

Article

# Assessing Environmental Control of Sap Flux of Three Tree Species Plantations in Degraded Hilly Lands in South China

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**Abstract:** Prerequisite for selection of appropriate tree species in afforestation programs is to understand their water use strategy. *Acacia mangium* Willd., *Schima wallichii* Choisy, and *Cunninghamia lanceolata* (Lamb.) Hook are the three main vegetation restoration pioneer species in southern China, but no comparative research on the water use strategy of these three tree species have been reported. Our objective was to gain a detailed understanding of how photosynthetically active radiation (PAR), vapor pressure deficit (VPD), and soil water content (SWC) at different soil depths control the sap flux density ( $J_s$ ) in the dry and wet seasons. We measured the  $J_s$  of these three tree species by using the thermal dissipation method in low subtropical China. We found that both *S. wallichii* and *C. lanceolata* differed clearly in their stomatal behavior from one season to another, while *A. mangium* did not. The canopy conductance per sapwood area of *S. wallichii* and *C. lanceolata* was very sensitive to VPD in the dry season, but not in the wet season. The  $J_s$  of *A. mangium* was negatively correlated to SWC in all soil layers and only positively correlated to SWC in dry season. Our results demonstrate that the three species have distinct water use strategies and may therefore respond differently to changing climate.

**Keywords:** sap flux density; canopy conductance per sapwood area; dry and wet season; soil water content; *Acacia mangium* Willd.; *Schima wallichii* Choisy; *Cunninghamia lanceolata* (Lamb.) Hook

# 1. Introduction

China, as the second largest plantation country in the world, has implemented large-scale planned afforestation since the 1950s, primarily focused on planting fast-growing and high production timber species during the 1970s and 1980s [1,2]. These programs have altered the coverage of forest in China from 16.0% in the 1980s to 21.66% in 2018 and this increase is expected to continue as China intends



to extend afforestation for carbon storage and environmental protection [3,4]. Since the 1980s, an extensive afforestation campaign has been conducted in Guangdong Province, and consequently the forest coverage in this region had risen from 26.2% in 1979 to 58.9% in 2016 [5,6]. Although the plantation of pioneer tree species promotes wood yield and increases commercial profits, it consumes a large amount of water [7–9]. However, the use of water by plantations and the selection of appropriate species in many afforestation programs have not previously been considered [10].

Since the 1980s, exotic pioneer species such as *Acacia mangium* Willd, an evergreen broad-leaved tree with nitrogen-fixing, drought-tolerant, and fast-growing characteristics, have been introduced in southern China [11,12]. They can be effectively used due to the nitrogen fixation of the nodule and rapid growth in the early stage to improve soil conditions at the plantations [13]. Observations show that the growth, photosynthetic rate and water use of A. mangium plantations decreases after approximately 20–22 years after planting [12]. It can be expected that the use of water is essential to support the growth rate of A. mangium [14]. Therefore, understanding the water use strategy of the mature A. mangium has been a concern. Schima wallichii Choisy is a pioneer, evergreen, broad-leaved and fire-resistant tree species used for timber production and fire protection [15]. It has a wide ecological niche, is particularly common in disturbed and secondary forests [15] and is an important native species for ecological restoration in subtropical southern China. At present, however, there is little research on the water usage of S. wallichii in degraded and non-degraded ecosystems. Cunninghamia lanceolata (Lamb.) Hook, as an evergreen conifer, is the main traditional pioneer species that has been used for cultivation and wood production due to its rapid growth and excellent wood quality [16]. Moreover, C. lanceolata plantations also have positive impacts on ecosystem services, including carbon sequestration [17] and decreasing runoff [18]. According to FAO (2010) [1], in the past four decades, C. lanceolata plantations have expanded rapidly and their total planted area has now exceeded 12 million ha in southern China. Despite the positive ecosystem services they provide, there is still a lack of studies on the water use of C. lanceolata [19]. Selecting appropriate species and managing forest effectively can optimize the water use in plantations [20,21] as well as potentially maximize economic benefits. However, no comparative research on the water use strategy of these three common vegetation restoration pioneer tree species in southern China has been published.

In South China, human disturbance seriously affected the native evergreen broad-leaved forest, causing soil erosion and leading to vegetation degradation [22]. Since the mid-1980s, a vegetation restoration campaign has been carried out to replace the barren, hilly grasslands with pioneer species including exotic and native species [23]. *A. mangium, S. wallichii*, and *C. lanceolata* are the main vegetation restoration tree species, planted in 1985–1990, and they have developed into secondary subtropical forests after more than 30 years under a monsoon climate. These secondary forests are the product of long-term influences of a monsoon climate. Long-term observations have shown that the total annual precipitation has changed little since 1950 in southern China [24]. In recent decades, however, rising air temperature in southern China has shifted the rainfall patterns toward intensified rainfall (i.e., more floods) but has not raised the soil water content (SWC) in the wet season, while droughts are becoming frequent and more severe leading to declining SWC in the extended dry season [24].

In the current study, we set out to find which of these three tree species would be most suitable for planting in the degraded hilly lands in terms of adaptive water-use strategy, especially under the changing climate. In order to answer this question, we should know how the water use of these species is influenced by the environmental factors. We studied the water use of *A. mangium*, *S. wallichii*, and *C. lanceolata* in the degraded hilly lands of southern China using the thermal dissipation technique [25] to measure the xylem sap flux density ( $J_s$ ) of these species. Our aim is to investigate how photosynthetically active radiation (PAR), vapor pressure deficit (VPD), soil water content (SWC) at different soil depths, and temperature affect  $J_s$  of these three tree species in the dry and wet seasons.

## 2. Materials and Methods

#### 2.1. Site description

The experimental site (112°54′E, 22°41′N) is located in the Heshan National Field Research Station of Forest Ecosystem, Chinese Academy of Sciences, Guangdong Province, China. The average elevation of the station is 80 m. This region is dominated by a subtropical monsoon climate, with an annual average precipitation of 1700 mm, and temperature of 21.7 °C. The annual accumulated temperature above 10 °C is 7600 °C, and the annual solar radiation is 4350 MJ m<sup>-2</sup>. There are distinct wet and dry seasons in this region. The wet season lasts approximately from April to September, while the dry season is approximately from October to March [26].

Our experiment was conducted in the three mono-species plantations of *A. mangium*, *S. wallichii*, and *C. lanceolata* (Table 1) from January to December in 2017. These three plantations were planted between 1985 and1990, located close to each other on different hill slopes with similar elevation (80 m), inclination, slope (20%–30%) direction, and soil properties (Table 2). We randomly selected 15 trees of each tree species for the sap flow experiment (Table 3).

Site	Plot Size (m <sup>2</sup> )	Tree Density (No. ha <sup>-1</sup> )	Total Stand Basal Area (m <sup>2</sup> ha <sup>-1</sup> )	Mean DBH ± Standard Error (cm)	Mean Height ± Standard Error (m)
A. mangium	1600	519	26.2	$23.5 \pm 1.1$	$14.5 \pm 0.5$
S. wallichii	900	867	31.0	$20.2 \pm 0.8$	$12.2 \pm 0.5$
C. lanceolata	800	725	11.1	$11.8\pm1.0$	$9.5 \pm 0.6$

Site	Soil Bulk Density (g·cm <sup>−3</sup> )	Maximum Water-Holding Capacity (g·kg <sup>-1</sup> )	Field Capacity (%)	Non-Capillary Porosity (%)	Capillary Porosity (%)	Total Porosity (%)
A. mangium	$1.3 \pm 0.04$	$327.0 \pm 17.2$	$25.6 \pm 0.9$	$8.6 \pm 1.1$	$33.9 \pm 1.0$	$42.5 \pm 0.8$
S. wallichii	$1.4 \pm 0.04$	$296.3 \pm 17.3$	$24.4 \pm 1.2$	$7.0 \pm 0.6$	$33.5 \pm 0.8$	$40.5\pm1.0$
C. lanceolata	$1.4 \pm 0.04$	$290.8 \pm 14.6$	$23.4\pm0.7$	$7.6 \pm 1.2$	$32.5\pm0.7$	$40.1\pm0.8$

DBH, diameter at breast height (1.3m).

Table 2. Physical properties, water holding capacity, and storage performance of three plantation soils.

**Table 3.** DBH, tree height and mean daily maximum sap flux density ( $J_{\text{smax}} \pm$  standard error) of the three species.

Species	A. mangium				S. wallichii			C. lanceolata		
Tree No.	DBH (cm)	Height (m)	Mean Daily J <sub>smax</sub> (g m <sup>-2</sup> s <sup>-1</sup> )	DBH (cm)	Height (m)	Mean Daily J <sub>smax</sub> (g m <sup>-2</sup> s <sup>-1</sup> )	DBH (cm)	Height (m)	Mean Daily J <sub>smax</sub> (g m <sup>-2</sup> s <sup>-1</sup> )	
1	27.6	16.3	$34.4 \pm 1.0$	22.9	14	$18.7\pm0.7$	17.5	13.5	$3.8 \pm 0.1$	
2	16	14.9	$14.2 \pm 1.1$	23.3	13	$18.7 \pm 0.7$	24.2	13.8	$18.2 \pm 0.6$	
3	40.3	17.8	$56.7 \pm 1.2$	20.1	13	$25.2 \pm 1.3$	22	13.5	$5.7 \pm 0.2$	
4	23.6	17.5	$8.8 \pm 0.4$	16.4	10.6	$19.2 \pm 0.7$	19	13	$5.3 \pm 0.2$	
5	27.3	17	$24.4 \pm 1.1$	19	12.3	$19.1 \pm 0.7$	14.3	11	$6.2 \pm 0.2$	
6	17.4	15.6	$17.2 \pm 0.6$	30.3	15.5	$38.5 \pm 1.4$	18.6	13.13	$8.2 \pm 0.3$	
7	33.9	17	$39.2 \pm 1.1$	13.1	11	$13.7 \pm 0.7$	18.1	13	$12.4 \pm 0.4$	
8	19.8	11	$30.8 \pm 0.8$	16.6	12	$10.7 \pm 0.5$	10.5	10.6	$3.0 \pm 0.1$	
9	29.2	17	$54.9 \pm 1.3$	16.1	11	$24.2\pm0.9$	21.2	11.5	$7.9 \pm 0.3$	
10	32.1	16.2	$28.2 \pm 1.4$	19.3	14	$32.4 \pm 1.0$	16.5	10.5	$6.4 \pm 0.2$	
11	40	17.5	$43.6 \pm 1.5$	18.4	11.5	$13.8 \pm 0.5$	22	13	$4.0 \pm 0.1$	
12	28.6	16.5	$16.3 \pm 0.9$	21.1	13	$26.4 \pm 1.0$	11.2	10.5	$13.5 \pm 1.2$	
13	34.8	15	$38.1 \pm 1.1$	32.2	17	$29.4 \pm 0.9$	18.3	11.1	$9.1 \pm 0.3$	
14	27.5	11	$10.2 \pm 0.6$	18.2	12.5	$29.3 \pm 1.0$	13.7	11.5	$3.4 \pm 0.1$	
15	30.5	15.2	$24.0 \pm 1.1$	17.4	12.3	$21.2\pm1.0$	19	13	$9.5 \pm 0.4$	

#### 2.2. Measurements

#### 2.2.1. Microclimate

PAR, temperature, relative humidity (above 2 m), and wind speed data (above 10m) were measured (VAISALA MAWS301, Vaisala, Espoo, Finland) and data was provided by the Heshan National Field

Research Station of Forest Ecosystem. The leaf area index (LAI) was measured by LAI 2000 (LI-COR, Lincoln, NE, USA) monthly. The linear distances from the station to the *A. mangium*, *S. wallichii*, and *C. lanceolata* sites were 300, 50 and 100 m, respectively. Hourly averages were used for all meteorological data and we calculated VPD (kPa) according to Campbell and Norman, 1998 [27]:

$$VPD = a \times exp\left(b \times \frac{T}{T+c}\right)(1-RH)$$
<sup>(1)</sup>

where a, b, and c are constant parameters i.e., 0.611 kPa, 17.502 (unitless), and 240.97 °C, respectively, and RH is relative humidity (Units), *T* is temperature (Units).

#### 2.2.2. Soil Water Content

The soil type at all the sites is lateritic red soil. The soil water content (SWC) was measured at 5, 10, 20, 30, 40, 50, 60, 90, 120, and 150 depths at three locations (up-, mid-, and downslope) at each site using soil moisture sensors (A755 GPRS, Adcon, Klosterneuburg, Austria). An Adcon A755 telemetry unit (Adcon) transmitted the data signals to a data server at 30 min intervals.

#### 2.2.3. Sap Flow

We used home-made Granier's sensors (thermal dissipation probes, TDPs) to measure sap flow of 15 sample trees in each of the three plantations [25]. The TDP sensors consisted of a pair of 20-mm-long and 2 mm in diameter stainless steel probes. Each pair of probes was inserted on the northern side of the stem (1.3 m above ground) approximately 10 cm apart along the axis of the hydro-active xylem. The upper probe was heated by a DC supply of 120 mA, yielding a constant power of 0.2 W, while the lower probe remained unheated. We converted the instantaneous temperature difference between the two probes into a voltage value recorded by a data logger (Delta-T logger DL2e, Delta-T Devices Ltd., Cambridge, UK). The data were measured every 30 s and stored as 10 min averages [14]. Finally, we calculated  $J_s$  (g m<sup>-2</sup>s<sup>-1</sup>) following Granier (1987) [25]:

$$J_s = 119 \times \left(\frac{\Delta T_{m-}\Delta T}{\Delta T}\right)^{1.231}$$
(2)

where  $\Delta T_{\rm m}$  is the temperature difference between the two probes obtained under zero flux conditions and  $\Delta T$  is the instantaneous temperature difference. The "zero baseline" was determined on nights when VPD was zero or nearly zero for several hours, so that there was no driving force for sap flux.  $\Delta T_{\rm m}$  was determined separately for each tree over 7 days to avoid the underestimation of nocturnal sap flow [28]. The voltage value data was converted to  $J_{\rm s}$  by applying the Baseliner 4.0 program [29] (https://github.com/Coweeta/Baseliner4\_exe).

#### 2.2.4. Canopy Conductance per Sapwood Area

Because of the difficulty in obtaining the leaf area data of measured trees, canopy conductance per sapwood area (g, mmol m<sup>-2</sup> s<sup>-1</sup>) was determined by using the following formula:

$$g = \frac{J_s}{VPD}$$
(3)

which presumes that  $J_s$  is equal to canopy transpiration, and  $J_s$  is not influenced by hydraulic capacitance [30,31].

#### 2.3. Data Analysis and Modeling

We analyzed both the daily and hourly relationships between the environmental conditions and  $J_s$  since the daily analysis fails to catch fast responses to changing environmental conditions, while the hourly analysis in obscured by time lags. We concentrated more on the analysis of the daily data by

looking at daily average values (which need not to occur at the same moment in time) to minimize the problems caused by the time lag due to the internal water stores, i.e., capacitance [32], and due to the slowness of the thermal dissipation probe method to respond to changes in flow rate [33,34]. We first used the daily average values of  $J_s$ , PAR, VPD, and SWC, then after correcting the time lag between VPD, PAR and  $J_s$ , we used the hourly average values minus the daily average values of  $J_s$ , PAR, and VPD to analyze the hourly dynamics of  $J_s$  within a day. We analyzed the relationship between the dependent variable  $J_s$  and the explanatory variables PAR, VPD, and SWC in the daily and hourly (only PAR and VPD) tree-level data:

$$\ln(J_s) = \ln(\alpha) + \beta 1 \times \ln(PAR) + \beta 2 \times \ln(VPD) + \beta 3 \times \ln(SWC)$$
(4)

The parameters  $\beta$ 1,  $\beta$ 2, and  $\beta$ 3 describe the sensitivity of  $J_s$  to the natural logarithm (better fit than other shapes) of PAR, VPD, and SWC, respectively (note that this is equivalent to fitting a power function  $J_s = \alpha (PAR)^{\beta 1} (VPD)^{\beta 2} (SWC)^{\beta 3}$ . All the statistical analyses were produced by R software (R Core Team; R version 3.5.3; RStudio version 1.1.463). The analysis for hourly data was made separately (1) for each species during the wet and dry seasons, (2) for small and large trees of each species, and (3) for each species with SWC measured at different soil depths. The size class in (2) was determined based on DBH separately for each species (note that in (1) and (2) the data were divided into two approximately similar size groups). The random term tree identity was added into the models to consider the dependence of observations for the same tree, and all values were transformed for the statistical analysis with natural logarithm. Possible differences in the relationship between  $J_s$  and the explanatory variables VPD, PAR, and SWC between species, between wet and dry seasons, between small and large trees, and between models with SWC measured at different soil depths were compared with 95% confidence intervals (Tables 4–6); for example, if the confidence interval of the estimate of the effect of VPD on  $I_s$  in the wet season overlapped with the estimate of the effect of VPD on  $I_s$  in the dry season in *A. mangium*, no significant difference was reported. Temperature was left out of the model because temperature is highly correlated with another variable in the model, VPD. However, we compared the residuals of the model with temperature to test whether temperature had a direct (i.e., not through VPD) effect on sap flow. The effect of wind speed on  $J_s$  was also analyzed, but it was not significant and was thus dropped from the final analyses.

# 3. Results

### 3.1. Micrometeorology

The total amount of precipitation recorded was 1673 mm from January 2017 to December 2017, which was in the range of the long-term annual mean in the Heshan area. Rainfall in the wet season (1289 mm) accounted for 77% of the total annual precipitation (Figure 1a). The mean daily PAR was 223 (±9)  $\mu$ mol m<sup>-2</sup>s<sup>-1</sup> and 326 (±13)  $\mu$ mol m<sup>-2</sup>s<sup>-1</sup> during the dry and wet periods, respectively (Figure 1c). The mean daily VPD was 0.55 ( $\pm$ 0.03) kPa and 0.59 ( $\pm$ 0.03) kPa in the dry and wet season, respectively (Figure 1d). The average daily temperature ranged from 8.7 to 31.8 °C during the whole measurement period (Figure 1f). The mean daily PAR, VPD, and temperature were all higher in the wet season than in the dry season. The difference in mean SWC of all layers between the wet and dry seasons was greater at the A. mangium and S. wallichii sites than at the C. lanceolata site (Figure 2). At the A. mangium site, average SWC of all layers was lower in the dry season (19%–28%) compared with the wet season (28%–33%) (Figure 2). At the S. wallichii site, average SWC of all layers ranged from 20% to 27% in the dry season and from 26% to 32% in the wet season, which can be compared with the average SWC of all layers of 20% to 26% in the dry period and 25% to 30% in the wet period at the C. lanceolata site (Figure 2). The leaf area index (LAI) of all the three sites decreased in the dry season compared with the wet season, and the decrease at the A. mangium site was larger (25%) than at the S. wallichii (18%) and *C. lanceolata* sites (10%) (Figure 1b).



**Figure 1.** (a) Daily precipitation, (b) monthly leaf area index (LAI), daily mean values of (c) photosynthetically active radiation (PAR), (d) vapor pressure deficit (VPD), (e) relative humidity (RH) and (f) temperature (*T*) during dry season (DS) and wet season (WS) in 2017.



**Figure 2.** Soil water content (SWC± standard error) at 10 different depths in the dry and wet seasons at three sites. (a) *A. mangium* site; (b) *S. wallichii* site; (c) *C. lanceolata* site.

#### 3.2. Sap Flow Density and Environmental Effects

The recorded mean daily maximum  $J_s$  was in the range of 8.8 (±0.4) to 54.9 (±1.3) gm<sup>-2</sup>s<sup>-1</sup> (DBH range = 16–40 cm) for the *A. mangium*, 10.7 (±0.5) to 38.5 (±1.4) g m<sup>-2</sup>s<sup>-1</sup> (DBH range = 13–32 cm) for the *S. wallichii*, and 3.0 (±0.1) to 18.2 (±0.6) g m<sup>-2</sup>s<sup>-1</sup> (DBH range = 11–24 cm) for the *C. lanceolata* (Table 3). The mean  $J_s$  of *A. mangium* and *S. wallichii* was two times larger than that of *C. lanceolata* in magnitude (Figure 3). At these three sites, the highest  $J_s$  occurred between April and October during the wet season, coinciding with the highest *T* and PAR measured during the year. The lowest values were recorded between December and March during the dry season. The  $J_s$  was similar between the dry and wet seasons for *A. mangium*, while  $J_s$  was different between the dry and wet seasons for *S. wallichii* and *C. lanceolata* (Figure 3).



**Figure 3.** Daily mean  $J_s$  averaged for all the sap flow-monitored trees in each plot during dry season (DS) and wet season (WS). (a) *A. mangium* site; (b) *S. wallichii* site; (c) *C. lanceolata* site.

We compared the analysis results regarding sensitivity of  $J_s$  to environmental variables separately during the wet and dry seasons and in small and large trees. No significant difference in the correlation coefficient of  $J_s$  with PAR or VPD between small and large trees of any species was found, and therefore, the results are not shown. Figure 4 demonstrates raw data (i.e., without using the statistical model) of  $J_s$  and single environmental drivers during the wet and dry seasons. Tables 4–6 show results from the mixed models that consider the effect of all the environmental drivers simultaneously, thus showing the actual dependencies between the studied variables when the effects of all environmental drivers are considered in the model. Table 4 shows the results for the daily average values (abbreviation daily data) for all the variables and Table 5 shows the hourly average values minus daily average values (abbreviation hourly data) for all the variables. Note that to obtain the response of canopy conductance per sapwood area to the environmental factors, 1 should be subtracted from coefficient  $\beta 2$  (compare Equation (3) and Tables 4 and 5), while coefficients  $\beta 1$  and  $\beta 3$  for the canopy conductance per sapwood area are the same as for  $J_s$ .

The  $J_s$  of *A. mangium* was affected on the daily scale by PAR, VPD, and SWC in both seasons, and it was more sensitive to PAR in the dry season than in the wet season (Table 4). SWC affected  $J_s$ negatively during both seasons and in all soil layers (Tables 4 and 6). On the daily scale,  $J_s$  of *S. wallichii* was sensitive to VPD but the parameter  $\beta$ 2 was nearly zero in dry season (Table 4). Note that this indicates strict canopy stomatal control as stomata closure occurs concurrently with increases in VPD, while transpiration ( $J_s$  used as a proxy) remains unchanged (Equation (3)). Moreover,  $J_s$  of *S. wallichii* was significantly correlated with SWC in the two topmost soil layers, SWC1 and SWC2 (Table 6), and the sensitivity of  $J_s$  to SWC was significant only during the dry season (Table 4). On the daily scale,  $J_s$ of *C. lanceolata* was strongly related to PAR and SWC but not affected by VPD in the dry season; in the wet season, it was positively affected by PAR and VPD (Table 4). The  $J_s$  of *C. lanceolata* showed no sensitivity to VPD and the parameter  $\beta$ 2 was nearly zero, also indicating that its canopy conductance per sapwood area was very sensitive to VPD. Only SWC in the topmost soil layer (SWC1) significantly affected the  $J_s$  (Table 6).  $J_s$  of *S. wallichii* and *C. lanceolata* was more sensitive to PAR but less sensitive to VPD in dry season than in wet season (Table 4). There were distinct differences among these three species in their sensitivity to the environmental factors. The  $J_s$  of *A. mangium* was less sensitive to PAR and SWC but more sensitive to VPD than that of the other two species in the dry season, but less sensitive to VPD in the wet season (Table 4).



**Figure 4.** Raw data of daily (including daytime and nighttime) sap flux density ( $J_s \pm$  standard error) to average vapor pressure deficit (VPD) at (**a**) *A. mangium* site, (**d**) *S. wallichii* site, (**g**) *C. lanceolata* site; photosynthetically active radiation (PAR) at (**b**) *A. mangium* site, (**e**) *S. wallichii* site, (**h**) *C. lanceolata* site; and soil water content (SWC) at (**c**) *A. mangium* site; (**f**) *S. wallichii* site; (**l**) *C. lanceolata* site in the dry and wet seasons. (note that the y-axis of *C. lanceolata* has a different scale compared with that of the other two species).

On the hourly scale, the results were similar to the daily scale, except for *S. wallichii* and *C. lanceolata* in dry season (see Table 4 vs. Table 5). The  $J_s$  of *S. wallichii* and *C. lanceolata* was more sensitive to VPD but less sensitive to PAR on hourly than daily scale.

For all species the correlation of the model residuals with temperature was statistically significant in the dry season and for *C. lanceolata* in the wet season as well. The strongest correlation was observed in *A. mangium* (Table 7). The effect of wind speed was also tested and no effect on  $J_s$  was found.

Effect	A. mangium		S. wa	llichii	C. lanceolata				
Season	Wet Dry		Wet Dry		Wet	Dry			
	$In (J_s) = In (\alpha) + \beta 1 \times In (PAR) + \beta 2 \times In (VPD) + \beta 3 \times In (SWC)$								
In (α)	-0.40A	–1.91 *a	0.27A	-4.00 *b	-1.46 *A	-4.31 *b			
T-value	-0.81	-5.28	0.40	-10.15	-3.31	-12.17			
β1	0.24 *A	0.70 *a	0.32 *A	1.25 *b	0.38 *A	1.00 *c			
T-value	6.30	14.74	6.93	25.82	10.40	21.20			
β2	0.19 *A	0.27 *a	<b>0.33</b> *B	<b>0.07</b> *b	<b>0.39</b> *B	<b>-0.01</b> b			
T-value	8.29	8.82	11.00	2.10	17.86	-0.37			
β3	-0.83 *A	-0.32 *a	-0.05A	0.78 *b	<b>-0.32</b> A	<b>0.35</b> *b			
T-value	-3.12	-3.71	-0.11	5.68	-1.31	3.87			

**Table 4.** Model relating daily *J*<sub>s</sub> to environmental factors in different seasons and species.

We compared the effects in one species between different seasons and in one season between different species based on the 95% confidence intervals (Supplementary Material Table S1). If they did not overlap, the difference was significant. The significant difference between seasons within one species is marked in bold. The significant difference between the species in one season is marked with a letter: Same letter indicates that the species behave in the same way and are not significantly different from each other. All estimates marked with an asterisk are significantly different from zero at p < 0.05.

Table 5. Model relating hourly J<sub>s</sub> to environmental factors in different seasons and species.

Effect	A. mangium		S. wa	llichii	C. lanceolata	
Season	Wet	Dry	Wet	Dry	Wet	Dry
	In	$(J_{\rm s}) = { m In} \left( \alpha \right) +$	$\beta 1 \times \ln (PAR)$	+ $\beta 2 \times \ln (VP)$	'D)	
In (α)	-0.27A	-0.06 a	-0.28A	−1.26 *b	-0.75 *A	−1.20 *b
T-value	-0.89	-5.28	0.40	-10.93	-4.46	-7.67
β1	0.33 *A	0.37 *a	0.38 *B	0.49 *b	0.26 *C	0.29 *c
T-value	47.20	58.08	38.86	57.51	35.11	39.24
β2	0.18 *A	0.40 *a	0.42 *B	0.73 *b	0.53 *C	0.54 *c
T-value	20.08	37.74	40.02	60.11	55.78	43.13

We compared the effects in one species between different seasons and in one season between different species based on the 95% confidence intervals (Supplementary Material Table S2). If they did not overlap, the difference was significant. The significant difference between seasons within a species is marked in bold. The significant difference between the species within a season is marked with a letter: The same letter indicates that the species behave the same way and are not significantly different from each other. All estimates marked with an asterisk are significantly different from zero at p < 0.05.

**Table 6.** Model estimates relating the daily mean sap flux density  $(J_s)$  to environmental factors in different soil water content (SWC) layers.

Effect	A. mangium			S. wallichii			C. lanceolata		
Level	SWC1	SWC2	SWC3	SWC1	SWC2	SWC3	SWC1	SWC2	SWC3
	$\ln (J_s) = \ln (\alpha) + \beta 1 \times \ln (PAR) + \beta 2 \times \ln (VPD) + \beta 3 \times \ln (SWC)$								
In (α)	-1.81 *	-1.32 *	-1.72 *	-1.43 *	-0.74	-1.74 *	-3.04 *	-3.33 *	-2.99 *
β1	0.55 *	0.51 *	0.52 *	0.70 *	0.65 *	0.74 *	0.73 *	0.76 *	0.74 *
β2	0.26 *	0.29 *	0.29 *	0.32 *	0.34 *	0.29 *	0.26 *	0.24 *	0.25 *
β3	-0.67 *	-0.55 *	-0.71 *	0.48 *	0.85 *	0.44	0.18 *	0.11	0.28

SWC was divided into three layers: SWC1 (0–30 cm), SWC2 (31–60 cm) and SWC3 (61–150 cm). All estimates marked with an asterisk are significant at p < 0.05.

Table 7. Effects of temperature on the residual of the model in wet and dry seasons.

Spacias Effect	Wet S	eason	Dry Season		
Species Ellect	R	р	R	р	
A. mangium	0.04	0.08	0.13	< 0.0001	
S. wallichii	-0.01	0.654	0.08	0.01	
C. lanceolata	0.07	0.01	0.09	< 0.0001	

#### 4. Discussion

We found that both native species (S. wallichii and C. lanceolata) differed clearly in their stomatal sensitivity (at the daily scale) from one season to another, while the exotic A. mangium did not (Table 4). In the dry season, the parameter  $\beta^2$  of both native species was close to zero (Table 4). This means tight stomatal control, i.e., high sensitivity of g to VPD in S. wallichii and C. lanceolate. Earlier studies had also shown a sensitive canopy stomatal regulation in some tropical trees, resulting in partial canopy stomatal closure at VPD >1 kPa [35]. This implies that tropical trees had a conservative water use strategy when exposed to short-term drought [36,37]. High sensitivity of canopy stomatal control to VPD has been linked to conditions of water stress [38,39]. This result could be explained by consequent drought stress in S. wallichii and C. lanceolata during the dry season. For these two species, the positive correlation between J<sub>s</sub> and SWC indicates that water availability was limiting their water use in the dry season (Table 4). In contrast, the difference of stomatal behavior between the wet and dry seasons was not clear for A. mangium (Table 4). This may be because increasing SWC had a negative effect on the  $J_s$ of A. mangium during both seasons (Table 4). One possible reason for this could be that A. mangium was suffering from too high soil water content. During the wet season, the  $I_s$  of two native species was more sensitive to VPD than that of A. mangium (Table 4), indicating that A. mangium was more sensitive in canopy stomatal control to VPD than the native species were.

On the hourly scale, the dynamics of actual transpiration rate, which responds quickly to changes in environmental conditions, might be considerably different from those of the sap flow rate due to the time lag between these two variables [40,41]. The response of  $J_s$  to the environmental conditions were similar to the daily scale when analyzed on the hourly scale, except in the case of *S. wallichii* and *C. lanceolata* in dry season (see Table 4 vs. Table 5). The canopy conductance per sapwood area response of these species was much stronger in daily than in hourly scale during the dry season. One reason for this difference in behavior could be the role of internal water stores within the tree and the decoupling of transpiration rate from the sap flow rate [42]. *S. wallichii* and *C. lanceolata* seemed to be suffering from drought stress during dry season (Table 4), and diurnal usage and refilling of internal water stores maybe a strategy under drought condition [43]. It is also known that the role of internal water stores increases when the total water usage is low [44,45], and the lowest water usage occurred in *S. wallichii* and *C. lanceolata* in the dry season (see the intercept, parameter in ( $\alpha$ ), in Table 4).

The  $J_s$  of *S. wallichii* and *C. lanceolata* was very sensitive to PAR during the dry season, even more sensitive than that of *A. mangium* (Table 4). Liu et al. (2014) [46] found the same result i.e., that the  $J_s$  of *C. lanceolata* was more sensitive to PAR than VPD during the dry season in Eastern China. A possible explanation for this could be the lower light levels during the dry season in winter as the light-response curve of photosynthesis is steeper at low light levels [47]. The greater sensitivity of the  $J_s$  of *C. lanceolata* to light during the dry season may also be linked to their suffering from drought stress, as drought stress has been found to increase the sensitivity of canopy stomatal control to light [48].

Increasing SWC had a negative effect on the  $J_s$  of *A. mangium* during both seasons (Table 4), suggesting that soil water content could have been too high for *A. mangium*. The  $J_s$  was similar between the dry and wet seasons for *A. mangium* (Figure 3). One would expect the  $J_s$  to be higher during the wet season because of the higher level of light. However, this was not the case and could be due to too much water in the soil in the wet season causing oxygen deficiency and preventing optimal root functioning [49]. It has been reported that *A. mangium* is intolerant of excessively wet soil and grows better on sites with good drainage [50]. We also found that  $J_s$  of *A. mangium* was sensitive to temperature. This finding corresponds to the report of Booth and Hong (1991) [11] that low temperatures in winter reduce the growth of *A. mangium* in Guangzhou (Guangdong Province). The effect of SWC on  $J_s$  was significantly positive for *S. wallichii* and *C. lanceolata* only during the dry season. For *C. lanceolata* in eastern China, Liu et al. (2014) [46] also found that SWC (at depths 5, 10, 15 and 40 cm) had positive effect on  $J_s$  in winter (dry season).

We also analyzed the effect of SWC at different soil depths on  $J_s$  (Table 6), because SWC at different layers makes a different contribution to plant water use due to a variety of root system depths for

different tree species [51]. The  $J_s$  of *A. mangium* was sensitive to SWC in all layers, but the native species (*S. wallichii* and *C. lanceolata*) were not sensitive to SWC in deeper soil layers (Table 6). This indicates that *A. mangium* may have deeper roots than both native species and could extract water down to at least 0–150 cm depth. Although Pan et al. (1996) [52] described that the roots of *A. mangium* were shallow (most roots concentrated in the upper 28cm), several other authors' reports support our results. For example, the rooting depth of *A. mangium* has been observed to be deeper than 1 m [53] and the fine roots to reach down to 12 m in monospecific stands of *A. mangium* [54]. Fine roots of *C. lanceolata* trees have been reported to be mainly distributed in the 0–20 cm soil layer in subtropical China [55], which is consistent with that *C. lanceolata* may only extract water from the soil layer at 0–30 cm depth (Table 6), while *S. wallichii* seemed to use water from 30–60 cm depth (Table 6). Also, Zeng (1988) [56] reported that most of the roots of *S. wallichii* in south China were concentrated in the 30–50 cm soil layer. Such differences in rooting depth may also explain why  $J_s$  was reduced in *S. wallichii*, and *C. lanceolata* but not in *A. mangium* (Figure 3) during dry season when soil water availability was low. *A. mangium* is likely the most deeply rooted among the three species studied, and therefore had the least response to dry season [57].

The mean daily maximum  $J_s$  of *A. mangium* at 9–55 g m<sup>-2</sup>s<sup>-1</sup> was lower than the values reported for A. mangium at Sardinilla, Panama (81 g  $m^{-2}s^{-1}$ ) of larger mean DBH [58], but similar to the values measured in an A. mangium plantation in South China (11–80 g m<sup>-2</sup>s<sup>-1</sup>) of similar DBH [12]. The maximum  $J_s$  of *S. wallichii* was 17 g m<sup>-2</sup>s<sup>-1</sup> in DBH = 15.5 cm trees in the Lesser Himalayas of Central Nepal [59], which was similar to the daily maximum  $J_s$  of S. wallichii (11–24 g m<sup>-2</sup>s<sup>-1</sup>) in the same DBH at our site. The  $J_s$  of *C. lanceolata* was much smaller than that of the two other species, and its peak value was less than half that of the other species (Table 3). The reason for the low  $J_s$ of C. lanceolata might be that C. lanceolata is a coniferous species, which generally uses less water in relation to broad-leaved trees [60]. Moreover, the canopy stomatal conductance has been found to be lower in *C. lanceolata* than in broad-leaved trees, which also leads to lower  $J_s$  in *C. lanceolata* stems [61]. This could also be explained by the thick wax layer on the leaf surface of *C. lanceolata* [61]. Although Zhang et al. (2016) [62] found a similar  $J_s$  of C. lanceolata with similar DBH to our results in Southwest China, the J<sub>s</sub> of *C. lanceolata* was much smaller than reported for other locations in southern China [61,63]. Moreover, Li and Ritchie (1999) [64] reported that C. lanceolata requires well-drained soil and that it will not grow well in wet conditions. Jøker (2000) [65] also found that the best growth of C. lanceolata is obtained on well-drained loamy soils. According to Li and Ritchie (1999) [64], there are only a few places in South China which offer suitable terrain for *C. lanceolata* to grow well. Our results of mean daily maximum  $I_s$  in the range 9–55 g m<sup>-2</sup>s<sup>-1</sup> for the *A. mangium* site and 11–39 g m<sup>-2</sup>s<sup>-1</sup> for the S. wallichii site both fall within the lower range of 4–139 g m<sup>-2</sup>s<sup>-1</sup> reported for subtropical and tropical tree species [58,60,66]. Low  $J_s$  was the result of continuously high air humidity at the study site (Figure 1e), with VPD rarely exceeding 1 kPa (Figure 1d), which was supported by earlier studies on different species in the same area [67] and on a perhumid tropical forest of Sulawesi, Indonesia [68].

The annual rainfall (1600+ mm/year) of the observation site is enough to keep SWC at over 20% even in the cool-dry season, which might not induce severe evapotranspiration depression for any of the species at present. However, long-term observations have shown that droughts are becoming frequent and more severe, leading to declining SWC in the extended dry season [24]. Hu et al. (2018) [26] also showed that the dry season extended from November–March during the 1964–1983 period to October–April during the 2001–2010 period in the Heshan area (our sites), and they found that the extended dry season reduced transpiration in *Schima superba* (the same family as *S. wallichii*). Based on our results, we speculate that the exotic species *A. mangium*, which prefers higher temperatures and drier soil, will become more suitable in Southern China, whereas the more drought-sensitive native species *S. wallichii* and *C. lanceolata* could suffer more severely from water stress under future meteorological and soil conditions.

## 5. Conclusions

We found distinct differences in how PAR, VPD and SWC controlled the water use of the three plantation species. *S. wallichii* and *C. lanceolata* differed clearly in their stomatal behavior and  $J_s$  at the daily scale from one season to another, while *A. mangium* did not. *S. wallichii* and *C. lanceolata* may suffer from water stress in dry season, but for *A. mangium* there seemed to be even an excess amount of water in the soil in both seasons. Extended dry season in the research area will likely impact the ecosystem hydrologic cycle and thus the water use of the studied species in the future.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/1999-4907/11/2/206/s1, Table S1: 95% confident interval of model relating daily sap flow density ( $J_s$ ) to environmental factors in different seasons and species. Table S2: 95% confident interval of model relating hourly sap flow density ( $J_s$ ) to environmental factors in different seasons and species.

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## References

- 1. FAO. *Global Forest Resources Assessment 2010;* FAO Forestry Paper No. 163; UN Food and Agriculture Organization: Rome, Italy, 2010.
- 2. Forest Stewardship Council (FSC). Strategic Review on the Future of Forest Plantations; FSC: Helsinki, Finland, 2012.
- 3. China Forestry Administration Returning Farmland to Forest Office. The National Forest Area is 3.12 Billion mu and the Forest Coverage Rate is the Highest in Fujian Province. 2018. Available online: http://www.forestry.gov.cn (accessed on 13 March 2018).
- 4. Zhou, G.Y.; Wei, X.H.; Luo, Y.; Zhang, M.F.; Li, Y.L.; Qiao, Y.N.; Liu, H.G.; Wang, C.L. Forest recovery and river discharge at the regional scale of Guangdong Province, China. *Water Resour. Res.* **2010**, *46*. [CrossRef]
- 5. Peng, S.L.; Hou, Y.P.; Chen, B.M. Vegetation Restoration and Its Effects on Carbon Balance in Guangdong Province, China. *Restor. Ecol.* **2009**, *17*, 487–494. [CrossRef]
- 6. Statistical Bureau of Guangdong Province. *Guangdong Statistical Yearbook;* China Statistical Publishing House: Guangzhou, China, 2016. Available online: www.stats.gov.cn/tjsj/ndsj/2016/indexeh.htm (accessed on 17 October 2016).
- Calder, I.R. Forests and water-Ensuring forest benefits outweigh water costs. *For. Ecol. Manag.* 2007, 251, 110–120. [CrossRef]
- Jackson, R.B.; Jobbagy, E.G.; Avissar, R.; Roy, S.B.; Barrett, D.J.; Cook, C.W.; Farley, K.A.; le Maitre, D.C.; McCarl, B.A.; Murray, B.C. Trading water for carbon with biological sequestration. *Science* 2005, *310*, 1944–1947. [CrossRef] [PubMed]
- 9. Peng, H.; Tague, C.; Jia, Y. Evaluating the eco-hydrologic impacts of reforestation in the Loess Plateau, China, using an eco-hydrologic model. *Ecohydrology* **2016**, *9*, 498–513. [CrossRef]
- 10. Ferraz, S.F.; Lima, W.D.; Rodrigues, C.B. Managing forest plantation landscapes for water conservation. *For. Ecol. Manag.* **2013**, *301*, 58–66. [CrossRef]
- 11. Booth, T.; Yan, H. *Identifying Climatic Areas in China Suitable for Acacia mearnsii and A. mangium;* ACIAR Proceedings Series; Australian Centre for International Agricultural Research: Canberra, Australia, 1991.
- 12. Zhao, P.; Zou, L.; Rao, X.; Ma, L.; Ni, G.; Zeng, X.; Cai, X.A. Water consumption and annual variation of transpiration in mature *Acacia mangium* plantation. *Acta Ecol. Sin.* **2011**, *31*, 6038–6048.

- 13. Yu, Z.Y.; Peng, S.L. *Ecological Study of Vegetation Restoration in Tropical and Subtropical Degraded Ecosystems*; Guangdong Science and Technology Press: Guangzhou, China, 1996.
- Wang, H.; Zhao, P.; Holscher, D.; Wang, Q.; Lu, P.; Cai, X.A.; Zeng, X.P. Nighttime sap flow of *Acacia mangium* and its implications for nighttime transpiration and stem water storage. *J. Plant Ecol.* 2012, *5*, 294–304. [CrossRef]
- 15. Li-Zhen, W.; Li, Z.W. Study on applied effectiveness of biological firebreak network of Schima. *Scientia Silvae Sinicae* **1997**, *33*, 338–348.
- 16. Tian, D.L. The Functioning of Chinese Fir Plantation Ecosystem; Science Press: Beijing, China, 2005.
- 17. Fang, J.Y.; Chen, A.P.; Peng, C.H.; Zhao, S.Q.; Ci, L. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science* 2001, *292*, 2320–2322. [CrossRef]
- 18. Tian, D.L.; Yan, W.D.; Chen, X.Y.; Deng, X.W.; Peng, Y.Y.; Kane, W.X.; Peng, C.H. Variation in runoff with age of Chinese fir plantations in Central South China. *Hydrol. Res.* **2008**, *22*, 4870–4876. [CrossRef]
- 19. Yan, W.D.; Deng, X.W.; Chen, X.Y.; Tian, D.L.; Xiang, W.H.; Peng, Y.Y. Long-term variations of rainfall interception in different growth stages of Chinese fir plantations. *Hydrol. Sci.* 2015, 60, 2178–2188. [CrossRef]
- 20. Van Dijk, A.I.; Keenan, R.J. Planted forests and water in perspective. *For. Ecol. Manag.* **2007**, 251, 1–9. [CrossRef]
- 21. Murgue, C.; Therond, O.; Leenhardt, D. Toward integrated water and agricultural land management: Participatory design of agricultural landscapes. *Land Use Policy* **2015**, *45*, 52–63. [CrossRef]
- 22. Fu, S.L.; Lin, Y.B.; Rao, X.Q.; Liu, S.P. The Dataset of Observation and Research on Chinese Ecosystem: Forest Ecosystem of Heshan Station, Guangdong Province (1998–2008); China Agriculture Press: Beijing, China, 2011.
- 23. Wang, Q.; Gao, J.G.; Zhao, P.; Zhu, L.W.; Ouyang, L.; Ni, G.Y.; Zhao, X.H. Biotic- and abiotic-driven variations of the night-time sap flux of three co-occurring tree species in a low subtropical secondary broadleaf forest. *AoB Plants* **2018**, *10*, ply025. [CrossRef]
- 24. Zhou, G.Y.; Wei, X.H.; Wu, Y.P.; Liu, S.G.; Huang, Y.H.; Yan, J.H.; Zhang, D.Q.; Zhang, Q.M.; Liu, J.X.; Meng, Z.; et al. Quantifying the hydrological responses to climate change in an intact forested small watershed in Southern China. *Glob. Chang. Biol.* **2011**, *17*, 3736–3746. [CrossRef]
- Granier, A. Evalution of transpration in a Douglas-fir stand by means of sap flow measurements. *Tree Physiol.* 1987, *3*, 309–319. [CrossRef]
- Hu, Y.T.; Zhao, P.; Shen, W.J.; Zhu, L.W.; Ni, G.Y.; Zhao, X.H.; Zhang, Z.Z.; Rao, X.Q.; Ouyang, L.; Zeng, X.M.; et al. Responses of Tree Transpiration and Growth to Seasonal Rainfall Redistribution in a Subtropical Evergreen Broad-Leaved Forest. *Ecosystems* 2018, *21*, 811–826. [CrossRef]
- 27. Campbell, G.S.; Norman, J.M. *An Introduction to Environmental Biophysics*, 2nd ed.; Springer: New York, NY, USA, 1998.
- 28. Lu, P.; Urban, L.; Zhao, P. Granier's thermal dissipation probe (TDP) method for measuring sap flow in trees: Theory and practice. *Acta Bot. Sin.* **2004**, *46*, 631–646.
- 29. Oishi, A.C.; Hawthorne, D.; Oren, R. Baseliner: An open-source, interactive tool for processing sap flux data from thermal dissipation probes. *SoftwareX* **2016**, *5*, 139–143. [CrossRef]
- 30. Barnard, H.R.; Ryan, M.G. A test of the hydraulic limitation hypothesis in fast-growing Eucalyptus saligna. *Plant Cell Environ.* **2003**, *26*, 1235–1245. [CrossRef]
- Gao, J.G.; Zhao, P.; Shen, W.J.; Niu, J.F.; Zhu, L.W.; Ni, G.Y. Biophysical limits to responses of water flux to vapor pressure deficit in seven tree species with contrasting land use regimes. *Agric. For. Meteorol.* 2015, 200, 258–269. [CrossRef]
- Martinez-Vilalta, J.; Korakaki, E.; Vanderklein, D.; Mencuccini, M. Below-ground hydraulic conductance is a function of environmental conditions and tree size in Scots pine. *Funct. Ecol.* 2007, 21, 1072–1083. [CrossRef]
- 33. Burgess, S.S.; Dawson, T.E. Using branch and basal trunk sap flow measurements to estimate whole-plant water capacitance: A caution. *Plant Soil* **2008**, *305*, 5–13. [CrossRef]
- Holtta, T.; Linkosalo, T.; Riikonen, A.; Sevanto, S.; Nikinmaa, E. An analysis of Granier sap flow method, its sensitivity to heat storage and a new approach to improve its time dynamics. *Agric. For. Meteorol.* 2015, 211, 2–12. [CrossRef]
- 35. Fetcher, N.; Oberbauer, S.F.; Chazdon, R.L. Physiological ecology of trees, shrubs, and herbs at La Selva. In La Selva: Ecology and Natural History of a Neotropical Rainforest; McDade, L.A., Bawa, K.S., Hespenheide, H.A., Hartshorn, G.S., Eds.; University of Chicago Press: Chicago, IL, USA, 1994; pp. 128–141.

- 36. Granier, A.; Huc, R.; Colin, F. *Transpiration and Stomatal Conductance of Two Rain Forest Species Growing in Plantations (Simarouba amara and Goupia glabra) in French Guyana;* Annales des Sciences Forestières; EDP Sciences: Les Ulis, France, 1992.
- 37. O'Brien, J.J.; Oberbauer, S.F.; Clark, D.B. Whole tree xylem sap flow responses to multiple environmental variables in a wet tropical forest. *Plant Cell Environ.* **2004**, *27*, 551–567. [CrossRef]
- 38. Tardieu, F.; Davies, W.J. Stomatal response to abscisic-acid is a function of current plant water status. *Plant Physiol.* **1992**, *98*, 540–545. [CrossRef]
- 39. Eamus, D.; Shanahan, S.T. A rate equation model of stomatal responses to vapour pressure deficit and drought. *BMC Ecol.* **2002**, *2*, 8. [CrossRef]
- 40. Hogg, E.H.; Hurdle, P.A. Sap flow in trembling aspen: Implications for stomatal responses to vapor pressure deficit. *Tree Physiol.* **1997**, *17*, 501–509. [CrossRef]
- Phillips, N.G.; Oren, R.; Licata, J.; Linder, S. Time series diagnosis of tree hydraulic characteristics. *Tree Physiol.* 2004, 24, 879–890. [CrossRef]
- 42. Phillips, N.; Nagchaudhuri, A.; Oren, R.; Katul, G. Time constant for water transport in loblolly pine trees estimated from time series of evaporative demand and stem sapflow. *Trees-Struct. Funct.* **1997**, *11*, 412–419. [CrossRef]
- 43. Daley, M.J.; Phillips, N.G. Interspecific variation in nighttime transpiration and stomatal conductance in a mixed New England deciduous forest. *Tree Physiol.* **2006**, *26*, 411–419. [CrossRef] [PubMed]
- 44. Phillips, N.G.; Ryan, M.G.; Bond, B.J.; McDowell, N.G.; Hinckley, T.M.; Cermak, J. Reliance on stored water increases with tree size in three species in the Pacific Northwest. *Tree Physiol.* **2003**, *23*, 237–245. [CrossRef] [PubMed]
- 45. Hölttä, T.; Cochard, H.; Nikinmaa, E.; Mencuccini, M. Capacitive effect of cavitation in xylem conduits: Results from a dynamic model. *Plant Cell Environ.* **2009**, *32*, 10–21. [CrossRef] [PubMed]
- 46. Liu, P.; Zhang, J.C.; Zhuang, J.Y.; Gu, Z.Y.; Han, C.H.; Wu, Y.W. Factors of sap flow of Chinese fir sapling and its contribution to transpiration of Chinese fir forest bulletin of soil and water conservation. *Bull. Soil Water Conserv.* **2014**, *34*, 73–78.
- 47. Nobel, P.S. Physicochemical and Environmental Plant Physiology; Academic Press: San Diego, CA, USA, 2005.
- 48. Knapp, A.K.; Smith, W.K. Effect of water-stress on stomatal and photosynthetic responses in subalpine plants to cloud patterns. *Am. J. Bot.* **1988**, *75*, 851–858. [CrossRef]
- 49. Niinemets, U.; Valladares, F. Tolerance to shade, drought, and waterlogging of temperate Northern Hemisphere trees and shrubs. *Ecol. Monogr.* **2006**, *76*, 521–547. [CrossRef]
- 50. DFSC. Acacia mangium Willd; Danida Forest Seed Centre: Humlebaek, Denmark, 2000; 2p.
- 51. Xu, X.Y.; Tong, L.; Li, F.S.; Kang, S.Z.; Qu, Y.P. Sap flow of irrigated *Populus alba* var. *pyramidalis* and its relationship with environmental factors and leaf area index in an arid region of Northwest China. *J. For. Res. JPN* **2011**, *16*, 144–152. [CrossRef]
- 52. Pan, Z.G.; Feng, S.; Lin, H.S. Introduction, growth and use of Acacia mangium. Trop. For. 1996, 24, 144–152.
- 53. Cienciala, E.; Kucera, J.; Malmer, A. Tree sap flow and stand transpiration of two *Acacia mangium* plantations in Sabah, Borneo. *J. Hydrol.* **2000**, *236*, 109–120. [CrossRef]
- 54. Germon, A.; Guerrini, I.A.; Bordron, B.; Bouillet, J.P.; Nouvellon, Y.; de Moraes Goncalves, J.L.; Jourdan, C.; Paula, R.R.; Laclau, J.P. Consequences of mixing *Acacia mangium* and *Eucalyptus grandis* trees on soil exploration by fine-roots down to a depth of 17 m. *Plant Soil* **2018**, 424, 203–220. [CrossRef]
- 55. Liao, Y.C.; McCormack, M.L.; Fan, H.B.; Wang, H.M.; Wu, J.P.; Tu, J.; Liu, W.F.; Guo, D.L. Relation of fine root distribution to soil C in a *Cunninghamia lanceolata* plantation in subtropical China. *Plant Soil* **2014**, *381*, 225–234. [CrossRef]
- 56. Zeng, T.X. Multi-purpose tree species-Schima wallichii Choisy. Guangdong For. Sci. Technol. 1988, 1, 7–10.
- 57. Stone, E.L.; Kalisz, P.J. On the maximum extent of tree roots. For. Ecol. Manag. 1991, 46, 59–102. [CrossRef]
- 58. Kunert, N.; Schwendenmann, L.; Hölscher, D. Seasonal Dynamics of Tree Sap Flux and Water Use in Nine Species in Panamanian Forest Plantations. *Agric. For. Meteorol.* **2010**, *150*, 411–419. [CrossRef]
- Ghimire, C.P.; Lubczynski, M.W.; Bruijnzeel, L.A.; Chavarro-Rincón, D. Transpiration and Canopy Conductance of Two Contrasting Forest Types in the Lesser Himalaya of Central Nepal. *Agric. For. Meteorol.* 2014, 197, 76–90. [CrossRef]
- 60. Meinzer, F.C.; Bond, B.J.; Warren, J.M.; Woodruff, D.R. Does Water Transport Scale Universally With Tree Size? *Funct. Ecol.* 2005, *19*, 558–565. [CrossRef]

- 61. Zhou, C.M.; Gu, D.X.; Huang, Y.Q.; Zhao, P.; Huang, K.C.; He, W.; Zeng, D.J.; Sun, Y.J. Analyses on Water Consumption Characteristics of Eucalyptus Urophylla × E. Grandis, Cunninghamia Lanceolata and Cinnamomun Camphora. *Eucalypt Sci. Technol.* **2017**, *34*, 9–15.
- 62. Zhang, X.; Zhang, H.L.; Wang, Y.J.; Wang, Y.Q.; Liu, C.X.; Yang, P.P.; Pan, S.L. Characteristics of Daily Sap Flow for Typical Species in Jinyun Mountain of Chongqing in Relation to Meteorological Factors. *J. Beijing For. Univ.* **2016**, *38*, 11–20.
- 63. Ouyang, S.; Xiao, K.; Zhao, Z.; Xiang, W.; Xu, C.; Lei, P.; Deng, X.; Li, J. Stand Transpiration Estimates from Recalibrated Parameters for the Granier Equation in a Chinese Fir (Cunninghamia Lanceolata) Plantation in Southern China. *Forests* **2018**, *9*, 162. [CrossRef]
- 64. Minghe, L.; Ritchie, G.A. Eight Hundred Years of Clonal Forestry in China: I. Traditional Afforestation With Chinese Fir (Cunninghamia Lanceolata (Lamb.) Hook.). *New For.* **1999**, *18*, 131–142. [CrossRef]
- 65. Jøker, D. Acacia Mangium Willd. Seed Leafl. 2000, 3.
- 66. McJannet, D.; Fitch, P.; Disher, M.; Wallace, J. Measurement of Transpiration Infour Tropical Rainforest Types of North Queensland. *Aust. Hydrol. Processes.* **2007**, *21*, 3549–3564. [CrossRef]
- 67. Otieno, D.; Li, Y.; Ou, Y.; Cheng, J.; Liu, S.; Tang, X.; Zhang, Q.; Jung, E.-Y.; Zhang, D.; Tenhunen, J. Stand Characteristics and Water Use at Two Elevations in a Sub-Tropical Evergreen Forest in Southern China. *Agric. For. Meteorol.* **2014**, *194*, 155–166. [CrossRef]
- 68. Horna, V.; Schuldt, B.; Brix, S.; Leuschner, C. Environment and Tree Size Controlling Stem Sap Flux in a Perhumid Tropical Forest of Central Sulawesi, Indonesia. *Ann. For. Sci.* **2011**, *68*, 1027–1038. [CrossRef]



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