012**, *85*, 193–202. [CrossRef]
8. Eusemann, P.; Petzold, A.; Thevs, N.; Schnittler, M. Growth patterns and genetic structure of *Populus euphratica* Oliv. (Salicaceae) forests in NW China—Implications for conservation and management. *For. Ecol. Manag.* **2013**, *297*, 27–36. [CrossRef]
9. Calagari, M.; Modirrahmati, A.R.; Asadi, F. Morphological variation in leaf traits of *Populus euphratica* Oliv. natural populations. *Int. J. Agric. Biol.* **2006**, *8*, 754–758.
10. Aishan, T. Degraded Tugai Forests under Rehabilitation in the Tarim Riparian Ecosystem, Northwest China: Monitoring, Assessing and Modelling. Ph.D. Thesis, Katholische Universität Eichstätt-Ingolstadt, Eichstätt, Germany, 2016.
11. Halik, U.; Kurban, A.; Mijit, M.; Schulz, J.; Paproth, F.; Coenradie, B. The potential influence of embankment engineering and ecological water transfer on the riparian vegetation along the middle and lower reaches of the Tarim River. In *Watershed and Floodplain Management along the Tarim River in China's Arid Northwest*; Hoppe, T., Kleinschmit, B., Roberts, B., Thevs, N., Halik, U., Eds.; Shaker Press: Aachen, Germany, 2006; pp. 221–236.
12. Halik, U.; Chai, Z.; Kurban, A.; Cyffka, B.; Wei, R. The positive response of some ecological indices of *Populus euphratica* to the emergency water transfer in the lower reaches of the Tarim River. *Resour. Sci.* **2009**, *31*, 1309–1314.
13. Aishan, T.; Halik, Ü.; Cyffka, B.; Kuba, M.; Abliz, A.; Baidourela, A. Monitoring the hydrological and ecological response to water diversion in the lower reaches of the Tarim River, Northwest China. *Quatern. Int.* **2013**, *311*, 155–162. [CrossRef]

14. Betz, F.; Halik, Ü.; Kuba, M.; Tayierjiang, A.; Cyffka, B. Controls on aeolian sediment dynamics by natural riparian vegetation in the Eastern Tarim Basin, NW China. *Aeol. Res.* **2015**, *18*, 23–34. [CrossRef]
15. Xu, H.; Song, Y.; Wang, Q.; Ai, M. The effect of groundwater level on vegetation in the middle and lower reaches of the Tarim River, Xinjiang, China. *Acta Phytoecol. Sin.* **2003**, *28*, 400–405.
16. Xu, H.L.; Mao, Y.E.; Li, J.M. Changes in groundwater levels and the response of natural vegetation to transfer of water to the lower reaches of the Tarim River. *J. Environ. Sci.* **2007**, *19*, 1199–1207. [CrossRef]
17. Keyimu, M.; Halik, Ü.; Aishan, T.; Abliz, A.; Baidourela, A. DBH change of juvenile *Populus euphratica* in the lower reaches of Tarim River under water conveyances. *J. Northeast For. Univ.* **2014**, *42*, 15–18.
18. Keyimu, M.; Halik, U.; Betz, F.; Wumaier, G.; Dilimulati, G. Spatial-temporal change of DBH of *Populus euphratica* under artificial water conveyances. *J. Forest Environ.* **2016**, *36*, 148–154.
19. Ginau, A.; Opp, C.; Sun, Z.; Halik, U. Influence of sediment, soil, and micro-relief conditions on vitality of *Populus euphratica* stands in the lower Tarim riparian ecosystem. *Quat. Int.* **2013**, *311*, 146–154. [CrossRef]
20. Aishan, T.; Halik, Ü.; Kurban, A.; Cyffka, B.; Kuba, M.; Betz, F.; Keyimu, M. Eco-morphological response of floodplain forests (*Populus euphratica* Oliv.) to water diversion in the lower Tarim River, northwest China. *Environ. Earth Sci.* **2015**, *73*, 533–545. [CrossRef]
21. Disse, M.; Keilholz, P.; Kliucininkaite, L. Sustainable water resources management of river oases along the Tarim River in North-West China on different scales. In Proceedings of the 2nd European Conference for Hydro-Environment Engineering, TU Munich, Germany, 21–22 January 2012.
22. Cyffka, B.; Rumbaur, C.; Kuba, M.; Disse, M. Sustainable management of river oases along the Tarim River (China) and the ecosystem services approach. *Sustainability* **2013**, *6*, 77–90. [CrossRef]
23. Rumbaur, C.; Thevs, N.; Disse, M.; Ahlheim, M.; Brieden, A.; Cyffka, B.; Doluschitz, R.; Duethmann, D.; Feike, T.; Frör, O.; et al. Sustainable management of river oases along the Tarim River in North-Western China under conditions of climate change. *Earth Syst. Dyn. Discuss.* **2014**, *5*, 1221–1273. [CrossRef]
24. Keilholz, P.; Disse, M.; Halik, U. Effects of land use and climate change on groundwater and ecosystems at the middle reaches of the Tarim River using the MIKE SHE integrated hydrological model. *Water* **2015**, *7*, 3040–3056. [CrossRef]
25. Zhang, X.Y.; Meng, T.T.; Kang, E.S. Conversion of water consumption of a single tree and a forest stand of *Populus euphratica*. *For. Stud. China* **2008**, *10*, 81–87. [CrossRef]
26. Bai, Y.G.; Zhang, J.H.; Wang, X.Y.; Li, B.; Fan, H.B. Studies on scale convention of individual *Populus euphratica* and forest water consumption in Tarim Basin. *China Water Resour.* **2008**, *5*, 24–25.
27. Thomas, F.M.; Jeschke, M.; Zhang, X.; Lang, P. Stand structure and productivity of *Populus euphratica* along a gradient of groundwater distances at the Tarim River (NW China). *J. Plant Ecol.* **2016**. [CrossRef]
28. Zhang, X.Y.; Kang, E.S.; Si, J.H. Stem sap flow of individual plant of *Populus euphratica* and its conversion to forest water consumption. *Sci. Silv. Sin.* **2006**, *42*, 28–32.
29. Song, Y.D.; Fan, Z.L.; Lei, Z.D. *Research on Water Resources and Ecology of the Tarim River, China*; Xinjiang People's Press: Urumqi, Xinjiang, China, 2000.
30. Thomas, F.M.; Foetzki, A.; Arndt, S.K.; Bruelheide, H.; Gries, D.; Li, X.; Runge, M. Water use by perennial plants in the transition zone between river oasis and desert in NW China. *Basic Appl. Ecol.* **2006**, *7*, 253–267. [CrossRef]
31. Pfautsch, S.; Bleby, T.M.; Rennenberg, H.; Adams, M.A. Sap flow measurements reveal influence of temperature and stand structure on water use of Eucalyptus regnans forests. *For. Ecol. Manag.* **2010**, *259*, 1190–1199. [CrossRef]
32. Keyimu, M.; Halik, U.; Kurban, A. Estimation of water consumption of riparian forest in the lower reaches of Tarim River, Northwest China. *Environ. Earth Sci.* **2017**. [CrossRef]
33. Cronk, Q. Vapor Pressure Deficit Calculation. University of British Columbia, Center for Plant Research. Available online: http://cronklab.wikidot.com/calculation-of-vapour-pressure-deficit (accessed on 18 August 2017).
34. Campbell, G.S.; Norman, J.M. *An Introduction to Environmental Biophysics*; Springer: New York, NY, USA; Berlin/Heidelberg, Germany, 1998; pp. 36–51.
35. Keilholz, P. Auswirkungen von Veränderter Landnutzung auf den Wasserhaushalt und die Auwaldvitalität in Einer Flussoase am Tarim (China). Ph.D. Thesis, Technical University Munich, Munich, Germany, 2014. (In German)

36. Guo, Q.Q.; Zhang, W.H. Sap flow of *Abies georgei* var. smithii and its relationship with the environment factors in the Tibetan subalpine region, China. *J. Mt. Sci.* **2015**, *12*, 1373–1382. [CrossRef]
37. Wang, R. Sapwood and heartwood. *Bull. Biol.* **1998**, *33*, 13–14.
38. Ma, L.Y.; Sun, P.S.; Ma, L.Y. Sapwood area calculation and water use scaling up from individual trees to stands of Chinese pine and black locust. *J. Beijing For. Univ.* **2001**, *23*, 1–5.
39. Medhurst, J.L.; Beadle, C.L. Sapwood hydraulic conductivity and leaf area–sapwood area relationships following thinning of a Eucalyptus nitens plantation. *Plant Cell Environ.* **2002**, *25*, 1011–1019. [CrossRef]
40. Vertessy, R.A.; Benyon, R.G.; O'sullivan, S.K.; Gribben, P.R. Relationships between stem diameter, sapwood area, leaf area and transpiration in a young mountain ash forest. *Tree Physiol.* **1995**, *15*, 559–567. [CrossRef] [PubMed]
41. Pfautsch, S.; Peri, P.L.; Macfarlane, C.; van Ogtrop, F.; Adams, M.A. Relating water use to morphology and environment of Nothofagus from the world's most southern forests. *Trees* **2014**, *28*, 125–136. [CrossRef]
42. Hatton, T.J.; Moore, S.J.; Reece, P.H. Estimating stand transpiration in a Eucalyptus populnea woodland with the heat pulse method: Measurement errors and sampling strategies. *Tree Physiol.* **1995**, *15*, 219–227. [CrossRef] [PubMed]
43. Vertessy, R.A.; Hatton, T.J.; Reece, P.; O'sullivan, S.K.; Benyon, R.G. Estimating stand water use of large mountain ash trees and validation of the sap flow measurement technique. *Tree Physiol.* **1997**, *17*, 747–756. [CrossRef] [PubMed]
44. Pinto, I.; Pereira, H.; Usenius, A. Heartwood and sapwood development within maritime pine (*Pinus pinaster* Ait.) stems. *Trees* **2004**, *18*, 284–294. [CrossRef]
45. Miranda, I.; Gominho, J.; Lourenço, A.; Pereira, H. The influence of irrigation and fertilization on heartwood and sapwood contents in 18-year-old *Eucalyptus globulus* trees. *Can. J. For. Res.* **2006**, *36*, 2675–2683. [CrossRef]
46. Climent, J.; Chambel, M.R.; Pérez, E.; Gil, L.; Pardos, J. Relationship between heartwood radius and early radial growth, tree age, and climate in Pinus canariensis. *Can. J. For. Res.* **2002**, *32*, 103–111. [CrossRef]
47. Bektas, I.; Alma, M.H.; Goker, Y.; Yuksel, A.; Gundogan, R. Influence of site on sapwood and heartwood ratios of Turkish calabrian pine. *For. Prod. J.* **2003**, *53*, 48–50.
48. Ericsson, T.; Fries, A. High heritability for heartwood in north Swedish Scots pine. *Theor. Appl. Genet.* **1999**, *98*, 732–735. [CrossRef]
49. Woeste, K.E. Heartwood production in a 35-year-old black walnut progeny test. *Can. J. For. Res.* **2002**, *32*, 177–181. [CrossRef]
50. Hörtensteiner, S. Chlorophyll degradation during senescence. *Annu. Rev. Plant Biol.* **2006**, *57*, 55–77. [CrossRef] [PubMed]
51. Christ, B.; Egert, A.; Suessenbacher, I.; Kraeutler, B.; Bartels, D.; Peters, S.; Hoertensteiner, S. Water deficit induces chlorophyll degradation via the 'PAO/phyllobilin' pathway in leaves of homoio-(Craterostigma pumilum) and poikilochlorophyllous (Xerophyta viscosa) resurrection plants. *Plant Cell Environ.* **2014**, *37*, 2521–2531. [CrossRef] [PubMed]
52. Bucci, S.J.; Goldstein, G.; Meinzer, F.C.; Scholz, F.G.; France, A.C.; Bustamante, M. Functional convergence in hydraulic architecture and water relations of tropical savanna trees: From leaf to whole plant. *Tree Physiol.* **2004**, *24*, 891–899. [CrossRef] [PubMed]
53. Chave, J.; Coomes, D.; Jansen, S.; Lewis, S.L.; Swenson, N.G.; Zanne, A.E. Towards a worldwide wood economics spectrum. *Ecol. Lett.* **2009**, *12*, 351–366. [CrossRef] [PubMed]
54. Sun, L. Sap flow flux of main forest types in eastern region of northeast China. *Sci. Silv. Sin.* **2006**, *1*, 387–393.
55. Zhang, X.Y.; Gong, J.D.; Zhou, M.X.; Si, J.H. Spatial and temporal characteristics of stem sap flow of *Populus euphratica*. *J. Desert Res.* **2004**, *24*, 489–492.
56. Zhang, X.Y.; Kang, E.S.; Zhang, Z.H. A study of the stem sap flux of *Populus euphratica* in the lower reaches of Heihe River. *J. Glaciol. Geocryol.* **2005**, *27*, 742–746.
57. Si, J.H.; Fen, Q.; Zhang, X.Y.; Chang, Z.Q.; Xi, H.Y.; Zhang, K. Sap flow of *Populus euphratica* in desert riparian forest in extreme arid region during the growing season. *J. Desert Res.* **2007**, *27*, 442–447. (In Chinese) [CrossRef]
58. Yu, M.M.; Zhang, X.J.; Yuan, F.H.; Xiu, H.E.; Guan, D.X.; Wang, A.Z.; Wu, J.B.; Jin, C.J. Characteristics of sap flow velocities for three tree species in a broad-leaved Korean pine forest of Changbai mountain, in relation to environmental factors. *Chinese J. Ecol.* **2014**, *33*, 1707–1714.

59. Wang, H.; Zhao, W.; Chang, X. Spatial variability of soil moisture and vegetation in desert-oasis ecotone in the middle reaches of Heihe River Basin. *Acta Ecol. Sin./Shengtai Xuebao* **2007**, *27*, 1731–1739.
60. Feng, Q.; Si, J.H.; Li, J.L.; Xi, H.Y. Feature of root distribution of *Populus euphratica* and its water uptake model in extreme arid region. *Adv. Earth Sci.* **2008**, *23*, 765–772.
61. Ma, J.X.; Chen, Y.N.; Li, W.H.; Huang, X. Response of sap flow in *Populus euphratica* to changes in groundwater depth in the middle and lower reaches of the Tarim River of northwestern China. *Chinese J. Plant Ecol.* **2010**, *34*, 915–923.
62. Zhao, C.Y.; Si, J.H.; Feng, Q. Xylem sap flow of *Populus euphratica* in relation to environmental factors in the lower reaches of Heihe River. *J. Desert Res.* **2014**, *34*, 718–724.
63. Shen, X.; Lv, C.Y.; Chai, Z.P.; Zhang, X.M. Characteristics of stem sap flow of *Populus euphratica* of Alagan area in the lower reaches of Tarim River. *J. Xinjiang Agric. Univ.* **2015**, *38*, 114–119.
64. Liu, C.; Du, T.; Li, F.; Kang, S.; Li, S.; Tong, L. Trunk sap flow characteristics during two growth stages of apple tree and its relationships with affecting factors in an arid region of northwest China. *Agric. Water Manag.* **2012**, *104*, 193–202. [CrossRef]
65. Jiang, J. Water regime of *Populus euphratica* in extreme climatic conditions and its relationship with environmental factors. *Arid Zone Res.* **1991**, *8*, 35–38.