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Provenance differences and factors influencing transpiration of *Cunninghamia lanceolata* in a common garden experiment

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Tree transpiration is a key component of forest evapotranspiration, and sap flow monitoring is the primary way to study tree canopy transpiration and water consumption. However, provenance differences in transpiration and the unique responses to environmental factors are not well understood. We measured the sap flow and calculated the canopy evapotranspiration (E_c) of 15 Chinese fir provenances from five provinces in a common garden and monitored soil moisture and meteorological variables between September 2020 and September 2022. Mean daily E_c of the provenances from Guangxi (GX), Sichuan (SC), Anhui (AH), Yunnan (YN), and Zhejiang (ZJ) were $1.31 \pm 0.99 \text{ g} \cdot \text{d}^{-1}$, $1.59 \pm 1.18 \text{ g} \cdot \text{d}^{-1}$, $1.62 \pm 1.43 \text{ g} \cdot \text{d}^{-1}$, $1.41 \pm 1.01 \text{ g} \cdot \text{d}^{-1}$, and $1.48 \pm 1.13 \text{ g} \cdot \text{d}^{-1}$ during the study period, respectively. The mean daily E_c of Guangxi, Sichuan, Anhui, Yunnan, and Zhejiang provenances exhibited significant differences ($p < 0.01$). Overall, the E_c of these provenances was high from June to August. Soil moisture had different effects on the E_c of the provenances. The provenances from Zhejiang, Sichuan, and Anhui showed higher E_c values when $\text{REW} < 0.4$ than $\text{REW} \geq 0.4$ conditions, but the E_c of Guangxi and Yunnan provenances showed no significant differences under the two conditions. When the soil was relatively moist, E_c of the provenances was mainly influenced by R_s and VPD. When the soil was relatively dry, the main influencing factors were the T_a and VPD. Overall, our findings revealed different provenance-specific responses of E_c to biophysical factors, providing valuable insights for the selection of superior provenances of Chinese fir from the perspective of water use in the context of a changing climate.

KEYWORDS

forest water consumption, sap flow, common garden, provenances, meteorological factors

1 Introduction

Global climate change has significantly affected the composition, structure, and functions of terrestrial ecosystems (Weiskopf et al., 2020). China has the world's largest planted forest area (Cheng et al., 2024). Planted forests in many regions are expected to experience increased frequency and intensity of seasonal drought and extreme precipitation episodes (Sinacore et al., 2019; Taylor et al., 2017), which may considerably affect the structural function and sustainability of forest ecosystems (Hammond et al., 2022). The risk of widespread decline and death in forests remains high (Choat et al., 2018), and scientific management measures must be implemented to prevent this as soon as possible (Manrique-Alba et al., 2022). Plant water use characteristics are critical for sustaining vegetative growth and productivity, particularly in the context of global climate change (Hiroki et al., 2021; Zhao et al., 2022).

Transpiration is the primary plant water consumption pathway and an important component of the water balance in forest ecosystems (Liu et al., 2020, 2021). It reflects the balance of rainfall–transpiration–infiltration, and is crucial for the establishment of water balance mechanisms and regional sustainable water resource management plans (Meusburger et al., 2022). Through photosynthesis, plant roots absorb water from the soil and transport it to the canopy through the stem (Cai et al., 2022). Water finally dissipates through the leaf stomata, which is key in connecting the soil–plant–atmosphere continuum (SPAC) (Deng et al., 2017; Kannenberg et al., 2023). Stem sap flow characterizes water consumption and reveals the characteristics of the specific transpiration response to meteorological conditions and the soil moisture environment (Wan et al., 2023; Li et al., 2023). Thermal dissipation probe technology (TDP) has been used to monitor the sap flow of tree sapwood, which is an important means of exploring changes in water consumption (Pasqualotto et al., 2019). Many studies have suggested that meteorological factors play a decisive role in tree transpiration (Li et al., 2024; Deng et al., 2021). Factors such as air vapor pressure deficit (VPD) and solar radiation (R_s) reflect the atmospheric evaporation demand and are the main driving forces of canopy transpiration (Sun et al., 2021; Chen et al., 2022a). R_s directly affects the opening and closing of leaf stomata, whereas VPD is the driving force of tree transpiration (Pieruschka et al., 2010; Fernandez et al., 2009). Integrating variables that characterize the changes in R_s and VPD comprehensively reflects the response characteristics of stem sap flow to these factors (Lyu et al., 2022). Whitley et al. (2008) found that, in addition to R_s and VPD, incorporating soil moisture into forest water consumption models can accurately estimate water consumption at the forest stand scale. Navarro et al. (2020) demonstrated that the photosynthetic photonflux density, VPD, soil temperature, air temperature, and soil water content all influence E_c . Wang et al. (2020) proposed a new temperature stress function to fit the entire range of sap flow. The response of plant water use to climate change is partly related to the tree species composition of the forest ecosystem (Christoph et al., 2023). In addition, plants respond to environmental conditions by regulating their specific hydraulic systems and leaf stomata (Chen et al., 2022b). Different species have different water-use strategies and

transpiration rates. For example, isohydric plants reduce water transpiration losses by closing stomata under water stress, whereas anisohydric plants maintain partial opening of stomata and higher transpiration rates even under water stress (Hochberg et al., 2018). Recent extreme heat events directly and severely affect tree health (Li et al., 2022). In the context of climate change, the effectiveness of water use strategies is important for tree survival. It is necessary to understand how transpiration in different tree species responds to environmental changes.

Cunninghamia lanceolata is the main timber forest species mentioned in the “National Reserve Forest Construction Plan (2018–2035)” of the “Hunan Hubei Jiangxi Luoxiao Mountain National Reserve Forest Construction Project,” which has a cultivation history of over 1,000 years in China. The ninth forest resource inventory data show that the total area of *C. lanceolata* plantations has reached $990.20 \times 10^4 \text{ hm}^2$, accounting for 29% of the total planted forest area, with a storage volume of $7.55 \times 108 \text{ m}^3$ (SFA, 2019). Maintaining the long-term productivity of *C. lanceolata* plantations is of great significance for improving the stability of regional ecosystems, quality of regional forests, and regional ecological environment (Tanay et al., 2023). However, changes in precipitation patterns caused by climate change and extreme weather pose a serious threat to improving *C. lanceolata* productivity in subtropical China (Zhang Y. et al., 2023). Hence, to better formulate scientific water management policies in the context of climate change, possible species-specific water-use regulations for *C. lanceolata* must be clarified.

The *C. lanceolata* provenance experiment conducted in the 1970s as a large-scale field control test site for studying the long-term response of plants to climate change was useful for analyzing the geographical provenance effects and providing a basis for selecting provenances (Hong, 1994). Studies have reported that genetic effects explain 50%–70% of the variations in *C. lanceolata* productivity (Wu et al., 2021), and it is necessary to reveal the mechanism of productivity from the perspective of adaptation of the provenance to a changing environment. Significant differences in genetic composition, morphology, adaptability, growth, resistance to temperature, humidity, and other factors in *C. lanceolata* plantations have been observed during evolution (Hong, 1994). *C. lanceolata* distributed between 25°N and 28°N exhibited better growth rates than those at other provenances (Wu et al., 2021). Experiments conducted in common gardens have been limited to research on growth characteristics and functional traits (Klisz et al., 2019), but the regulation of plant growth is crucial under changing climate conditions (Jiao et al., 2021; Zhang et al., 2023), while there are few reports on water consumption in common garden experiments. At present, research on sap flow and its response to environmental conditions is being conducted both domestically and internationally for different vegetation types (Steppe et al., 2015). However, further research is required to explain the adaptability of provenances to the environment from the perspective of water use in the context of climate change. Therefore, we compared and determined the water use relationships of the provenances in a common garden of *C. lanceolata*, to reveal the regulatory mechanism of plant water consumption and provide scientific water management for plantations in subtropical areas. Specifically, we hypothesized that (1) the canopy transpiration of *C. lanceolata* provenances would be

significantly different, (2) the response of canopy transpiration to soil water conditions varies for different provenances, and (3) the response of canopy transpiration to environmental factors varies for different provenances because provenances will exhibit different water use strategies during the dry and wet seasons.

2 Materials and methods

2.1 Study site

This study was conducted in Dagangshan, JiangXi Province (Figure 1), China (114°31'23"E–114°44'31"E, 27°32'2"N–27°49'31"N). The mean annual air temperature and precipitation are 15.8°C and 1,600 mm, respectively. Most of the precipitation occurs from April to June, accounting for 45% of the annual precipitation.

In 1981, the Chinese Academy of Forestry conducted a geographical provenance experiment on Chinese fir in Dagangshan, which established a common garden containing 183 Chinese fir provenances. In this study, we selected 15 provenances (Table 1) from five provinces growing in the common garden in Dagangshan for 41 years under the same climatic conditions with consistent slope orientation, soil, and altitude conditions, located in adjacent groups, during the provenance experiment design to investigate the transpiration characteristics of Chinese fir from different regions.

The area of Chinese fir sapwood (A_s) was indirectly measured using the growth cone method, and 20 Chinese fir trees with good growth status and different diameters at breast height were selected from the plot. During the growing season, sapwood samples were collected from the diameter at breast height using a growth cone drill, and the length of the sapwood was measured using a Vernier caliper to calculate A_s (Figure 2).

2.2 Monitoring environmental factors

Meteorological factors, including precipitation (P , mm), air temperature (T_a , °C), relative air humidity (RH , %), solar radiation (R_s , $W \cdot m^{-2}$), and wind speed (W_s , $m \cdot s^{-1}$), were measured by an automatic weather station (Campbell Scientific, Inc., Logan, UT, USA) every 10 min in an open field approximately 100 m away from the study plot. The vapor pressure deficit (VPD , kPa) was calculated using T_a and RH using Equation 1 (Campbell and Norman, 1998).

$$VPD = 0.611 \times (1 - RH) \times \exp\left(\frac{17.502 \times T_a}{T_a + 240.97}\right) \quad (1)$$

The soil volumetric water content (VWC) in the different layers of (0 cm–20 cm, 20.1 cm–40 cm, 40.1 cm–60 cm, 60.1 cm–80 cm, and 80.1 cm–100 cm) was monitored at a single location close to the sap flow-measured in the Chinese fir plot using TDR 100 soil moisture sensors (Campbell Scientific, Inc., Logan, UT, USA). Data were recorded using a CR1000 logger (Campbell Scientific, Inc., Logan, UT, USA) every 10 min. The relative extractable water (REW) in the soil layer was calculated using Equation 2:

$$REW = \frac{VWC_a - VWC_w}{VWC_c - VWC_w} \quad (2)$$

where VWC_a (%), VWC_w (%), and VWC_c (%) are the averages of the actual VWC, soil wilting moisture, and soil field capacity in the 0 cm–100 cm soil layer, respectively. In a previous study, stand transpiration was found to be more affected by soil moisture when $REW < 0.4$ (Chen et al., 2022a). Thus, soil water availability can be classified into two categories: no soil water stress when $REW \geq 0.4$, and water stress when $REW < 0.4$.

2.3 Sap flow measurement and transpiration calculation

This study focused on 15 different Chinese fir provenances (with good growth conditions, consistent environment, minimal difference in diameter at breast height, and no pests or diseases). Continuous measurements were performed using a thermal dissipation liquid flow measurement system (TDP-100, China) between 1 September 2020 and 30 September 2022. To prevent the effects of direct sunlight heating on the sensor, a location on the shaded surface of a tree where the sensor was installed was chosen. By shaving off the dried bark, a rectangular space of approximately 3 cm × 6 cm was cleared to avoid damaging the living tissue of the tree. The sensors were installed 1.3 m from the ground to avoid heat gradients caused by cold stem flow coming out of the soil, and one-quarter spherical foam was installed on each side of the TDP probe to protect the sensor wire from twisting pressure and to increase thermal insulation around the probe. Reflective foam, foam balls, and TDP installation parts were used to wrap the outermost layers of the trees. Data from the TDP sensors were collected every 10 min using CR1000 (Campbell Scientific Inc., Logan, UT, USA). Sap flow was calculated using Equation 3 proposed by Granier (1987):

$$V = 0.0119 \times [(dT_M - dT)/dT]^{1.231} \quad (3)$$

where dT is the temperature difference between the two probes (°C), dT_M is the maximum dT value within a day, and V is the sap flow rate ($g \cdot m^{-2} \cdot s^{-1}$).

The transpiration water consumption of the trees was determined based on the sap flow rate and the sapwood area of the trunk, which can be calculated using Equation 4:

$$E_c = A_s \times V \times 3600 \times 24 \quad (4)$$

where E_c is the water consumption within a day ($g \cdot d^{-1}$) and A_s is the sapwood area of the trunk (cm^2).

2.4 Statistical analysis

The E_c of the provenances was studied by province. The provenances from each province were collected, and the mean value was calculated at different timescales. To avoid the possible uncertainty generated by wet canopies and the atmosphere (Chen et al., 2020), data on rainy days were removed when analyzing the responses of stand transpiration to environmental factors (a total of

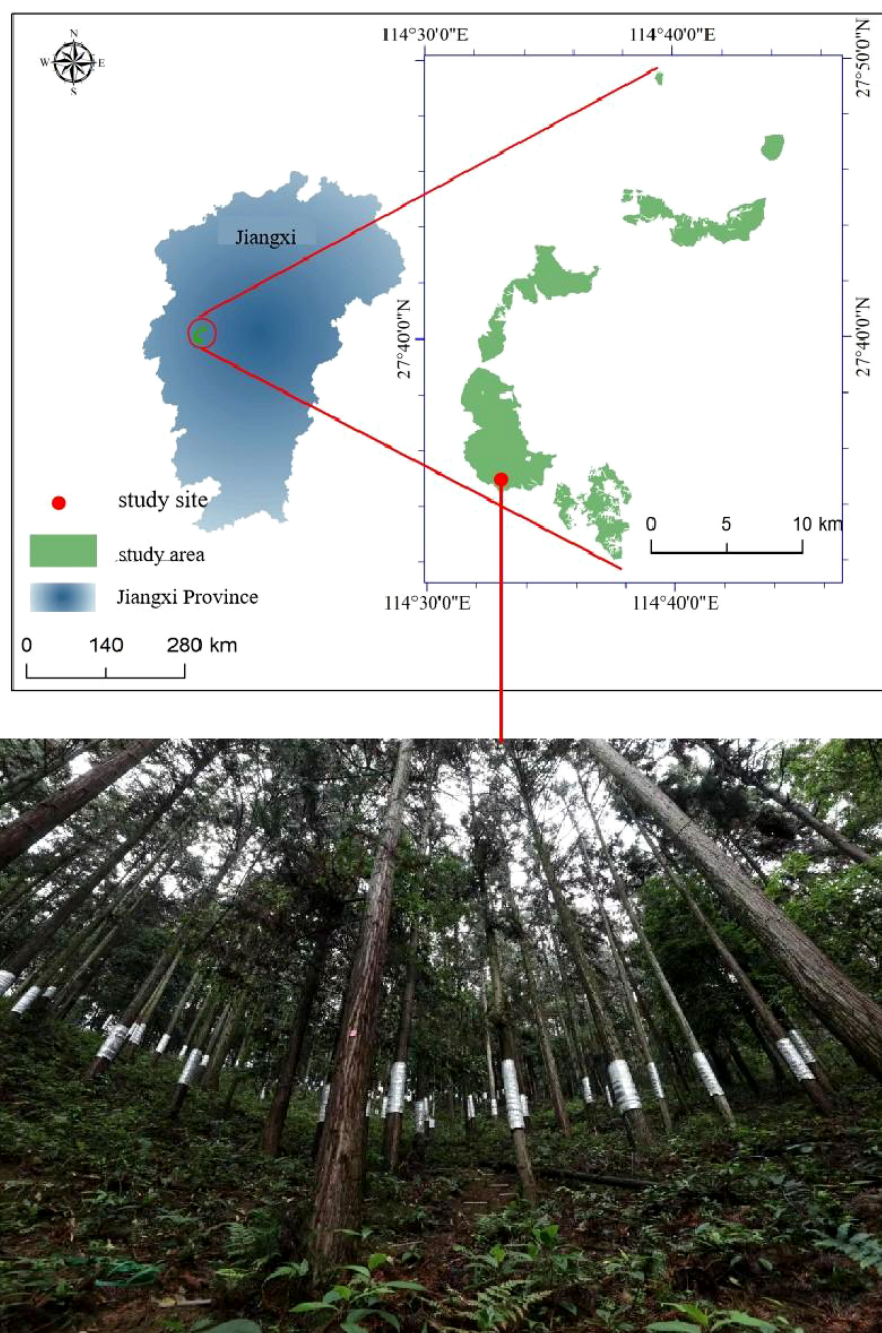


FIGURE 1
The location of study area.

404 days with 0 rainfall were used). Before the analysis, homogeneity of variance and normality tests were performed on the data. If the prerequisites for analysis of variance were not met, Kruskal–Wallis tests were performed to examine the differences in the E_c among provenances, and the Mann–Whitney U test was performed to examine the differences in transpiration under different soil moisture conditions of the provenances.

We used path analysis to quantify the direct and indirect effects of environmental factors on the E_c of the provenances. All explanatory

variables (VPD, R_s , and T_a) were assumed to impact the predicted variables (E_c) before the path analysis. The direct and indirect effects of each factor were quantified by standardized path coefficients, which were calculated using the maximum likelihood method, and the total effects were the sum of the direct and indirect effects. The final model structure was determined when the root mean square error of approximation (RMSEA) was <0.05 , and the goodness of fit index (GFI) was >0.95 . Path analysis was performed using AMOS (version 26.0; IBM SPSS, Chicago, IL, USA).

TABLE 1 Basic characteristics of the provenances.

Province	Provenance	DBH (cm)	Sapwood area (cm ²)
Guangxi(GX)	Guigang, Guangxi	21.0	47.9
	Gongcheng, Guangxi	24.4	59.8
	Lingchuan, Guangxi	32.3	90.5
Sichuan(SC)	Hongya, Sichuan	22.3	52.3
	Pengxian, Sichuan	18.8	40.6
	Nanhong, Sichuan	23.2	55.5
Anhui(AH)	Taihu, Anhui	23.4	56.2
	Jinzhai, Anhui	13.7	25.4
	Xiuning, Anhui	23.6	56.9
Yunnan(YN)	Zhenxiong, Yunnan	18.2	38.7
	Xichou, Yunnan	18.8	40.6
	Maguan, Yunnan	21.3	48.9
Zhejiang(ZJ)	Lishui, Zhejiang	20.4	45.8
	Longquan, Zhejiang	32.0	89.4
	Yunhe, Zhejiang	23.8	57.6

3 Results

3.1 Climatic and soil moisture characteristics

The daily variations in meteorological factors are summarized in Figure 3. The daily mean VPD, Rs, Ta, RH, and Ws values were $0.95 \text{ kPa} \pm 0.79 \text{ kPa}$, $181.07 \text{ W} \cdot \text{m}^{-2} \pm 136.97 \text{ W} \cdot \text{m}^{-2}$, $16.77^\circ\text{C} \pm 9.02^\circ\text{C}$, $56.18\% \pm 38.66\%$, and $0.49 \text{ m} \cdot \text{s}^{-1} \pm 0.18 \text{ m} \cdot \text{s}^{-1}$, respectively. Overall, VPD and Rs reached their maxima in May 2021. Ta was the highest in July and lowest in January. There were 145 days with RH $\geq 90\%$. The P was mainly distributed in April and May. P was $\leq 10 \text{ mm}$ in August and September 2022. The daily mean VWC was $0.313 \text{ m}^3 \cdot \text{m}^{-3} \pm 0.043 \text{ m}^3 \cdot \text{m}^{-3}$. Variations in VWC were generally similar to those in P, which reached the highest values in May and June.

3.2 Differences in water consumption of the provenances

The mean daily Ec values of the provenances from Guangxi, Sichuan, Anhui, Yunnan, and Zhejiang were significantly different ($P < 0.01$). The Ec were $1.31 \text{ g} \cdot \text{d}^{-1} \pm 0.99 \text{ g} \cdot \text{d}^{-1}$, $1.59 \text{ g} \cdot \text{d}^{-1} \pm 1.18 \text{ g} \cdot \text{d}^{-1}$, $1.62 \text{ g} \cdot \text{d}^{-1} \pm 1.43 \text{ g} \cdot \text{d}^{-1}$, $1.41 \text{ g} \cdot \text{d}^{-1} \pm 1.01 \text{ g} \cdot \text{d}^{-1}$, and $1.48 \text{ g} \cdot \text{d}^{-1} \pm 1.13 \text{ g} \cdot \text{d}^{-1}$ during the study period, respectively. The Ec of Guangxi provenances was significantly lower than that of the other provenances ($P < 0.05$). The Anhui and Zhejiang provenances did not show significantly different water consumption patterns ($P > 0.05$). Overall, the Ec of the provenances was high from June to August. The Ec of the provenances from Guangxi reached its

maximum value in August 2022, whereas the other four provenances reached a maximum in June 2021. All the provenances experienced low levels between December and February (Figure 4).

3.3 Differences in water consumption under different soil water conditions

The soil moisture had different effects on the Ec of the provenances (Figure 5). Sichuan, Anhui, and Zhejiang provenances had significantly higher Ec values when $\text{REW} < 0.4$ than $\text{REW} > 0.4$. However, the difference in the Ec of the Guangxi and Yunnan provenances under the two conditions was not significant. Among them, the Anhui provenances showed the greatest difference between the two cases, with 18.19% higher Ec in $\text{REW} < 0.4$ than $\text{REW} \geq 0.4$.

3.4 Provenance differences in the environmental responses of Ec

Path analysis was conducted to assess the effects of meteorological factors on Ec under different REW conditions for provenances in Sichuan, Anhui, and Zhejiang. For provenances from Guangxi and Yunnan, we tested the meteorological influence on Ec throughout the study period (Figure 6). When $\text{REW} \geq 0.4$, the main factors affecting Ec were Rs and VPD ($p < 0.001$). However, Ta and VPD become dominant influencing factors under $\text{REW} < 0.4$ conditions ($p < 0.001$), and only AH provenances also be affected by Rs under these conditions ($p < 0.001$). The effectiveness of VPD on Ec diminished as REW decreased, except for SC provenance. Throughout the study period, the Ec of Guangxi provenances was influenced by Rs, VPD, Ws, and RH, while the impact factors for the Yunnan provenances were limited to Rs and VPD. The effects of environmental factors on Ec varied among provenances.

4 Discussion

4.1 Ec of the provenances

Sap flux and sap flux density exhibited considerable variation across tree species. Many studies have shown that significant differences exist among species, attributed to physiological differences, such as DBH and lifestyle (Schoppach et al., 2021; Siddiq and Cao, 2018). In this study, the Ec of the provenances was significantly different ($P < 0.01$) during the study period. The Ec of the Anhui provenances was relatively higher than that of the other provenances, whereas the Guangxi provenances exhibited a lower Ec. Tree species, size, and physiological characteristics influence tree transpiration (Jose et al., 2021). Wu et al. (2021) found that the growth rate of different provenances varies, leading to significant differences in tree height and DBH. Many studies have indicated that trees with a larger DBH typically have higher transpiration requirements, thus requiring higher sap flow rates to meet their water demands (Wang et al., 2023). However, in this study, the

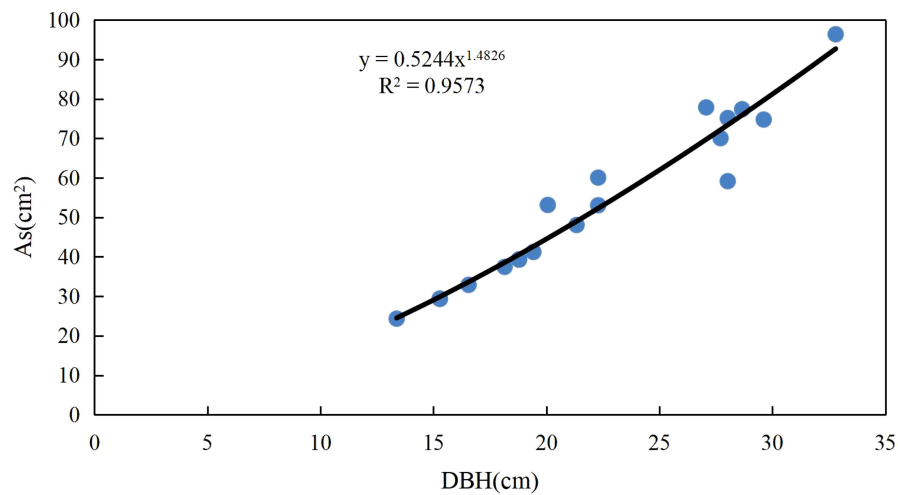


FIGURE 2

The relationship between sapwood area and diameter at breast height.

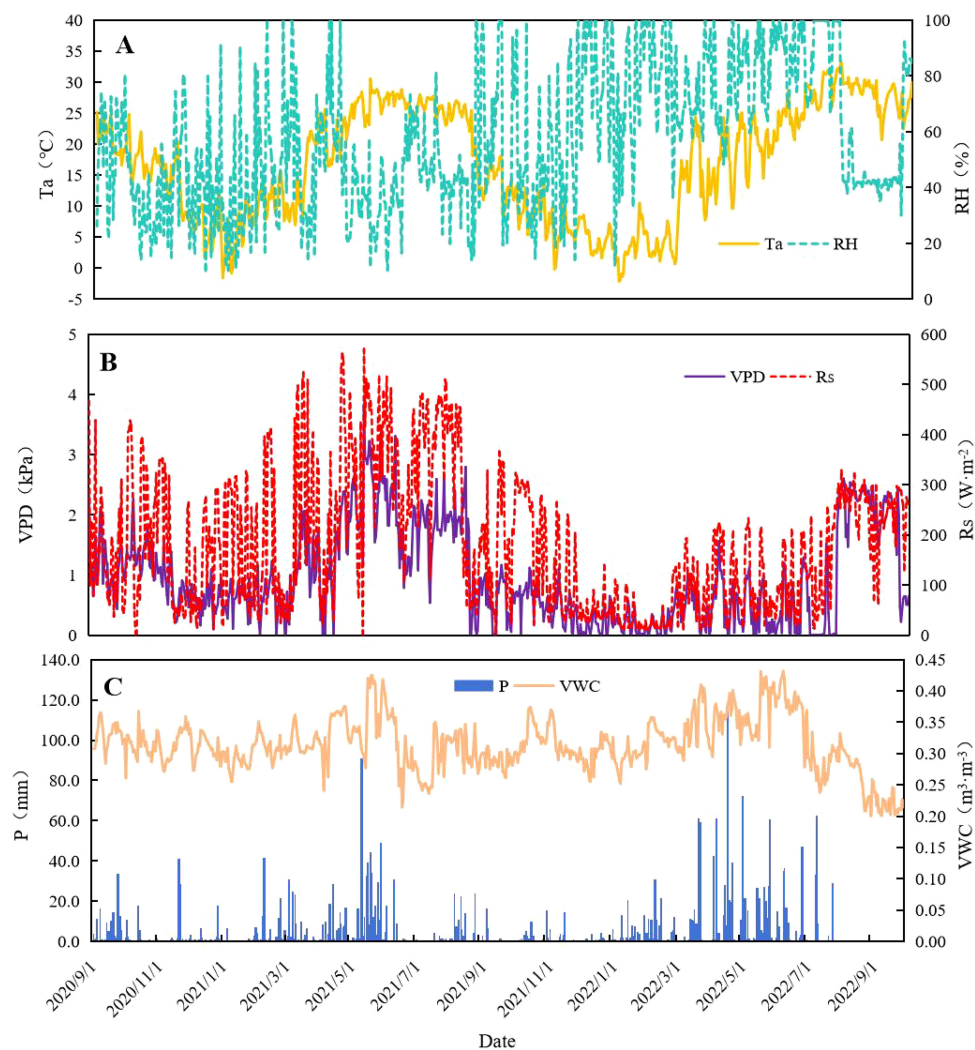


FIGURE 3

Variations in daily air temperature (T_a), relative air humidity (RH) (A), solar radiation (R_s , $\text{w}\cdot\text{m}^{-2}$), vapor pressure deficit (VPD) (B), precipitation (P), and soil volumetric water content (VWC) (C) during the study period.

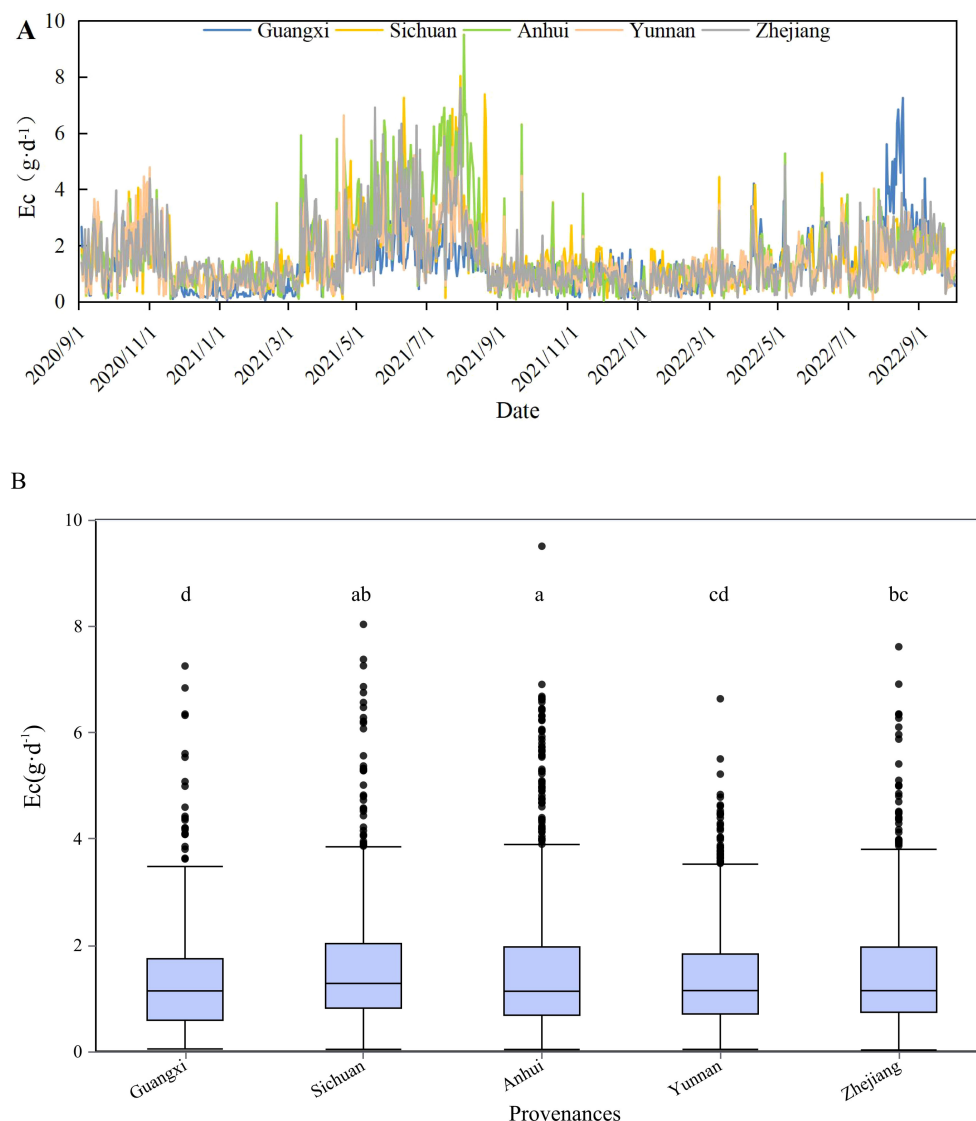


FIGURE 4
Daily variations (A) in the E_c of different provenances and distribution of E_c of different provenances (B). Different letters indicate significant differences among the provenances ($P < 0.05$).

Guangxi provenance, which had the largest DBH, exhibited the lowest E_c . This phenomenon can primarily be attributed to the fact that DBH is not the sole factor affecting sap flow, such as crown size, as well as the number of branches and leaves, also play significant roles (Tfwala et al., 2019). The differences in transpiration among the different provenances may be related to their physiological mechanisms (Gao et al., 2021). The structure of the xylem directly affects the efficiency of water transmission. The size, quantity, and arrangement of xylem conduits influence both the speed and efficiency of the sap flow (Trueba et al., 2019). Species with larger diameters and a larger number of conduits usually exhibit higher transpiration rates (Zhang et al., 2022). Furthermore, studies have demonstrated that stomatal density and the mechanisms governing stomatal opening and closing differ among provenances (Chen et al., 2023; Xu R. et al., 2023), which can affect transpiration rates and, consequently, overall water consumption. Differences in

hydraulic conductivity among tree species are also critical factors affecting transpiration. Species with high hydraulic conductivity can maintain high sap flow rates under different conditions (Chen et al., 2022b). Provenances from low-rainfall areas tend to possess strong tolerance to diverse climatic conditions and employ more effective water conservation strategies, whereas provenances from high-rainfall areas may exhibit different adaptive strategies, resulting in differences in E_c among provenances. Wang et al. (2022) found that the response of provenances to temperature and precipitation can be divided into various geographic groups along longitudinal and latitudinal gradient, leading to distinct patterns in growth and transpiration. Additionally, studies have identified significant functional trait differences among provenances (Xu R. et al., 2023; Shou et al., 2024), which can influence resource acquisition and utilization, ultimately resulting in differences in growth or water consumption (Xu T. Y. et al., 2022). Moreover, water use efficiency

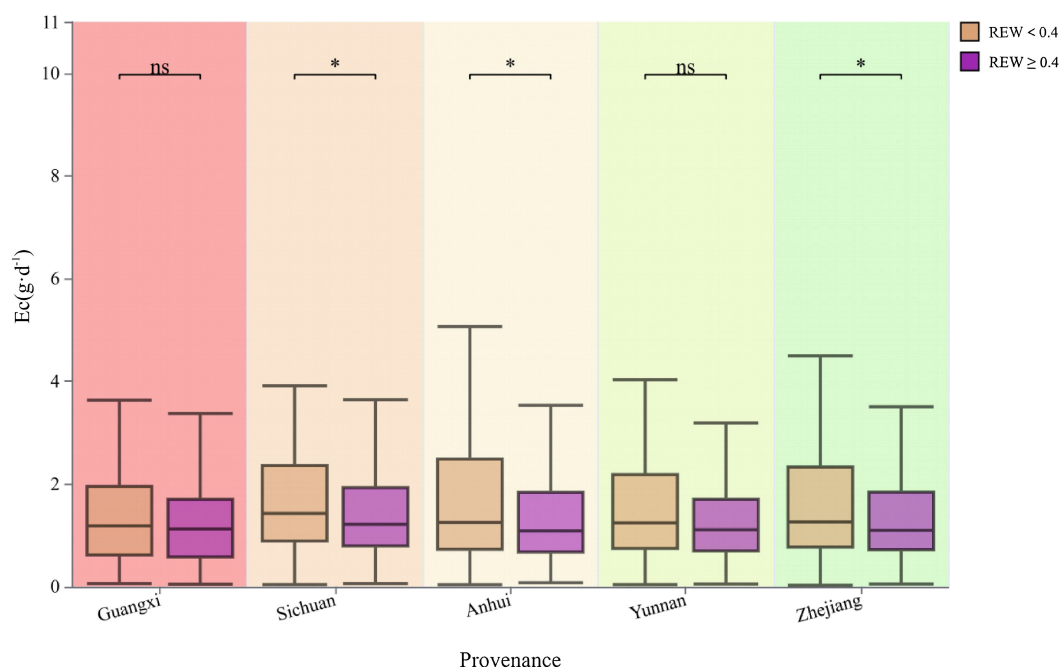


FIGURE 5

Provenance differences in Ec under different soil water availability conditions. NS, no significant difference ($P > 0.05$); *, significant difference ($P < 0.05$).

varies among different provenances (Xu R. et al., 2023), contributing to significant differences in water consumption.

4.2 Differences in Ec under different soil water conditions

The results of this study indicated that the Ec of all provenances was higher when $REW < 0.4$ than $REW > 0.4$. This phenomenon can be attributed to the fact that high Rs and VPD facilitate transpiration pull and capillarity, enabling water uptake at the beginning of the drought (Justyna et al., 2022). Conditions with $REW > 0.4$ often occurred the day after rainfall, during which RH was relatively high, VPD was relatively low, and the boundary layer was unsuitable for tree transpiration (Xu et al., 2020). Some studies conducted in arid regions have presented differing results compared with the present study. For instance, research in a semi-arid area has shown that a relatively low REW increases the degree of xylem embolism and reduces the gas exchange rate when plants experience drought, leading to a significant decrease in Ec (Lyu et al., 2022). Chen et al. (2022a) found that soil moisture significantly affects tree transpiration in semi-arid urban environments, where trees reduce transpiration during the dry season to minimize excessive water consumption. Conversely, other studies have indicated that these trees tend to have more stable water consumption in non-urban areas (Chen et al., 2023). Additionally, some tree species have been identified as insensitive to drought, suggesting that they possess a high adaptability to soil moisture deficiency (Du et al., 2011). Based on the present results, soil moisture may not be a vital factor affecting plantations in subtropical areas of China. Some studies

have reached similar conclusions. The impact of soil moisture content on transpiration throughout the drought period was very low (Oogathoo et al., 2020; Song et al., 2020). Research in the subtropical regions of China has found that canopy transpiration of *Schima superba* is less limited by soil moisture during the rainy season, and the overall effect is mainly influenced by energy factors (Li et al., 2023). Even under dry conditions, these trees can maintain relatively stable transpiration rates, thereby enhancing water-use efficiency and ultimately promoting growth (Ouyang et al., 2022). Regarding Ec under different REW conditions, the range of Ec from the Anhui provenances was the highest, indicating that they adopted a progressive strategy with less sensitivity to stomatal regulation. Differences in soil moisture conditions did not significantly affect the transpiration of Guangxi and Yunnan provenances, likely because of their overall weaker transpiration.

4.3 Differences in environmental controls on the Ec among the provenances

The differences in transpiration among provenances are related to provenance-specific water use and sensitivity to environmental factors (Wang et al., 2019). Many studies have shown that physiological and environmental factors influence the plant Ec (Hayat et al., 2022; Ma et al., 2019). Meteorological conditions, particularly Rs and VPD, are the primary factors that control canopy transpiration (Oogathoo et al., 2020). Liu et al. (2023) found that there is a significant nonlinear relationship among Rs, VPD, REW, and LAI and Ec. Although VPD and Rs are the main controlling factors for Ec changes, their effects diminish during the

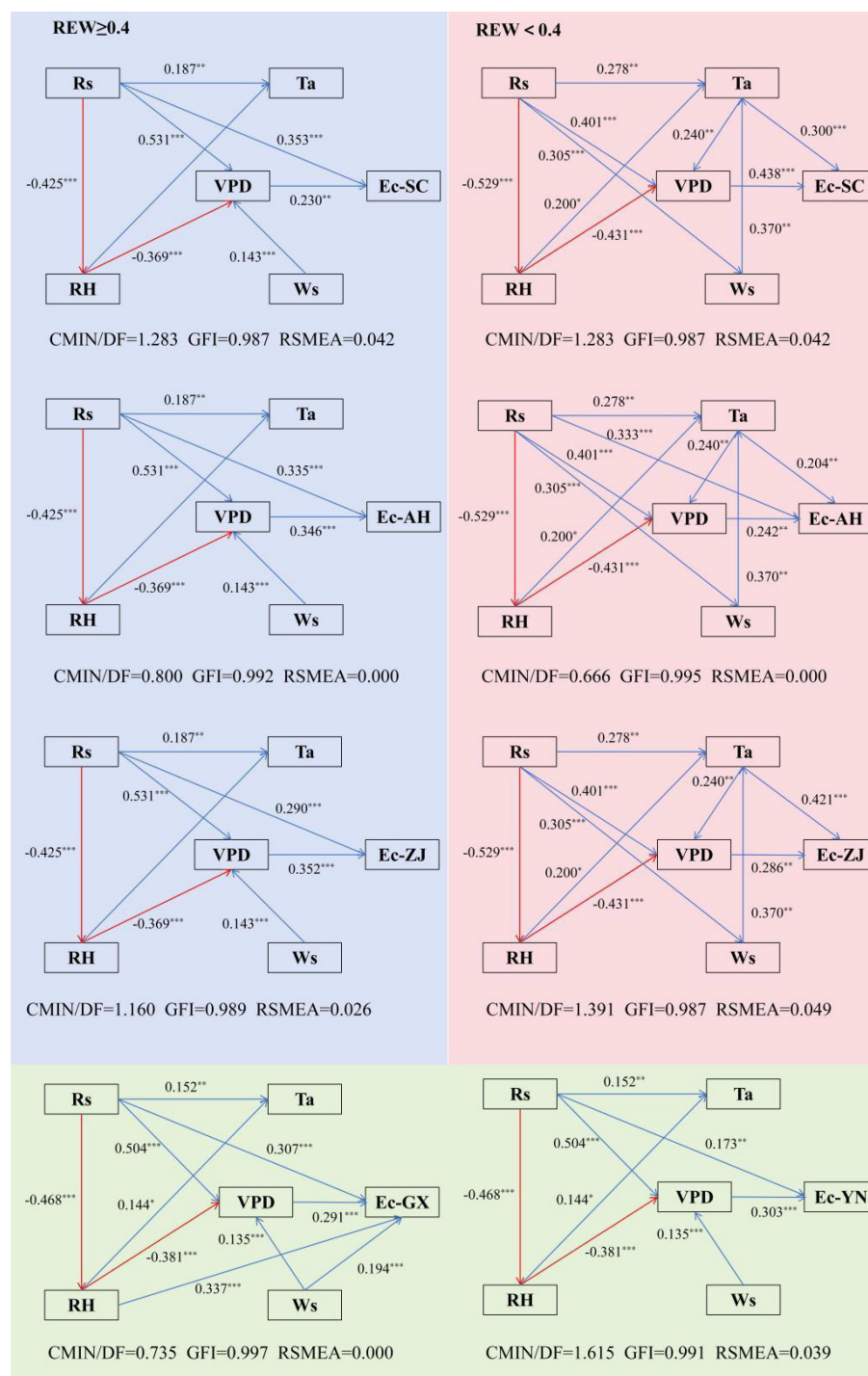


FIGURE 6

Direct and indirect effects of meteorological variables on Ec. The blue area is the analysis for REW ≥ 0.4 condition, the red area is the analysis for REW < 0.4 condition, the green area is the analysis for the entire study period. Red and blue arrows represent significant positive and negative impacts, respectively. ***: $p < 0.001$, **: $p < 0.01$.

drought period, which aligns with the findings of this study. [Chen et al. \(2023\)](#) and [Song et al. \(2022\)](#) also reported such results. The Ec of these provenances was affected by both the energy and water conditions throughout the study period. In the present study, we observed a correlation between Ec and Ta under drought conditions, which is consistent with the findings of

[Ouyang et al. \(2022\)](#) and [Tie et al. \(2017\)](#). Previous studies have also demonstrated that incorporating Ta, Rs, and VPD into transpiration prediction models can improve their accuracy of model predictions ([Navarro et al., 2020](#); [Wang et al., 2020](#)). [Wang et al. \(2022\)](#) analyzed the sensitivity of different provenances to climate using tree ring analysis methods, demonstrated that there is

the greatest differentiation among Chinese fir provenances occurs in the strength of the correlations between climate variables (temperature and precipitation) and tree ring indices. Furthermore, tree ring width and iWUE are primarily sensitive to temperature (Wang et al., 2024), further confirming the impact of temperature on forest growth and water consumption.

4.4 Implications and limitations

Plantations consume large volumes of water to maintain physiological activities (Marchionni et al., 2019). Particularly, during the relatively dry period of June and July 2021, the higher atmospheric evaporation demand promoted the loss of tree water more than in any other month. As the plantation experienced reduced physiological activities from September to March, Ec was maintained at a relatively low level. However, climate change also has a significant effect on water use (Choat et al., 2018). Chinese fir plantations not only ensure timber security but also provides multiple ecosystem services in China's subtropical region (Zeng et al., 2021), as one of the most effective nature-based solutions (NBS) to mitigate global change. Therefore, it is important to understand the water use and the biophysical governing mechanisms of different provenances to select provenances for afforestation to maximize comprehensive benefits. However, our study focused on the water consumption of provenances from five provinces, which did not provide a complete picture of plant transpiration or the governing mechanisms for all provenances across different climate zones. Provenances collected in a common garden provide an opportunity to comprehensively understand the regulatory mechanisms of tree transpiration and help guide the selection of sustainable forest management objectives for provenances under global climate change.

5 Conclusions

This study revealed the difference in canopy transpiration of Chinese fir provenances from five provinces and their unique responses to meteorological factors. The mean daily Ec values of Guangxi, Sichuan, Anhui, Yunan, and Zhejiang provenance were significantly different ($p < 0.05$). Overall, the provenances of Ec were high from June to August. Soil moisture has different effects on the Ec of the provenances. Soil moisture had different effects on the Ec of the provenances. All provenances had higher Ec values when REW < 0.4 . However, the difference between Guangxi and Yunnan provenances under the two conditions was not significant. When the soil was relatively moist, Ec of the provenances was mainly affected by Rs and VPD. Ta and VPD were the main factors when the soil was relatively dry.

This study highlights the distinct responses of Ec to meteorological conditions among the provenances. The unique response of Ec to varying environments reveals different water use strategies among provenances. Comprehensive insights are needed to understand the complex forest-water relationships and

integrated regional forest-water management under the climate change scenario from a water use perspective. The intrinsic physiological mechanisms of plants should also be considered in subsequent research on the factors that affect plant Ec.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

TX: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. XN: Methodology, Writing – review & editing. BW: Investigation, Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Cai, G., Ahmed, M. A., Abdalla, M., and Carminati, A. (2022). Root hydraulic phenotypes impacting water uptake in drying soils. *Plant Cell Environ.* 45, 650–663. doi: 10.1111/pce.14259
- G. S. Campbell and J. M. Norman (Eds.) (1998). *An Introduction to Environmental Biophysics*. (New York, NY: Springer New York).
- Chen, S. N., Chen, Z. S. N., Feng, Z. Y., Kong, Z., Xu, H., and Zhang, Z. Q. (2023). Species difference of transpiration in three urban coniferous forests in a semiarid region of China. *J. Hydrol.* 617, 129098. doi: 10.1016/j.jhydrol.2023.129098
- Chen, S. N., Chen, Z. S. N., Kong, Z., and Zhang, Z. Q. (2022b). The increase of leaf water potential and whole-tree hydraulic conductance promotes canopy conductance and transpiration of *Pinus tabulaeformis* during soil droughts. *Tree* 37, 41–52. doi: 10.1007/s00468-022-02322-z
- Chen, S. N., Chen, Z. S. N., Xu, H., Kong, Z., Xu, Z. B., Liu, Q. Q., et al. (2022a). Biophysical regulations of transpiration and water use strategy in a mature Chinese pine (*Pinus tabulaeformis*) forest in a semiarid urban environment. *Hydrol. Process.* 36, e14485. doi: 10.1002/hyp.14485
- Chen, Z., Zhang, Z., Sun, G., Chen, L., Xu, H., and Chen, S. (2020). Biophysical controls on nocturnal sap flow in plantation forests in a semi-arid region of northern China. *Agric. For. Meteorol.* 284, 107904. doi: 10.1016/j.agrformet.2020.107904
- Cheng, K., Yang, H. T., Tao, S. L., Su, Y. J., Guan, H. C., Ren, Y., et al. (2024). Carbon storage through China's planted forest expansion. *Nat. Commun.* 15, 4106. doi: 10.1038/s41467-024-48546-0
- Choat, B., Brodribb, T. J., Brodersen, C. R., Duursma, R. A., López, R., and Medlyn, B. E. (2018). Triggers of tree mortality under drought. *Nature* 558, 531–539. doi: 10.1038/s41586-018-0240-x
- Christoph, B., Rafael, P., Víctor, F., Jordi, M., Maurizio, M., Víctor, G., et al. (2023). Stand structure of Central European forests matters more than climate for transpiration sensitivity to VPD. *J. Appl. Ecol.* 60, 886–897. doi: 10.1111/1365-2664.14383
- Deng, Y., Wu, S., Ke, J., and Zhu, A. (2021). Effects of meteorological factors and groundwater depths on plant sap flow velocities in karst critical zone. *Sci. total Environ.* 781, 146764. doi: 10.1016/j.scitotenv.2021.146764
- Deng, Z., Guan, H., Hutson, J., Forster, M., Wang, Y., and Simmons, C. (2017). A vegetation-focused soil-plant-atmospheric continuum model to study hydrodynamic soil-plant water relations. *Water Resour. Res.* 53, 4965–4983. doi: 10.1002/2017WR020467
- Du, S., Wang, Y. H., Kume, T., Zhang, J. G., Otsuki, K., Yamanaka, N., et al. (2011). Sapflow characteristics and climatic responses in three forest species in the semiarid Loess Plateau region of China. *Agric. For. Meteorol.* 151, 1–10. doi: 10.1016/j.agrformet.2010.08.011
- Fernandez, M. E., Gyenge, I., and Schlichter, T. (2009). Waterflux and canopy conductance of natural versus planted forests in Patagonia, South America. *Trees* 23, 415–427. doi: 10.1007/s00468-008-0291-y
- Gao, S., Cai, Z.-Y., Yang, C.-C., Luo, J.-X., and Zhang, S. (2021). Provenance-specific ecophysiological responses to drought in *Cunninghamia lanceolata*. *J. Plant Ecol.* 14, 1060–1072. doi: 10.1093/jpe/rtab045
- Granier, A. (1987). Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. *Tree Physiol.* 3, 309–320. doi: 10.1093/treephys/3.4.309
- Hammond, W. M., Williams, A. P., Abatzoglou, J. T., Adams, H. D., Klein, T., López, R., et al. (2022). Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. *Nat. Commun.* 13, 1761–1711. doi: 10.1038/s41467-022-29289-2
- Hayat, M., Yan, C. H., Xiang, J., Xiong, B., Qin, L. J., Khan, A., et al. (2022). Multiple-temporal scale variations in nighttime sap flow response to environmental factors in *Ficus concinna* over a subtropical megacity, southern China. *Forests* 13, 1059. doi: 10.3390/f13071059
- Hiroki, H., Tomomitsu, K., Atsushi, K., and Yuko, T. H. (2021). Responses of leaf photosynthetic traits, water use efficiency, and water relations in five urban shrub tree species under drought stress and recovery. *Trees* 37, 53–67. doi: 10.1007/s00468-021-02083-1
- Hochberg, U., Rockwell, F. E., Holbrook, N. M., and Cochard, H. (2018). Iso-Anisohydry: A plant-environment interaction rather than a simple hydraulic trait. *Trends Plant Sci.* 23, 112–120. doi: 10.1016/j.tplants.2017.11.002
- Hong, J. S. (1994). Excellent provenance selection of *Cunninghamia lanceolata* afforestation. *For. Res.* 7, 1–25.
- Jiao, W. Z., Wang, L. X., Smith, W. K., Chang, Q., Wang, H. L., and D'Odorico, P. (2021). Observed increasing water constraint on vegetation growth over the last three decades. *Nat. Commun.* 12, 3777. doi: 10.1038/s41467-021-24016-9
- Jose, G. L., Pantana, T., Ram, O., Nataliia, K., Hjalmar, L., and Niles, J. H. (2021). How tree species, tree size, and topographical location influenced tree transpiration in northern boreal forests during the historic 18 drought. *Global Change Biol.* 27, 3066–3078. doi: 10.1111/gcb.v27.13
- Justyna, S., Ina, Z., Ondrej, N., Jan, K., Peter, J., Matjaž, Č., et al. (2022). Species-specific growth and transpiration response to changing environmental conditions in floodplain forest. *For. Ecol. Manage.* 516, 120248. doi: 10.1016/j.foreco.2022.120248
- Kannenberg, S. A., Barnes, M. L., Bowling, D. R., Driscoll, A. W., Guo, J. S., and Anderegg, W. R. L. (2023). Quantifying the drivers of ecosystem fluxes and water potential across the soil-plant-atmosphere continuum in an arid woodland. *Agric. For. Meteorol.* 329, 109269. doi: 10.1016/j.agrformet.2022.109269
- Klisz, M., Buras, A., Sass-Klaassen, U., Puchalka, R., Koprowski, M., and Ukalska, J. (2019). Limitations at the limit? Diminishing of genetic effects in Norway spruce provenance trials. *Front. Plant Sci.* 10, 306. doi: 10.3389/fpls.2019.00306
- Li, X. M., Xi, B. Y., Wu, X. C., Choat, B., Feng, J. C., Jiang, M., et al. (2022). Unlocking drought-induced tree mortality: physiological mechanisms to modeling. *Front. Plant Sci.* 13, 835921. doi: 10.3389/fpls.2022.835921
- Li, X., Zhai, J. Q., Sun, M., Liu, K., Zhao, Y., Cao, Y. K., et al. (2024). Characteristics of changes in sap flow-based transpiration of Poplars, Locust Trees, and Willows and their response to environmental impact factors. *Forests* 15, 90. doi: 10.3390/f15010090
- Li, Y. Q., Zhu, L. W., Ouyang, L., Zhao, X. H., and Zhao, P. (2023). Environmental controls on transpiration of Schima superba trees with different tree sizes under ten years' climate fluctuations in south subtropics, China. *For. Ecol. Manage.* 539, 120995. doi: 10.1016/j.foreco.2023.120995
- Liu, Y., Kumar, M., Katul, G. G., Feng, X., and Konings, A. G. (2020). Plant hydraulic accentuates the effect of atmospheric moisture stress on transpiration. *Nat. Climate Change* 10, 691–695. doi: 10.1038/s41558-020-0781-5
- Liu, Z. Q., Liu, Q. Q., Wei, Z. J., Yu, X. X., Jia, G. D., and Jiang, J. (2021). Partitioning tree water usage into storage and transpiration in a mixed forest. *For. Ecosys.* 8, 72. doi: 10.1186/s40663-021-00353-5
- Liu, Z. B., Yu, S. P., Xu, L. H., Wang, Y. H., Yu, P. T., and Chao, Y. (2023). Differentiated responses of daytime and nighttime sap flow to soil water deficit in a larch plantation in Northwest China. *Agric. Water Manage.* 289, 108540. doi: 10.1016/j.agwat.2023.108540
- Lyu, J. L., He, Q. Y., and Chen, Q. W. (2022). Distinct transpiration characteristics of black locust plantations acclimated to semiarid and subhumid sites in the Loess Plateau, China. *Agricultural Water Management* 2022, 262.
- Ma, C. K., Luo, Y., Shao, M. A., Li, X. D., Sun, L., and Jia, X. X. (2019). Environmental controls on sap flow in black locust forest in Loess Plateau, China. *Sci. Rep.* 7, 13160. doi: 10.1038/s41598-017-13532-8
- Manrique-Alba, A., Begueria, S., and Camarero, J. J. (2022). Long-term effects of forest management on post-drought growth resilience: An analytical framework. *Sci. total Environ.* 810, 152374. doi: 10.1016/j.scitotenv.2021.152374
- Marchionni, V., Guyot, A., Tapper, N., Walker, J. P., and Daly, E. (2019). Water balance and tree water use dynamics in remnant urban reserves. *J. Hydrol.* 575, 343–353. doi: 10.1016/j.jhydrol.2019.05.022
- Meusburger, K., Trotsiuk, V., Schmidt-Walter, P., Baltensweiler, A., Brun, P., Bernhard, F., et al. (2022). Soil-plant interactions modulated water availability of Swiss forests during the 2015 and 2018 droughts. *Global Change Biol.* 28, 5928–5944. doi: 10.1111/gcb.v28.20
- Navarro, A., Portillo-Estrada, M., and Ceulemans, R. (2020). Identifying the best plant water status indicator for bio-nergy poplar genotypes. *GCB Bioenergy* 12, 426–444. doi: 10.1111/gcb.12687
- Oogathoo, S., Houle, D., Duchesne, L., and Kneeshaw, D. (2020). Vapour pressure deficit and solar radiation are the major drivers of transpiration of balsam fir and black spruce tree species in humid boreal regions, even during a short-term drought. *Agric. For. Meteorol.* 291, 108063. doi: 10.1016/j.agrformet.2020.108063
- Ouyang, L., Lu, L. W., Wang, C. L., Li, Y. Q., Wang, J. Y., Zhao, X. H., et al. (2022). A 14-year experiment emphasizes the important role of heat factors in regulating tree transpiration, growth, and water use efficiency of Schima superba in South China. *Agric. Water Manage.* 273, 107902. doi: 10.1016/j.agwat.2022.107902
- Pasqualotto, G., Carraro, V., Menardi, R., and Anfodilo, T. (2019). Calibration of Granier-type (TDP) sap flow probes by a high precision electronic potometer. *Sensors* 19, 2419. doi: 10.3390/s19102419
- Pieruschka, R., Gregor Huber, G., and Berry, J. A. (2010). Control of transpiration by radiation. *PNAS* 107, 13372–13377. doi: 10.1073/pnas.0913177107
- Schoppach, R., Chun, K. P., He, Q., Fabiani, G., and Klaus, J. (2021). Species-specific control of DBH and landscape characteristics on tree-to-tree variability of sap velocity. *Agric. For. Meteorol.* 3017, 108533. doi: 10.1016/j.agrformet.2021.108533
- Shou, Y., Wang, B., Niu, X., Song, X. Q., Xu, T. Y., and Wang, Y. H. (2024). Fine root respiration and its relationship with morphological and chemical traits of *Cunninghamia lanceolata* provenances. *For. Res.* 37, 148–156. doi: 10.12403/j.1001-1498.20240068
- Siddiq, J., and Cao, K. F. (2018). Nocturnal transpiration in 18 broadleaf timber species under a tropical seasonal climate. *For. Ecol. Manage.* 418, 47–54. doi: 10.1016/j.foreco.2017.12.043
- Sinacore, K., Asbjornsen, H., Hernandez-Santana, V., and Hall, J. S. (2019). Drought differentially affects growth, transpiration, and water use efficiency of mixed and monospecific planted forests. *Forests* 10, 153. doi: 10.3390/f10020153
- Song, X. W., Lyu, S., and Wen, X. F. (2020). Limitation of soil moisture on the response of transpiration to vapor pressure deficit in a subtropical coniferous

- plantation subjected to seasonal drought. *J. Hydrol.* 291, 125301. doi: 10.1016/j.jhydrol.2020.125301
- Song, L., Zhu, J., Zheng, X., Wang, K., Zhang, J. X., Hao, G. Y., et al. (2022). Comparison of canopy transpiration between *Pinus sylvestris* var. *mongolica* and *Pinus tabulaeformis* plantations in a semiarid sandy region of Northeast China. *Agric. For. Meteorol.* 314, 108784. doi: 10.1016/j.jhydrol.2020.125301
- State Forestry and Grassland Administration of China (2019). *China Forest resources report, (2014–2018)* (Beijing: China Forestry Press).
- Steppe, K., Vandegehuchte, M. W., Tognetti, R., and Mencuccini, M. (2015). Sap flow as a key trait in the understanding of plant hydraulic functioning. *Tree Physiol.* 35, 341–345. doi: 10.1093/treephys/tpv033
- Sun, X., Li, J., Cameron, D., and Moore, G. (2021). On the use of sap flow measurements to assess the water requirements of three Australian native tree species. *Agronomy* 12, 52. doi: 10.3390/agronomy12010052
- Tanay, B., Almuth, H., Bernard, S., Jolanda, R., and Wingfield, M. J. (2023). Continuous replanting could degrade soil health in short-rotation plantation forestry. *Curr. Forest Rep.* 9, 230–250. doi: 10.1007/s40725-023-00188-z
- Taylor, C. M., Belusic, D., Guichard, F., Parker, D. J., Viscel, T., and Bock, O. (2017). Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature* 544, 475–478. doi: 10.1038/nature22069
- Tfwala, C. M., Rensburg, L. D., Bello, Z. A., and Zietsman, P. C. (2019). Transpiration dynamics and water sources for selected indigenous trees under varying soil water content. *Agric. For. Meteorol.* 275, 296–304. doi: 10.1016/j.agrformet.2019.05.030
- Tie, Q., Hu, H. C., Tian, F. Q., Guan, H. D., and Lin, H. (2017). Environmental and physiological controls on sap flow in a subhumid mountainous catchment in North China. *Agric. For. Meteorol.* 240–241, 46–57. doi: 10.1016/j.agrformet.2017.03.018
- Trueba, S., Deizon, S., Isnard, S., and Lens, F. (2019). Similar hydraulic efficiency and safety across vesselless angiosperms and vessel-bearing species with scalariform perforation plates. *J. Exp. Bot.* 70, 3227–3240. doi: 10.1093/jxb/erz133
- Wan, L. L., Zhang, Q., Cheng, L., Liu, Y. J., Qin, S. J., Xu, J. J., et al. (2023). What determines the time lags of sap flux with solar radiation and vapor pressure deficit? *Agric. For. Meteorol.* 333, 109414. doi: 10.1016/j.agrformet.2023.109414
- Wang, H., Duan, A. G., Liu, X. Y., Zhu, A. M., and Zhang, J. G. (2024). Combining tree-ring growth and carbon isotope data enhances the understanding of climate sensitivity and physiological responses for Chinese fir in a common garden. *Agric. For. Meteorol.* 358, 110246. doi: 10.1016/j.agrformet.2024.110246
- Wang, H. L., Guan, H. D., Liu, N., Soulsby, C., Tetzlaff, D., and Zhang, X. P. (2020). Improving the Jarvis-type model with modified temperature and radiation functions for sap flow simulations. *J. Hydrol.* 587, 124981. doi: 10.1016/j.jhydrol.2020.124981
- Wang, Z., Sun, Z., and Cui, J. (2023). Time lag effect on solar radiation of tree sap flux density for different DBH of *Larix olgensis*. *J. Plant Ecol.* 16, rtac092. doi: 10.1093/jpe/rtac092
- Wang, X. M., Wang, X. K., Su, Y. B., and Zhang, H. X. (2019). Land pavement depresses photosynthesis in urban trees especially under drought stress. *Sci. Total Environ.* 653, 120–130. doi: 10.1016/j.scitotenv.2018.10.281
- Wang, H., Zhu, A. M., Duan, A. G., et al. (2022). Responses to subtropical climate in radial growth and wood density of Chinese fir provenances, southern China. *For. Ecol. Manage.* 521, 120428. doi: 10.1016/j.foreco.2022.120428
- Weiskopf, S. R., Rubenstein, M. A., Crozier, L. G., Gaichas, S., Griffis, R., and Halofsky, J. E. (2020). Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Sci. Total Environ.* 733, 137782. doi: 10.1016/j.scitotenv.2020.137782
- Whitley, R., Zeppel, M., Armstrong, N., MacinnisNg, C., Yunusa, I., and Eamus, D. (2008). A modified Jarvis-Stewart model for predicting stand-scale transpiration of an Australian native forest. *Plant Soil* 305, 35–47. doi: 10.1007/s11104-007-9399-x
- Wu, H., Lei, J., Li, X., Wang, H., Duan, A., and Zhang, J. (2021). Aggregation distributions across stand age in provenances of *Cunninghamia lanceolata* (Lamb.) Hook. *For. Ecol. Manage.* 494, 119317. doi: 10.1016/j.foreco.2021.119317
- Xu, R., Cheng, S., Zhou, J., T. M., Ma, X. Q., and Li, M. (2023). Intraspecific variations in leaf functional traits of *Cunninghamia lanceolata* provenances. *BMC Plant Biol.* 23, 92. doi: 10.1186/s12870-023-04097-y
- Xu, T. Y., Niu, X., Wang, B., Qiu, X. H., Shou, Y., Luo, J. N., et al. (2023). Variations in leaf functional traits and photosynthetic parameters of *Cunninghamia lanceolata* Provenances. *Forests* 14, 1708. doi: 10.3390/f14091708
- Xu, K., Zheng, C., and Ye, H. (2020). The transpiration characteristics and heat dissipation analysis of natural leaves grown in different climatic environments. *Heat Mass Transfer* 56, 95–108. doi: 10.1007/s00231-019-02701-2
- Zeng, Y. L., Wu, H. L., Ouyang, S., Chen, L., Fang, X., Peng, C. H., et al. (2021). Ecosystem service multi functionality of Chinese fir plantations differing in stand age and implications for sustainable management. *Sci. Total Environ.* 788, 147791. doi: 10.1016/j.scitotenv.2021.147791
- Zhang, S. B., Wen, G. J., Qu, Y. Y., Yang, L. Y., and Song, Y. (2022). Trade-offs between xylem hydraulic efficiency and mechanical strength in Chinese evergreen and deciduous savanna species. *Tree Physiol.* 42, 1337–1349. doi: 10.1093/treephys/tpac017
- Zhang, Y., Xu, Q., Zhang, B. B., Gao, D. Q., Wang, T., Xu, W. B., et al. (2023). Contrasting water-use patterns of Chinese fir among different plantation types in a subtropical region of China. *Front. Plant Sci.* 13, 946508. doi: 10.3389/fpls.2022.946508
- Zhao, M., Geruo, A., Liu, Y., L. M., and KÖNINGS, A. (2022). Evapotranspiration frequently increases during droughts. *Nature Climate Change* 12, 1024–1030. doi: 10.1038/s41558-022-01505-3