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Thinning vs. Pruning: Impacts on Sap Flow Density and Water Use Efficiency in Young *Populus tomentosa* Plantations in Northern China

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Abstract: Water is a vital resource for tree growth, and changes in plantation and canopy structure can affect stand transpiration (E_c), consequently influencing water use efficiency (*WUE*). *Populus tomentosa* is a fast-growing and productive timber species in China. In recent years, thinning combined with pruning has become a widely used silvicultural practice for timber management. However, its effect on water utilization has been less well studied. To address this gap, we designed experiments with two thinning intensities and three pruning treatments. Thermal dissipation probes were employed to monitor tree sap flow density (J_s), and estimated E_c and canopy conductance (g_c). We established a relationship between the canopy transpiration per unit leaf area (E_L) and g_c and climatic factors. Finally, we compared basal area increment (*BAI*) and *WUE* among treatments under different rainfall conditions. The results indicated that: (1) The pattern of transpiration changes was consistent at both the individual tree and stand level. (2) The combined effect of T1 (thinning intensity of 833 trees per hectare) and pruning reduced E_c, decreasing the sensitivity of tree transpiration to the climate, with no discernible impact on E_L and g_c. Conversely, T2 (thinning intensity of 416 trees per hectare) and pruning increased E_L and g_c but had no effect on E_c, enhancing the sensitivity of tree transpiration to the climate. The sensitivity of g_c to *VPD* suggested a flexible stomatal regulation of transpiration under different combined thinning and pruning treatments. (3) Under T1, only P2 (4 m pruning from ground) promoted *WUE*, while pruning effects significantly reduced *WUE* under T2. Overall, the *WUE* of T2P0 (thinning intensity of 416 trees per hectare combined with no pruning) was significantly higher than that of the other treatments, and that of T1P0 (thinning intensity of 833 trees per hectare combined with no pruning) was significantly lower than that of the other treatments. Additionally, significant differences in E_c and *BAI* were observed among treatments under different rainfall conditions, with the promotion effect of E_c on *BAI* being more pronounced in the dry season.

Keywords: thinning; pruning; sap flow density; water use efficiency; *Populus tomentosa*

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1. Introduction

Plantations are the largest terrestrial ecosystems, covering more than 30% of global land. Plantations are crucial in maintaining biodiversity, regulating climate, conserving water resources, and providing numerous ecological services, production, and other industries [1]. Plantations are a viable solution for meeting timber demand, and they currently cover about 3% (about 1.31 billion ha) of the global forest area, with China leading

the world in planted forest area at about 0.89 billion ha [1–4]. However, in contrast to natural forests, plantations are more vulnerable to environmental changes, such as rising temperatures and decreasing water availability, which may impede their growth in the future [5–8]. Conventional plantation management practices are designed to promote growth by regulating the resources available to the trees and increasing their efficiency. Thinning alters the access of individual trees to resources like light, water, and nutrients, while pruning is an important management practice to produce high-quality, knot-free timber with large diameters by removing the shaded and least-efficient foliage, regulating the distribution of photosynthates among organs, and increasing aboveground biomass allocation utilization efficiency [9–13]. However, there is limited research on how these management practices affect the physiological and ecological processes that respond to the environment of plantations.

Thinning and pruning represent common practices in sustainable plantation management. Thinning can enhance tree growth and increase radial growth [14–16]. However, some studies have found that thinning in arid regions does not significantly affect radial growth [17]. Additionally, thinning can reduce the vulnerability of plantations to climate change, such as drought [18,19], improve *WUE* [18,20], and mitigate drought-induced growth decline [21,22]. Pruning lower-level canopy branches and leaves can increase knot-free timber yield [19,23] and may not influence growth, as decreases in canopy resource capture rates are often offset by increases in the photosynthetic efficiency of the remaining canopy leaves [11,24–26]. The effects of thinning and pruning on tree growth are not uniform, and few studies have reported on the combined effects. Forrester et al. [9,11,27] studied the effects of coupled thinning and pruning on Eucalyptus growth and found that thinning had a more significant impact on growth than pruning.

Water is a vital resource for tree growth, and tree transpiration plays a crucial role in the water cycle of terrestrial ecosystems [28]. Plantation management can affect tree–water physiological and ecological processes. Thinning can reduce stand density and directly alter photosynthetically active radiation (*PAR*) and vapor pressure deficit (*VPD*) [29–31], thereby affecting tree transpiration and canopy conductance [32–34]. Previous research has demonstrated that thinning can lead to an increase in tree sap flow density [15,21], significantly enhancing tree transpiration [18,35]. The widely adopted sap flow density method is particularly effective for assessing transpiration from individual trees and can be extrapolated to the stand level [36,37]. It is crucial to note that the response of stands to water conditions differs significantly from that of individual trees [38]. After thinning, a reduction in tree amount reduces stand-level transpiration [21,39]. However, some studies have shown that stand transpiration after thinning was significantly differ from that before thinning [40]. This outcome is attributed to factors such as increased photosynthetically active radiation, improved air movement within the canopy, and enhanced water and nutrient availability for retained individual trees, all contributing to heightened transpiration [41,42]. Meanwhile the majority of studies indicate that pruning significantly reduces tree transpiration [35,43], though this effect may only be observed in the short term [23].

WUE represents the carbon gain efficiency per water consumption unit [44,45]. At both the individual tree and stand levels, *WUE* is often determined by using the ratio of diameter increments at breast height (*DBH*) to transpiration [46]. Plantation management practices such as thinning and pruning can increase WUE by providing more light to the lower canopy and improving the efficiency of the remaining foliage [11,15,16,21,47,48]. Understanding *WUE* under the combined effects of thinning and pruning is crucial to comprehend and regulate the forest water cycle, as well as to optimize plantation management practices.

Poplar (*Populus* spp.) is a fast-growing and adaptable tree widely recognized as a vital species in timber production and ecological services. The area of poplar plantations in China has reached 8.5 million hectares, accounting for 27% of the total plantation area in the country, making it the largest area of poplar plantations in the world [30]. *Populus tomentosa* is the predominant species in poplar plantations across the North China

Plain region and is the first development species in the National Reserve Forest Program from 2018 to 2035 [4]. In recent years, thinning combined with pruning has become a widely used plantation management practice that enhances wood yield and quality [49]. Although the growth-promoting effects of combined thinning and pruning have been demonstrated in species such as Eucalyptus (*Eucalyptus nitens*) [11], Pine (*Pinus patula*) [50], Sitka spruce (*Picea sitchensis*), Western hemlock (*Tsuga heterophylla*) [49], and European beech (*Fagus sylvatica* L.) [51], no research has yet been conducted on the effects of this combination of treatments on sap flow density and *WUE* specifically in poplar.

The primary objective of this study was to examine the combined effects of two thinning intensities and three pruning heights on the transpiration of 4-year-old *Populus tomentosa* at the stand and individual levels during the growing season of June–October 2022. Furthermore, the regulation mechanism of tree–water relations under different treatments was explored through the sensitivity of g_c to *VPD*, and the relationship between *WUE* and the growth of trees in different rainfall periods under diverse treatments was also investigated. The specific scientific questions addressed were: (1) Is there a consistent response pattern of transpiration in single trees and stands under different combinations of thinning and pruning? (2) Are there differences in stand-level g_c and transpiration and their relationships with environmental factors under the different thinning and pruning combinations? (3) Are there differences in stand *WUE* among the different thinning and pruning combinations? The result of this study can provide helpful information to inform the basis for poplar plantation management strategies to mitigate tree stress under changing environmental conditions.

2. Materials and Methods

2.1. Introduction to Study Sites and Species

The experiment was conducted at the Wen County Forestry Science Research Institution, situated in Henan Province (34°50′~35°03′ N, 112°51′~113°13′ E), with an elevation of 102.3~116.1 m (Figure 1). This area has a warm temperate continental monsoon climate, featuring an average annual temperature of 14.3 °C, and an average annual precipitation of 552.4 mm, of which 80% precipitation is during the rainy season from June to September.

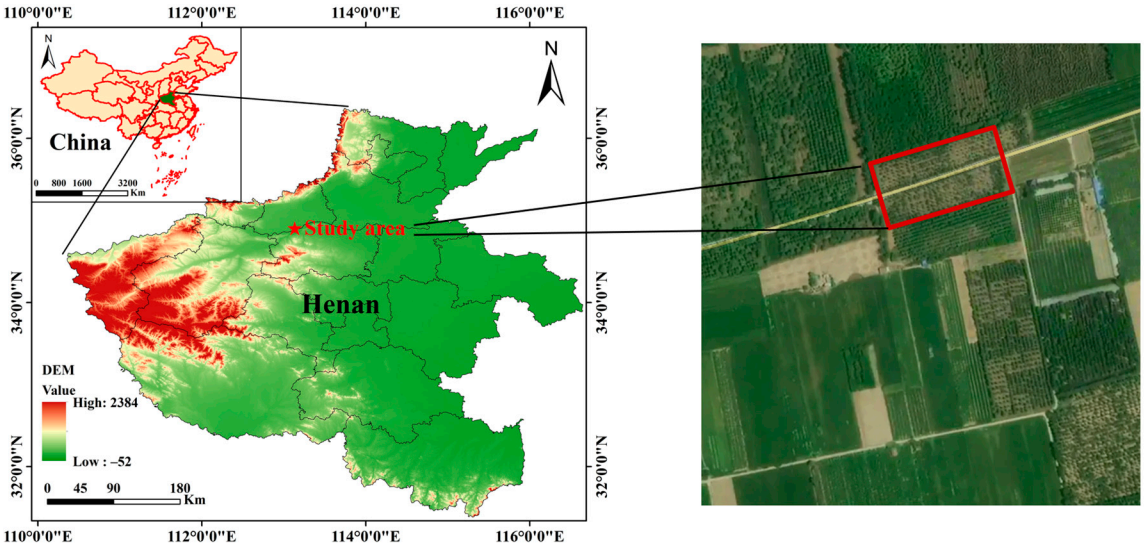


Figure 1. Location of the study site.

In 2018, the experimental plantation of *P. tomentosa 'Jiangan No.1'* was established at a density of 1666 trees ha^{-1} (1.5 m × 4 m). In the spring of 2022, a randomized block design was employed in a 2 × 3 factorial scheme with two thinning intensities (833 trees per hectare, T1, and 416 trees per hectare, T2) and three pruning heights (no pruning, P0; 3 m pruning from ground, P1; and 4 m pruning from ground, P2) across three 60 × 40 m

blocks (blocks I, II, and III). Six combined treatments were implemented: 3 × 4 m—no pruning (T1P0), 3 × 4 m—3 m pruning (T1P1), 3 × 4 m—4 m pruning (T1P2), 6 × 4 m—no pruning (T2P0), 6 × 4 m—3 m pruning (T2P1), 6 × 4 m—4 m pruning (T2P2) (Figure 2). Each treatment had three replicates, each with a randomized plot measuring 20 m × 20 m, resulting in 18 plots.

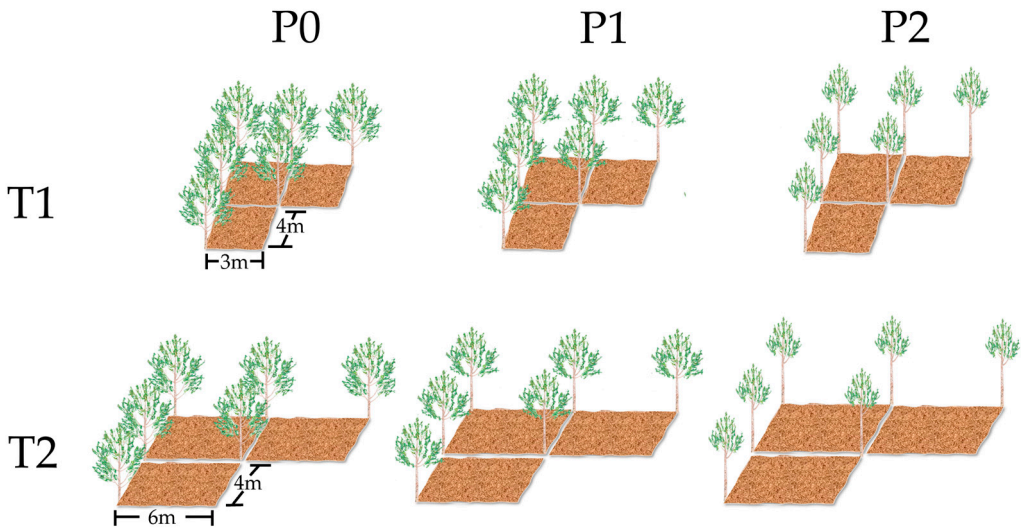


Figure 2. Schematic diagram of experimental design.

An automatic weather station (Sinton Technology Ltd., Beijing, China) was installed at a distance of 200 m from the experimental site to continuously monitor meteorological variables such as wind speed (W_s, m s^{-1}), photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}), air temperature (T_{air}, °C), and relative air humidity (RH, %) at 2 m, precipitation (P, mm), soil volumetric water content (θ, m^3 m^{-3}), and soil temperature (T_{soil}, °C). Meteorological data were recorded at 10 min intervals. The atmospheric vapor pressure deficit (VPD, kPa) was calculated according to the empirical equation developed by Campbell and Norman (1998) [52], while reference evapotranspiration (ET_0, mm d^{-1}) was calculated by the Penman–Monteith equation as recommended by FAO-56 (Allen et al., 1998 [53]):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{air}+273} W_s(es - ea)}{\Delta + \gamma(1 + 0.34)W_s} \quad (1)$$

where R_n is the net radiation (MJ m^{-2} d^{-1}); G is the soil heat flux density (MJ m^{-2} d^{-1}) (soil heat flux beneath the vegetation is relatively small for the daily average, it may be neglected, i.e., $G \approx 0$); T_{air} is the mean air temperature (°C); W_s is the wind speed at 2 m height above ground (m s^{-1}), es is saturation vapor pressure (kPa), ea is actual vapor pressure (kPa); Δ is the slope of the relationship curve between saturation vapor pressure and temperature (kPa $°C^{-1}$); and γ is the psychrometric constant (kPa $°C^{-1}$).

Leaf area index (LAI, m^2 m^{-2}) was measured every two weeks by using a Yaxin-1201 plant canopy analyzer (Yasin Science and Technology Ltd., Beijing, China) from June to November 2022. We selected 5 positions in each treatment, and then obtained the LAI values through the software. Their mean values were calculated as the representative LAI for each treatment. Finally, we fitted the time dynamics of the mean values of LAI for each treatment by using linear interpolation (Figure S1).

2.2. Sap Flow Density Measurement and Stand Transpiration Estimation

2.2.1. Sampling Tree Selection

According to the frequency distribution of DBH from three replicated blocks (surveyed before sap flow density measurement), three sample trees were selected for each treatment

plot. The variations in *DBH* of the selected three sampling trees for sap flow density measurement mainly ranged between 7 cm and 9 cm, following the interval probabilities for normal distribution and reflecting the average stand growth status (Table 1; Figure S2).

Table 1. Traits of the sampling trees in T1P0, T1P1, T1P2, T2P0, T2P1, T2P2.

Treatment	Tree Number	Height (m)	*DBH* (cm)	Height to Canopy Base (m)	Crown Width (m)	*SA* (cm^2)
T1P0	1	7.6	8.18	2.7	2.7 × 3.6	46.10
	2	8.8	7.9	2.4	2.8 × 3.6	43.06
	3	10.2	8.21	2	3.3 × 3.8	46.43
T1P1	4	7.7	8.5	2.4	2.3 × 3.6	49.69
	5	8.8	8.12	2.6	2.7 × 2.9	45.44
	6	7.2	7.22	2.3	2.2 × 2.1	36.12
T1P2	7	8	8.76	2.18	2.2 × 3.7	52.70
	8	8.1	8.52	2.6	2.8 × 3.7	49.92
	9	7.8	6.82	2.1	3 × 3	32.31
T2P0	10	9.3	9	2.2	3.1 × 3.9	55.56
	11	10.3	9.22	2.4	3.4 × 4.5	58.24
	12	7.3	7.7	2.3	2.2 × 2.8	40.96
T2P1	13	9.4	8.31	2.7	2.8 × 4	47.54
	14	8.4	7.75	2.07	2.3 × 3.3	41.48
	15	8.5	8.38	2.1	2.3 × 3.1	48.33
T2P2	16	7.5	7.85	2.2	3 × 3.2	42.53
	17	8.6	7.35	2.3	2.5 × 2.9	37.40
	18	8.8	7.7	2.3	3.4 × 4.6	40.96

2.2.2. Probe Installation and Calculation of Sap Flow Density

Sap flow density (J_s, cm s^{-1}) was obtained by the thermal dissipation probes (TD-30, 3 cm in length) (Dynamax Inc., Houston, TX, USA). The probes were inserted into the sapwood on the north-facing side of each sampling tree at a height of 1.3 m–1.5 m above the ground. To prevent exposure to precipitation and thermal radiation effects, the probes were cemented with waterproof glue, and we used foam to fix them. At last, reflective bubble insulation was wrapped around the probes and the stem [28]. The J_s was measured every 10 s, and its average value, calculated every 10 min, was stored in the data loggers (CR1000, Campbell Scien-tific Inc., Logan, UT, USA). J_s was estimated using the formula proposed by Granier (1987) [54]:

$$J_s = 0.0119 \times K^{1.231} \quad (2)$$

where the temperature difference coefficient $K = (dTM - dT)/dT$; dTM is the maximal temperature difference between two probes (°C); dT is the temperature difference between the heated probe and unheated reference probe (°C); dTM is determined over a 7–10-day period by taking the maximum value of dT to avoid the underestimation of night-time J_s.

The J_s measured using the TD-30 probes can be influenced by many error sources, such as wounding, radial velocity profile, and wood properties [55–57]. It has been found in many studies that J_s can be over- or under-estimated to different degrees [56,58,59]. Therefore, we have verified that the original Granier's equation of Equation (2) is credible as accurate and valid for our *P. tomentosa* plantation [60,61], and the variation in azimuthal was ignored. And this function has been also widely applied to many related studies on poplars [30,62,63].

2.2.3. Estimation of Transpiration and Canopy Conductance

The whole-tree transpiration (E_t, mm d^{-1}) was calculated according to the following equation [64]:

$$E_t = J_s \left(\frac{A_{s\text{-}plot}}{A_{g\text{-}plot}} \right) \quad (3)$$

where J_s is the standard wood sap flow density (cm s^{-1}); $A_{s\text{-}plot}$ is the sampling tree sapwood area (cm^2); and $A_{g\text{-}plot}$ is the plot area per sampling tree (cm^2) (the $A_{g\text{-}plot}$ at T1 and T2 are 12 m^2 and 24 m^2, respectively).

Due to the high variability in J_s in single trees, the sapwood area-weighted average fluid flow density (J_m) of all sampling trees was employed to extend from single trees to the stand scale. Subsequently, daily scale transpiration (E_c, mm d^{-1}) was derived by multiplying J_m and the sapwood area index (*SAI*) (sapwood area per stand ground surface) [65].

$$E_c = J_m \frac{A_{s\text{-}stand}}{A_{g\text{-}stand}} \quad (4)$$

where $A_{s\text{-}stand}$ is the total sapwood area of the stand (cm^2), and $A_{g\text{-}stand}$ is the total ground area of the stand (m^2) (1200 m^2).

The sapwood area (A_s) was calculated by using the anisotropic equation established in the previous study on *P. tomentosa* by Zhao et al. (2023) [36], with the diameter at the location of the J_s measurement as the independent variable ($A_s = 0.7587 \times DBH^{1.9541}$). Additionally, the canopy transpiration per unit leaf area (E_L, mm d^{-1}) was estimated by dividing E_c by the leaf area index (*LAI*, m^2 m^{-2}) [66]. Canopy conductance (g_c, mm s^{-1}) was calculated from E_L through a simplified reverse form of the Penman–Monteith equation [67]:

$$g_c = \frac{\gamma \lambda E_L G_a}{\Delta R_n + \rho C_p VPD G_a - \lambda(\Delta + \gamma) E_L} \quad (5)$$

where Δ (kPa $°C^{-1}$) is the slope of the saturation vapor pressure curve at T_{air}; R_n (MJ m^{-2}) is the net radiation; γ (kPa $°C^{-1}$) is the psychrometric constant; λ (MJ kg^{-1}) is the latent heat of vaporization of water; G_a (m s^{-1}) is aerodynamic conductance; ρ (kg m^{-3}) is the density of the air; and C_p (MJ kg^{-1} $°C^{-1}$) is the specific heat of air at constant pressure.

Aerodynamic conductance was calculated from wind speed using the following equation [68]:

$$G_a = \frac{k^2 \cdot u_z}{\left[\ln\left(\frac{z-d}{z_o} \right) \right]^2} \quad (6)$$

where u_z (m s^{-1}) is the wind speed above the forest canopy; z (m) is the wind measurement height; z_o is the roughness height (0.1 h); d is the displacement height (0.75 h); h is the forest canopy height; and k (0.4) is the von Karman constant. u_z was calculated from the measured wind speed at 2.0 m height (u_2) based on Equation (7) [53]:

$$u_z = \frac{\ln(67.8z - 5.42)}{4.87} u_2 \quad (7)$$

2.2.4. The Sensitivity of Canopy Conductance to *VPD*

The sensitivity of g_c to *VPD* was calculated as follows [69]:

$$g_c = -m \ln VPD + g_{cr} \quad (8)$$

where $-m$ represents the sensitivity of g_c to *VPD*. g_{cr} is reference canopy conductance when *VPD* is 1.0 kPa and can be used as a surrogate for the maximum g_c [70]. The ratio of m/g_{cr} can be used as a criterion for evaluating the response of tree species to environmental conditions, and despite the different environmental conditions under which they are grown,

most species have m/g_{cr} ratios of ~0.6, with values less than 0.6 indicating that leaf water potential is not tightly regulated and values greater than 0.6 indicating that the ratio of boundary layer conductance to canopy conductance is low in the leaf [69,71].

2.2.5. Stand-Level Water Use Efficiency

Stand-scale water use efficiency was calculated as follows [19]:

$$WUE = \frac{BAI}{E_c} \quad (9)$$

where BAI and E_c are the total basal area increment and transpiration, respectively. Monthly BAI was obtained from the difference in basal area (BA) at the stand scale between two adjacent months, and BAI for the main growing season (June–October) was obtained from the difference between the BA in October and the BA in June. We calculated BA through DBH, which was measured at the beginning of each month.

2.3. Statistical Analysis

Data analysis in this study was conducted from 18 June to 25 October. The data collected from the thermal dissipation probes were processed and calculated by using Baseliner software (version 3.0, Ram Oren, Duke University, Durham, NC, USA) [72]. Two-way analysis of variance (ANOVA) was performed on E_t, J_s, E_c, E_L, and g_s to explore the interaction effects of different treatments on each indicator. Tukey's mean comparison test was then applied at a 5% significance level using the statistical software SPSS 22.0 (IBM Corporation, Chicago, IL, USA). Standardized major axis (SMA) regression analysis was used to test the differences between the slopes of the equation of different meteorological factors with E_L.

To ensure accurate estimations of g_c, only data corresponding to VPD greater than 0.6 kPa and PAR greater than 100 μmol m^{-2} s^{-1} were selected. Boundary line analysis (BLA) was employed to analyze the physiological reactions of g_c and VPD under the given conditions [73] (Figure S3). All g_c data were sorted into intervals of VPD = 0.2 kPa. The means and standard deviations of g_c were calculated based on the VPD intervals, and outliers were excluded according to the Dixon test ($p < 0.05$). Intervals with $n < 5$ were excluded to avoid the influence of inadequate information about the VPD interval on the relationship [73]. Values of g_c above the mean and one standard deviation from each VPD interval were filtered for fitting. The figures were drawn using Origin 2022b (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Environmental Variables and Soil Moisture

The daily mean T_{air} during the study period showed a decreasing trend, with the highest value recorded in June and values ranging from 8.1 °C to 33.14 °C (Figure 3a). Similarly, the daily mean RH increased and then decreased, reaching its peak in July with a range of 38.38% to 96.85% (Figure 3a). The daily mean PAR and VPD both had their highest values in June, before declining, with ranges of 22.24 μmol m^{-2} s^{-1} to 475.95 μmol m^{-2} s^{-1} and 0.09 kPa to 3.14 kPa, respectively (Figure 3b). The daily mean W_s had a maximum of 1.73 m s^{-1} during the measurement period (Figure 3c). Rainfall P was unevenly distributed, with a total of 313.69 mm accumulated (Figure 3c). The daily mean θ increased with rainfall and decreased afterwards, varying from 13.66 m^3 m^{-3} to 17.79 m^3 m^{-3} (Figure 3d). The daily mean ET_0 generally decreased, fluctuating between 0.72 mm and 6.84 mm (Figure 3d).

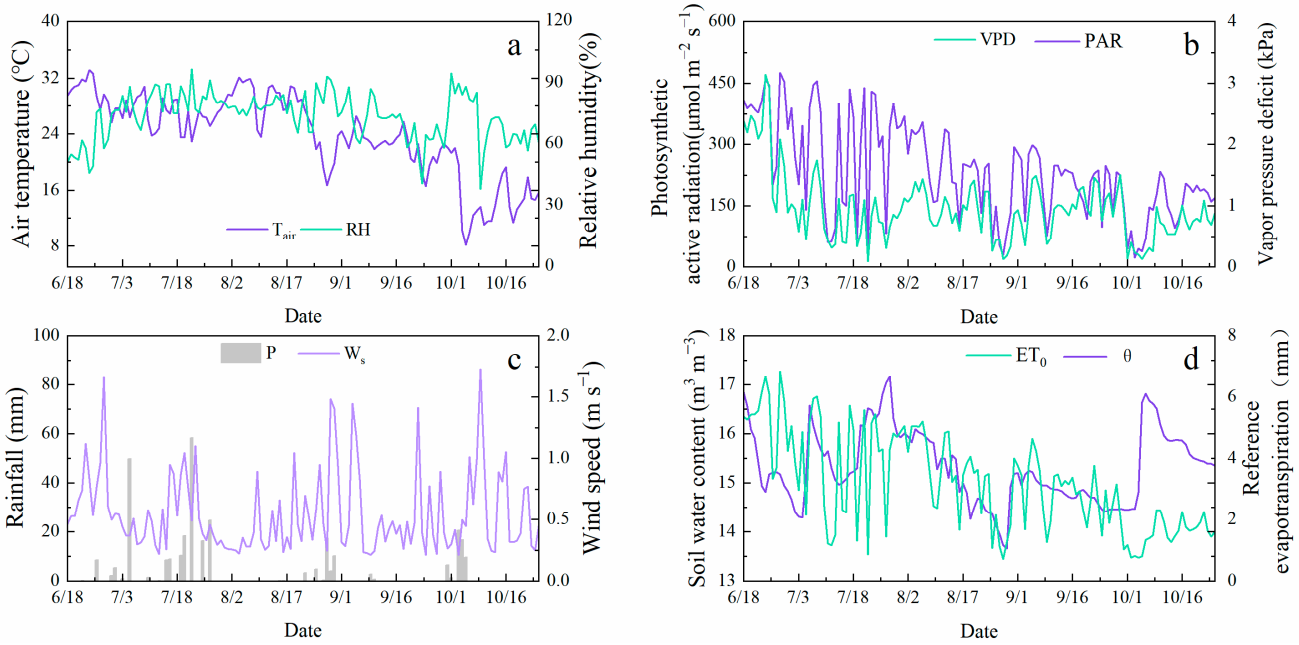


Figure 3. Seasonal variations in daily mean values of air temperature ((**a**), T_{air}), relative humidity ((**a**), *RH*), photosynthetic active radiation ((**b**), *PAR*), vapor pressure deficit ((**b**), *VPD*), daily total rainfall ((**c**), *P*), wind speed at 2 m height ((**c**), W_s), soil water content ((**d**), θ) at the depths of 20 cm soil layer, and reference evapotranspiration ((**d**), ET_0) in 2022 main growing season.

3.2. Dynamics of Sap Flow Density, Individual Tree and Stand-Level Transpiration, and Canopy Conductance

3.2.1. Sap Flow Density

The daily variations in J_m exhibited similar dynamic patterns across all treatments, displaying a continuous response to environmental conditions similar to the daily changes in T_{air}, *PAR*, and *VPD*. It tended to increase, reaching a peak around 4:00 a.m., as T_{air}, *PAR*, and *VPD* increased. Subsequently, J_m gradually declined after maintaining a relatively higher level between 8:00 a.m. and 4:00 p.m., approaching zero during the nighttime (Figure 4).

The interaction effect of J_m was significant (Table 2). In T1, the J_m significantly decreased by 16.81% in P2 compared to P0 ($p < 0.001$), while there were no significant differences in J_m between P1 and P2 ($p > 0.05$). Similarly, the J_m significantly increased by 41.08% in P2 compared to P0 for the same T2 treatment ($p < 0.001$), while there were no significant differences in J_m between P1 and P0 ($p > 0.05$) (Table 3). Regardless of any pruning treatments, the J_m reduced by 42.83% for T2P0 relative to T1P0, 27.71% for T2P1 relative to T1P1, and 3.05% for T2P2 relative to T1P2 due to thinning (Table 3).

Table 2. Two-way analysis of variance (ANOVA) of transpiration (E_t), sapwood area-weighted mean sap flow density (J_m), stand transpiration (E_c), transpiration per unit leaf area (E_L), and canopy conductance (g_c) of different treatments.

Variables	Thinning		Pruning		Thinning × Pruning	
	F	*p*	F	*p*	F	*p*
E_t	788.026	<0.001	7.786	<0.001	9.737	<0.001
J_m	101.589	<0.001	1.746	0.175	25.299	<0.001
E_c	222.487	<0.001	4.836	<0.05	17.827	<0.001
E_L	3.236	0.072	13.777	<0.001	13.690	<0.001
g_c	10.288	0.001	14.455	<0.001	19.776	<0.001

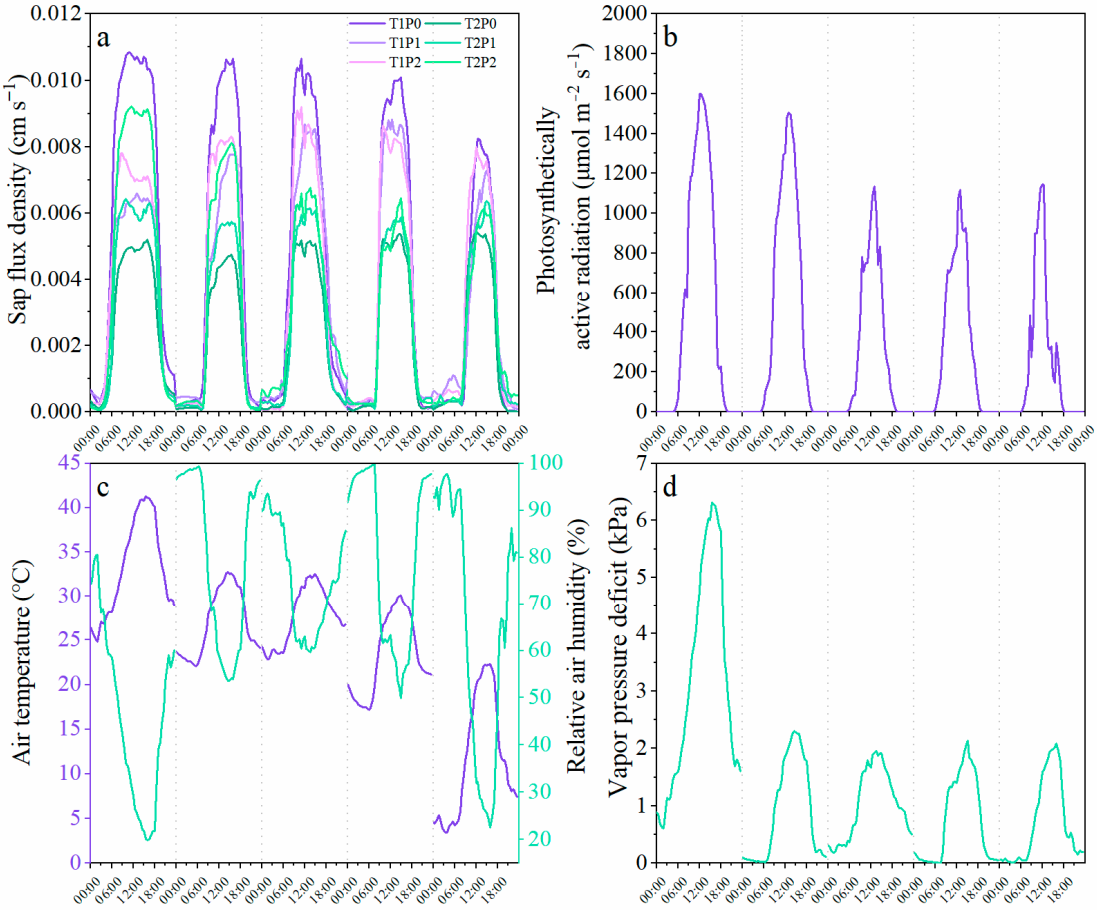


Figure 4. Diurnal course of sap flow density (J_m) of different treatments (**a**) for five selected sunny days (24 June, 29 July, 17 August, 2 September, and 11 October) and the corresponding daily photosynthetically active radiation (*PAR*) (**b**), air temperature (T_{air}), relative air humidity (*RH*) (**c**), and vapor pressure deficit (*VPD*) (**d**).

Table 3. Mean (±standard deviation) values of individual transpiration (E_t), sapwood area-weighted mean sap flow density (J_m), stand transpiration (E_c), transpiration per unit leaf area (E_L), and canopy conductance (g_c) of different treatments.

Variables	T1P0	T1P1	T1P2	T2P0	T2P1	T2P2
E_t (mm d^{-1})	1.5 ± 0.66 a	1.27 ± 0.49 b	1.24 ± 0.45 b	0.51 ± 0.18 c	0.47 ± 0.17 c	0.57 ± 0.21 c
J_m (cm s^{-1})	0.0032 ± 0.0015 a	0.0029 ± 0.0011 ab	0.0027 ± 0.0010 b	0.0018 ± 0.0007 c	0.0021 ± 0.0008 c	0.0026 ± 0.0010 b
E_c (mm d^{-1})	0.83 ± 0.37 a	0.69 ± 0.26 b	0.65 ± 0.24 b	0.43 ± 0.15 c	0.47 ± 0.17 c	0.50 ± 0.19 c
E_L (mm d^{-1})	0.96 ± 0.43 ab	0.90 ± 0.33 ab	0.98 ± 0.36 ab	0.73 ± 0.25 c	0.93 ± 0.35 b	1.04 ± 0.41 a
g_c (mm s^{-1})	1.96 ± 0.67 ab	1.61 ± 0.54 cd	2.04 ± 0.73 a	1.46 ± 0.55 d	1.81 ± 0.60 bc	1.90 ± 0.44 ab

Different letters next to numbers represent significantly different means between treatments ($p < 0.05$).

3.2.2. Individual Tree and Stand-Level Transpiration

E_t was the highest in June across all treatments, decreased slightly from July to September, and then decreased sharply in October due to rainfall events (Figure 5a). The interaction effect on E_t was statistically significant ($p < 0.001$) (Table 2). At the same T1 treatment, E_t was significantly reduced by 15.34% ($p < 0.001$) and 20.39% ($p < 0.001$) at P1 and P2 compared to P0, respectively. However, there was no significant difference in E_t between pruning treatments ($p > 0.05$) at the same T2 treatment (Figure. 5b). Regardless of pruning treatments, thinning had a significant effect on reducing E_t ($p < 0.001$) by 65.74% for T2P0 relative to T1P0, 62.65% for T2P1 relative to T1P1, and 54.26% for T2P2 relative to T1P2 (Figure 5b; Table 3).

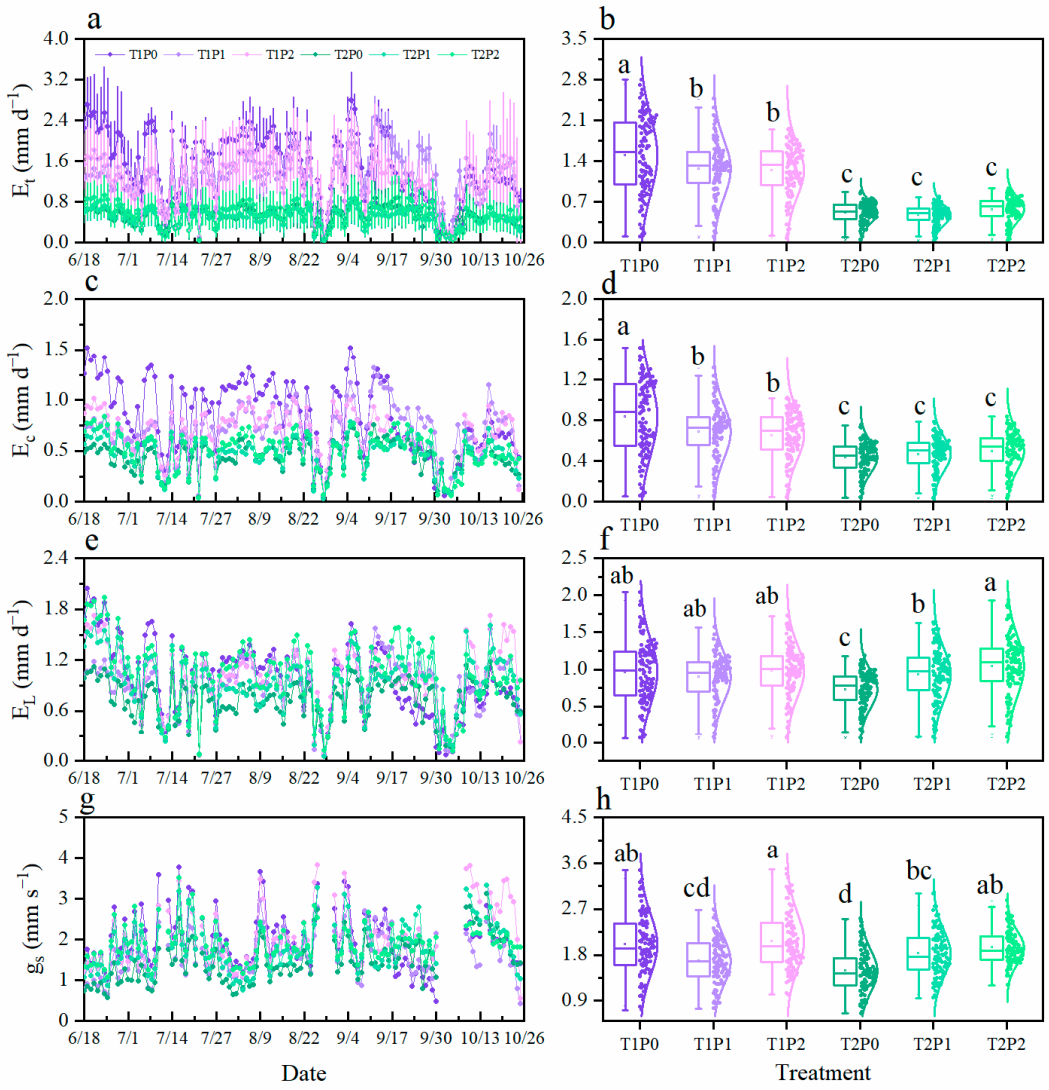


Figure 5. Seasonal dynamics of individual transpiration (E_t), stand transpiration (E_c), transpiration per unit leaf area (E_L), and canopy conductance (g_c) under different treatments (**a**,**c**,**e**,**g**). Box plots indicate the range of distributions, and the data points represent sample sizes of the treatments, which were fitted with normal curves (**b**,**d**,**f**,**h**). Different letters represent significantly different means between treatments ($p < 0.05$).

The interaction effect on E_c was found to be significant ($p < 0.001$) (Table 2). At the same T1 treatment, E_c was significantly reduced by 17.38% ($p < 0.001$) and 21.70% ($p < 0.001$) at P1 and P2 compared to P0, respectively. In the case of T2 treatment, there was no significant difference in E_c between pruning treatments ($p > 0.05$) (Figure 5d). Regardless of pruning treatments, the thinning effect was found to reduce E_c significantly ($p < 0.001$) by 47.89% for T2P0 relative to T1P0, 31.94% for T2P1 relative to T1P1, and 23.74% for T2P2 relative to T1P2 (Figure 5d). The total E_c of the treatments during the main growing period were 108.30, 89.48, 84.80, 56.43, 60.90, 64.67 mm, which accounted for 34.52%, 28.52%, 27.03%, 17.99%, 19.41%, 20.62% of rainfall, respectively.

3.2.3. Canopy Transpiration per Unit Leaf Area and Canopy Conductance

The results showed that the seasonal variations in E_L were relatively moderate (Figure 5e). Statistical analysis revealed that the interaction effect of thinning and pruning significantly influenced E_L ($p < 0.001$) (Table 2). Specifically, in T2, P1 and P2 significantly increased E_L by 27.75% ($p < 0.05$) and 43.21% ($p < 0.001$) compared to P0 (Figure 5f). In the case of P0, T2 decreased E_L by 24.52% ($p < 0.001$) compared to T1. Conversely, when P1

and P2 were applied, there was no significant difference in E_L between T1 and T2 ($p > 0.05$) (Figure 5f; Table 3).

Seasonal changes in g_c were insignificant from the beginning of the measurements until mid-September for all treatments (Figure 5g). The interaction effect on g_c was found to be significant ($p < 0.001$) (Table 2). In comparison to P0, P1 was found to be significantly reduced g_c by 18.02% ($p < 0.001$), while there was no significant difference in g_c between P0 and P2 ($p > 0.05$) at the same T1 treatment (Figure 5h). P1 and P2 significantly increased g_c by 23.73% ($p < 0.001$) and 29.81% ($p < 0.001$) compared to P0 at the same T2 treatment (Figure 5h; Table 3). Only in P0 was the g_c of T2 lower by 25.40% compared to T1 (Figure 5h).

3.3. Responses of Canopy Transpiration per Unit Leaf Area and Canopy Conductance to Environmental Variables

Daily E_L had a significantly positive relationship with *VPD*, *PAR*, and ET_0 ($p < 0.001$) (Figure 6; Tables S1–S3). E_L was more affected by *VPD*, *PAR*, and ET_0 than the other atmospheric factors. T_{air}, W_s, and θ were not highly correlated with E_L for different treatments (Figure S4; Tables S4–S6). Additionally, it is noteworthy that the slope of the regression equations of E_L with *VPD*, *PAR*, and ET_0 decreased significantly in T1 while the slope increased significantly in T2 as pruning height increased (Figure 6; Table 4). Only in T1P0 did *VPD* explain a lower proportion of the variation in E_L than *PAR* and ET_0 (67%, 70%, and 77%), respectively. For the other treatments, *VPD* was the main factor that explained the variation in E_L (greater than *PAR* and ET_0) (Tables S1–S3).

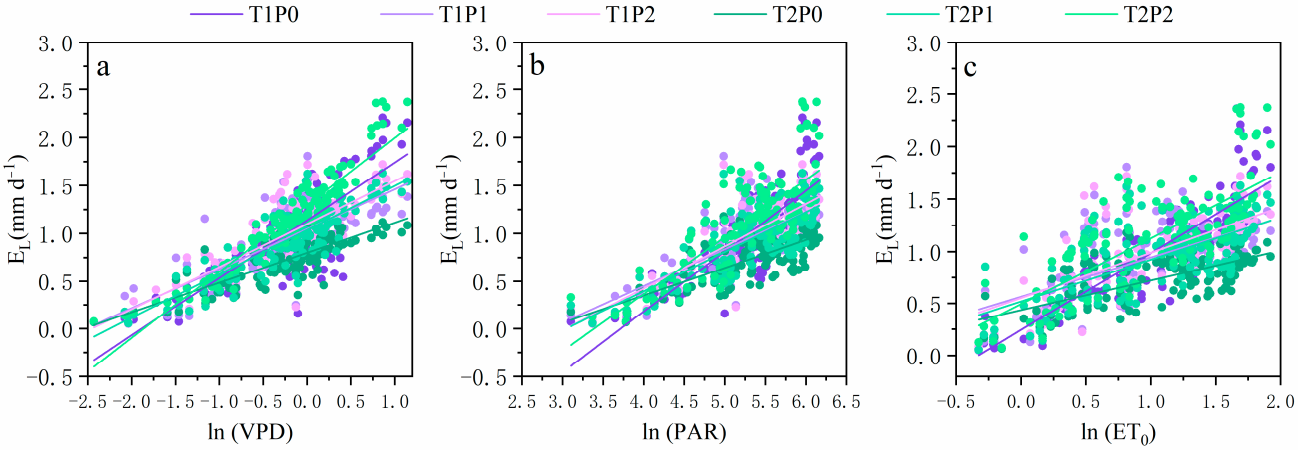


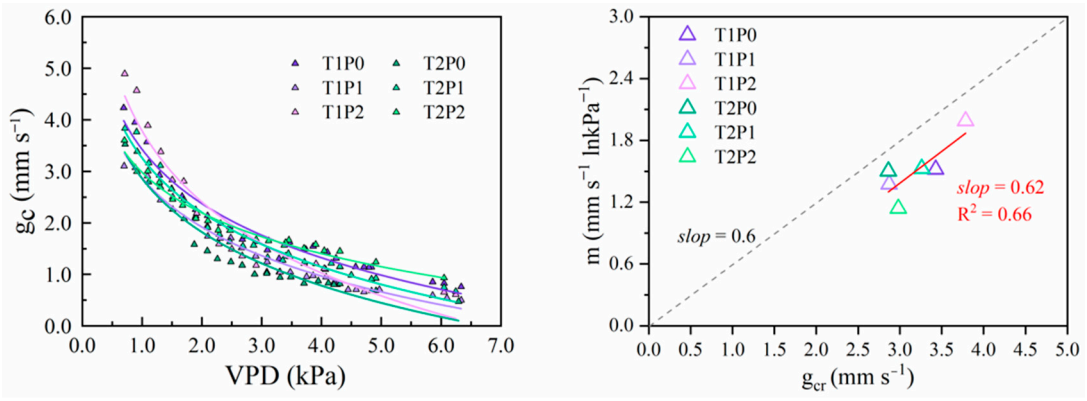
Figure 6. Response relationship between transpiration rate per unit leaf area (E_L) and vapor pressure deficit ((**a**), ln(*VPD*)), photosynthetic active radiation ((**b**), ln(*PAR*)), and reference evapotranspiration ((**c**), ln(ET_0)) for different treatments.

Table 4. Test for slope between vapor pressure deficit (*VPD*), photosynthetic active radiation (*PAR*), reference evapotranspiration (ET_0), and transpiration rate per unit leaf area (E_L) among different treatments.

Treatments	*VPD*		*PAR*		ET_0	
	Slope	*p*	Slope	*p*	Slope	*p*
T1P0	0.739 a	<0.001	0.757 a	<0.001	0.842 a	<0.001
T2P2	0.535 b	<0.001	0.548 b	<0.001	0.610 b	<0.001
T1P2	0.549 b	<0.001	0.563 b	<0.001	0.626 b	<0.001
T2P1	0.383 c	<0.001	0.393 c	<0.001	0.437 c	<0.001
T1P1	0.538 b	<0.001	0.551 b	<0.001	0.613 b	<0.001
T2P0	0.736 a	<0.001	0.754 a	<0.001	0.839 a	<0.001

Different letters next to numbers represent significantly different means between treatments ($p < 0.05$).

The daily mean g_c exhibited a higher sensitivity to *VPD* than *PAR* in all treatments, with a significant decrease in g_c as *VPD* increased ($p < 0.001$) (Figures 7 and S5; Tables S7 and S8). Boundary line analysis revealed no significant difference in m between T1P0 and T1P1, T2P0 and T2P1, nor T1P0 and T2P0 ($p > 0.05$), but there was a significant difference in m between the other treatments ($p < 0.05$) (Figure 7b; Table S7). Meanwhile, there was no significant difference in g_{cr} between T1P0 and T1P2, nor T1P2 and T2P2 ($p > 0.05$), but there was a significant difference in g_{cr} the other treatments ($p < 0.05$) (Figure 7b; Table S7). The strong linear relationship between m and g_{cr} across treatments, with approximately 0.6 slopes (Figure 7b), indicated an isohydric water strategy across all treatments.



(**a**) (**b**)

Figure 7. Logarithmic function of canopy conductance (g_c) and vapor pressure deficit (*VPD*) (**a**), the sensitivity of g_c to *VPD* and maximum canopy conductance (g_{cr}) under different treatments (**b**).

3.4. Stand Water Use Efficiency in Different Rainfall Periods

During the study period, stand *WUE* was significantly higher ($p > 0.05$) in the T2P0 treatment compared to the other treatments (Figure 8b). However, *BAI* showed no significant differences ($p > 0.05$) among all treatments (Figure 8a) but differed in different rainfall periods (Table 5). The total rainfall from 18 June to 22 August (wet summer) was 218.44 mm (Figure 8c). During this period, *BAI* was positively correlated with E_c for T1P0, T2P1, and T2P2 and negatively correlated with E_c for T1P1, T1P2, and T2P0 (Figure 9a). Additionally, *WUE* was significantly higher for T2P0 than the other treatments ($p < 0.05$) (Figure 9c). *BAI* showed a significant difference among treatments ($p < 0.05$), with T2P0 and T1P0 each having significantly higher *BAI* than other treatments ($p < 0.05$) (Figure 8c; Table 5). In terms of transpiration, E_c was significantly higher in T1P0 than in the other treatments ($p < 0.05$), while it was significantly lower ($p < 0.05$) in T2P0 than in T1P0 (Figure 8c).

During the dry autumn period from 23 August to 25 October, the rainfall was low at 95.25 mm (Figure 8c). In all treatments, *BAI* and E_c were positively correlated (Figure 9b), and there were no significant differences ($p > 0.05$) in *BAI* among treatments (Table 5). T2P0 had the highest *BAI*, while T1P0 exhibited the lowest (Figure 8c). For E_c, no significant differences were noted ($p > 0.05$) among pruning treatments under the same thinning treatment. However, T1P0 had significantly higher E_c than T2P0 ($p < 0.05$) (Figure 8c). *WUE* was significantly higher in T2P0 than in both T1P0 ($p < 0.05$) and T1P1 ($p < 0.05$) (Figure 9c). Notably, the correlation coefficients between *BAI* and E_c were higher in all treatments during dry autumn than during wet summer, except for T1P1 and T2P1, even though precipitation during dry autumn was less than that during wet summer (Figure 9a,b). This suggests that the contribution of E_c to *BAI* was more significant in dry autumn than in wet summer.

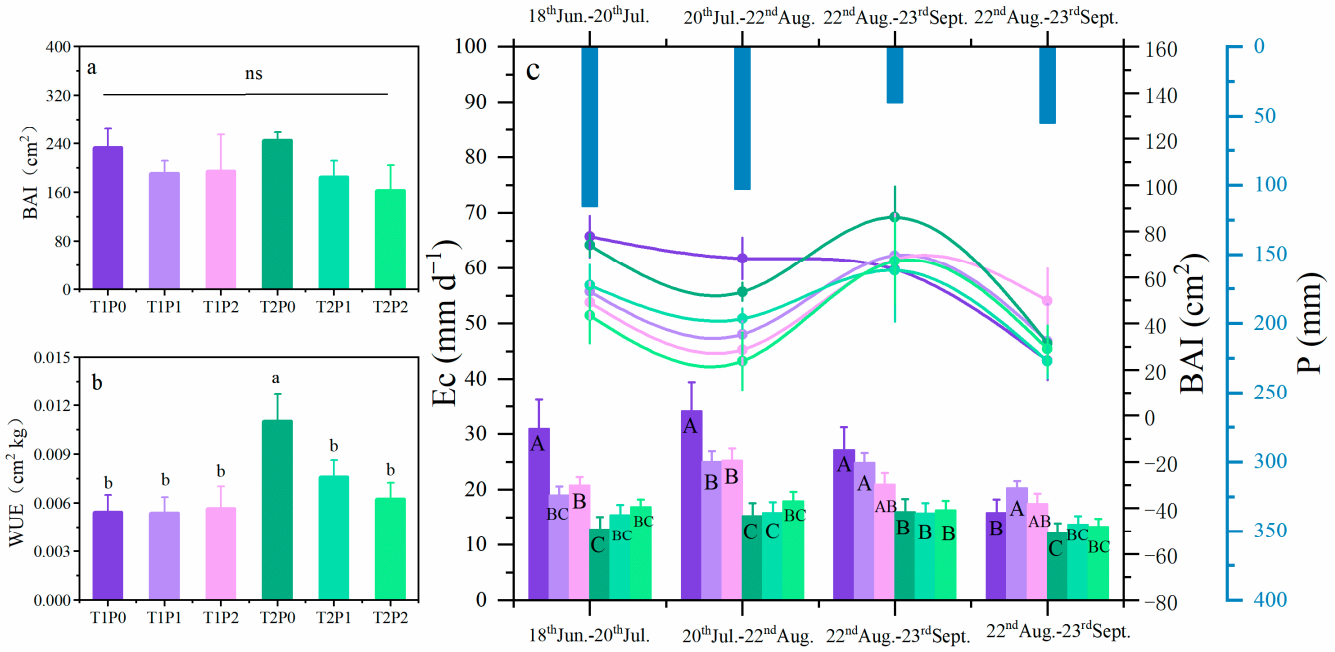


Figure 8. Analysis of total stand-scale basal area increment (*BAI*) (**a**), water use efficiency (*WUE*) (**b**), and differences between basal area increment (*BAI*) and transpiration (E_c) in different precipitation periods under different thinning–pruning treatments (**c**). In (**c**), the bar located at the top represents the cumulative rainfall (*P*) in each period; the bars located at the bottom represent the transpiration (E_c) of T1P0, T1P1, T1P2, T2P0, T2P1, and T2P2 in each period, respectively; the curve located in the middle represents the change in basal area increment (*BAI*) in each period. Different uppercase letters and lowercase letters represent significantly different means between treatments in E_c and *WUE* ($p < 0.05$), respectively.

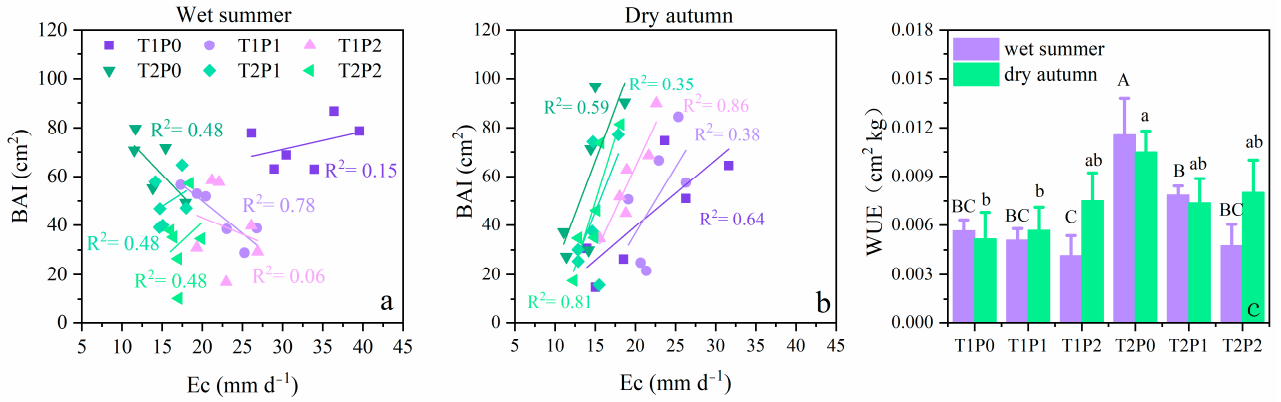


Figure 9. Differences in synergistic patterns of change in stand-scale basal area increment (*BAI*) and transpiration (E_c) in wet summer (**a**) and dry autumn (**b**), i.e., differences in water use efficiency (*WUE*) under different thinning and pruning treatments (**c**). Different uppercase letters and lowercase letters represent significantly different means between treatments in wet summer and dry summer ($p < 0.05$), respectively.

Table 5. Basal area increment (*BAI*) and leaf area index (*LAI*) at the stand scale under different thinning and pruning treatments in different precipitation periods.

Treatment	Wet Summer				Dry Autumn			
	18 June–20 July		20 July–22 August		22 August–23 September		23 September–25 October	
	BAI	*LAI*	*BAI*	*LAI*	*BAI*	*LAI*	*BAI*	*LAI*
T1P0	77.78 ± 8.96 a	0.85 ± 0.21 a	68.27 ± 9.02 a	0.96 ± 0.20 a	63.40 ± 11.96	0.82 ± 0.02 a	23.90 ± 8.19	0.80 ± 0.12 ab
T1P1	53.8 ± 2.47 abc	0.75 ± 0.10 ab	35.35 ± 5.61 bc	0.78 ± 0.10 ab	69.48 ± 13.68	0.77 ± 0.04 a	32.33 ± 15.96	0.73 ± 0.10 b
T1P2	49.07 ± 15.68 bc	0.71 ± 0.05 ab	28.69 ± 11.43 c	0.81 ± 0.05 abc	67.75 ± 22.45	0.55 ± 0.04 b	49.74 ± 14.18	0.55 ± 0.06 c
T2P0	74.08 ± 4.88 ab	0.61 ± 0.03 bc	53.71 ± 3.88 ab	0.67 ± 0.03 bcd	86.11 ± 13.17	0.55 ± 0.03 b	31.46 ± 5.09	0.91 ± 0.07 a
T2P1	56.45 ± 9.03 abc	0.51 ± 0.06 c	42.02 ± 4.37 bc	0.60 ± 0.06 cd	63 ± 22.18	0.44 ± 0.06 c	23.75 ± 7.33	0.45 ± 0.04 c
T2P2	43.43 ± 12.05 c	0.48 ± 0.07 c	23.77 ± 12.34 c	0.51 ± 0.07 d	67.06 ± 18.62	0.48 ± 0.04 bc	29.07 ± 10.04	0.46 ± 0.04 c

Different letters next to numbers represent significantly different means between treatments ($p < 0.05$).

4. Discussion

4.1. Response Patterns of Individual Tree and Stand-Level Transpiration under Thinning and Pruning Treatments

Our study observed that the daily mean E_t and E_c decreased with different combined thinning and pruning treatments, indicating similar transpiration patterns at individual tree and stand levels (Figure 5a–d). This finding addresses the first scientific question of our study. In addition, regardless of pruning heights, T1 showed higher average daily transpiration compared to T2 (Figure 5d). This suggests that transpiration decreases with increasing thinning intensity, which is consistent with the findings of Forrester et al. [11], Guohui Wang et al. [74], Tsamir et al. [75], and Thibaud Andr'e-Alphonse et al. [39]. Two main factors contribute to these results. Firstly, the *LAI* was higher in T1 compared to T2 (Figure S1). The decline in transpiration with increasing thinning intensity can be attributed to the reduction in leaf area at both the individual tree and stand levels, a phenomenon supported by other studies that have also noted a decrease in transpiration with reduced stand leaf area [42,76]. Secondly, the reductions in stand basal area (*BA*) in T2, which resulted from thinning, were 10.21% (P0), 5.38% (P1), and 21.83% (P2) lower than T1. The reduction in stand transpiration was more significant relative to the percentage reduction in the stand density, which can be attributed to the reduction in transpiration of the individual tree level following thinning (Figure 5b). These findings differ from those of Timo Gebhardt et al. [19], where sap flow density rates decreased in both individual trees and stand with increasing thinning intensity (Figure 4a). Additionally, negative correlations between transpiration and thinning intensity have been observed in arid regions [41,77–79], but our study area experienced abundant rainfall. André-Alphonse et al. found variations in moisture conditions across different regions [39], leading to different relationships between transpiration and thinning intensity outcomes.

After pruning, Forrester et al. [11] found that trees exhibited increased efficiency in water and light use, increasing transpiration per unit leaf area. This pattern is consistent with the observed effects of pruning on transpiration in T2 (Figure 5f). Despite no significant difference in stand transpiration among all the pruning heights in T2 (Figure 5d), the number of leaves decreased after pruning (Figure S1), which would typically result in reduced transpiration. However, in T2, where the thinning intensity was higher, the remaining leaves exhibited greater transpiration per unit leaf area (P1 and P2) compared to P0 (Figure 5f), and J_m was higher also (Figure 4a). This aligns with the leaf compensation mechanism, where the photosynthetic and transpiration capacities of remaining leaves are enhanced after pruning [11,23,35,80]. This promotes transpiration at both the individual tree and stand levels. Contrastingly, in T1, which had a higher tree density, pruning did not increase the canopy conductance and transpiration rate per unit leaf area, resulting in a decrease in transpiration. This can be attributed to shaded foliage in the lower canopy of high-density stands causing self-thinning due to insufficient light conditions [10], and pruning does not induce a compensatory effect. These findings align with the studies by Chen et al. [35], Molina et al. [43], and Alcorn et al. [23].

4.2. Response of Transpiration and Canopy Conductance to Environmental Factors

Different treatments change the response of E_L to climatic factors. Firstly, the E_L of T1P0 and T2P2 had the highest response to *VPD*, *PAR*, and ET_0 (Figure 6). That was because the g_c did not decrease rapidly with increasing *VPD* and remained open at high levels (Figure 7a). Pruning had an opposite effect on the stands of different densities of E_L. It showed a negative effect on dense stands and a promotive effect on sparse stands. This suggests that we should consider the role of stand density when researching the effect of pruning o E_L, since the reduction in E_L response to the environment caused by thinning may be eliminated by pruning effects. Secondly, different treatments altered the proportion of environmental factors to explain the variation in E_L. The explanation of variation in E_L by *VPD* was the lowest only in T1P0 and the highest in the other treatments. This may be due to the fact that pruning and thinning reduce the *LAI* of the stand (Figure S1), which tends to make the environment drier and warmer, increasing the limitations on evapotranspiration by the *VPD*.

g_c plays a critical role in governing canopy transpiration. During periods of elevated VPD, stomatal closure becomes essential to preventing excessive water loss, maintaining leaf water potential above a critical threshold, and averting xylem cavitation or dysfunction [81–83]. Our study found that g_c was more strongly correlated to *VPD* than to *PAR* (Figures 7 and S5), which is consistent with Du et al. [32]. This correlation is attributed to the relatively low stand density observed across all treatments, allowing the entire canopy to receive more sunlight and subsequently reducing the saturation threshold for *PAR* [34,37]. This suggests that *VPD* significantly influences stomatal regulation and transpiration in poplar trees [30,32].

The sensitivity of g_c to *VPD* is related to g_{cr} [69]. In our study, T1P2 exhibited high g_c under low *VPD* conditions, indicating stomatal closure (evidenced by high m values) in response to increased *VPD* (Figure 7). This suggests that stomata are more responsive to dry air under T1P2. They are more responsive to stimuli, which may cause stomatal closure. Isohydric tree species, employing an active control of g_c, maximize carbon uptake under low *VPD* conditions, thereby avoiding the risk of wilting due to soil drought. This tree feature, regulating the leaf minimum water potential to circumvent xylem cavitation, is reflected in the m/g_{cr} ratio [84]. Most species typically exhibit m/g_{cr} values of 0.6, indicative of relatively stringent stomatal regulation and a low ratio of boundary layer conductance to canopy conductance [69,71,85]. Larger canopy exposures resulted in changes in *VPD* and boundary layer conductance, which increased with increasing tree spacing due to increased wind speed [86]. In our experiments, the value of m/g_{cr} was less than 0.6 for all treatments, which was due to the fact that the average value of the decoupling coefficient (Ω) for all treatments was less than 0.1 (0.001–0.23), indicating that there was a high degree of canopy coupling to the atmosphere. This suggests that the effect of boundary layer conductance was very small [69].

Stomatal regulation of transpiration can be flexible [87]. A three-year study conducted in an arid zone demonstrated that poplars can alter transpiration by actively controlling stomata in response to varying environmental conditions [32]. In this study, *P. tomentosa* trees showed differences in g_{cr} under different pruning heights in T2, which resulted in the variation in the magnitude of transpiration rate per unit leaf area (Figures 5f and 7b). In T2, the pruning treatment of 3 m (P1) had no significant effect on the m, but g_{cr} was significantly increased in comparison to P0. The pruning treatment of 4 m (P2) significantly decreased the m and increased g_{cr}. This suggests that in lower density stands (T2), the increase in g_{cr} is the main reason for the increase in E_L after pruning treatment. Similar conclusions were obtained by Chen et al. [35] in a study on the influence of branch removal on m and g_{cr}. Meanwhile, in lower density stands, the pruning-induced significant reduction in the number of more-light-exposed leaves in the lower crowns of the trees may account for the reduced response of g_c to *VPD*. In T1, both pruning treatments of 3 m (P1) significantly decreased m and g_{cr}, and pruning treatments of 4 m (P2) significantly increased m but had no effect on g_{cr}. Although pruning treatments could produce significant changes in m and

g_{cr} in the higher density stands (T1), the difference between the two did not cause changes in E_L. In addition to this, this suggests that in higher density stands, only pruning away a sufficient proportion of lower canopy shading leaves (4 m) can improve the g_c response to *VPD*. The results of *m* and g_{cr} may be biased due to the limited sample size [32]. The results indicate that *P. tomentosa* can flexibly regulate its transpiration to maintain its growth and survival, which answers the second scientific question.

4.3. Water Use Efficiency and Basal Area Increment

Poplar is a fast-growing species sensitive to the environment, and short-term moisture changes can affect its growth [88,89]. Thinning can alter the microclimate of the stand and its *WUE* [48]. This study found that stand *WUE* was increased after thinning, with T2P0 showing a statistically significant increase compared to the other treatments. This answers the third scientific question of this study. Notably, the differences in *WUE* among the thinning and pruning treatments were more pronounced at the monthly scale and were associated with rainfall. However, the *BAI* of the stands did not show significant differences at the annual level (Figure 8a). It also differed significantly at different monthly levels (Figure 8c; Table 5). Thus, the changes in *WUE* and *BAI* of poplar stands should be investigated under different rainfall conditions.

Studies have presented conflicting findings on stand *WUE* in relation to rainfall, with some reporting an increase in *WUE* as rainfall decreases [48] and others observing a decrease as rainfall increases [90]. In this study, the *WUE* of T2P0 was significantly higher than other treatments during the rainy season, while there was no significant difference between T2P0, T2P1, T2P2, and T1P2 in the dry season. Additionally, stand diameter growth showed uncertainty under varying moisture conditions. For instance, He et al. [91] found that reduced precipitation led to lower growth, while Xue et al. [92] noted that excessive precipitation also resulted in reduced radial growth. In contrast, Rahman et al. [93] observed opposing effects of precipitation on radial growth at different rainfall periods. In our study, a significant decreasing trend in *BAI* was observed with increasing pruning intensity under the same thinning treatment (Table 5) because pruning reduces the canopy and decreases the *LAI* of the stand (Figure S1; Table 5), aligning with findings by Huang et al. [94]. However, *BAI* did not exhibit any difference across all treatments in the dry season (Table 5).

Since *WUE* is influenced by both E_c and *BAI*, and both factors are impacted by rainfall [29,46], we further explored the relationship between E_c and *BAI* under different rainfall conditions (Figure 9a,b). In the wet summer, negative correlations were observed between E_c and *BAI* in T1P1, T1P2, and T2P0, while the remaining treatments showed an increase in *BAI* with rising E_c (Figure 9a). This phenomenon was attributed to a decrease in *BAI* with rising E_c (Table 5; Figure 8c). In the dry autumn, E_c and *BAI* had a positive correlation in all treatments (Figure 9b). This aligns with the findings of Li et al. [30], suggesting that the contribution of transpiration to growth was further enhanced under water deficit conditions.

From a plantation management perspective, the *BAI* of all the thinning and pruning treatments increased during the late growing season (22 August to 23 September) compared to T1P0. This suggests that thinning and pruning can promote tree growth and prolong the growth period of *P. tomentosa*. Although there was no statistically significant difference in the *BAI* among treatments at the end of the season, the *BAI* of T1P2, T2P1, and T2P0 was higher due to higher g_c and *WUE* in the late growing season (Figures 5g and 9c). It should be noted that these findings were obtained in one growing season, and further research at longer time scales is needed to fully understand the effects of poplar sensitivity to environmental changes and plantation management.

5. Conclusions

In this paper, we systematically investigated the response of *P. tomentosa* plantations' J_s, E_c, E_L, g_c, *WUE*, and *BAI* of to different thinning and pruning intensities. Six treatments

with two densities and three pruning heights were established, and the results show that the transpiration patterns were consistent at both individual tree and stand levels. We observed that stand transpiration and growth varied across treatments, and that these differences were related to the rainfall period within the year. In T1, thinning and pruning reduced E_c and decreased the sensitivity of tree transpiration to climate, while in the sparse plantation, T2, the combination of thinning and pruning promoted E_L and g_s but increased the sensitivity of tree transpiration to climate. The stomatal regulation of *P. tomentosa* under different treatments was flexible, and the pruning effects significantly reduced *WUE* in T2. Overall, T2P0 had the highest *WUE*, and T1P0 had the lowest. Moreover, there were significant differences in E_c and *BAI* among the treatments under different rainfall conditions, with E_c having a more significant impact on *BAI* during the dry autumn. Thinning and pruning moderated the decline in plantation growth at the end of the growing season due to the effect of improving canopy conductance and water use efficiency.

In conclusion, thinning and pruning can promote the growth of *P. tomentosa* plantations by changing their water utilization capacity, but local water conditions should be considered when managing these plantations. Long-term studies are necessary to obtain the optimal plantation management plan for the entire cycle.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15030536/s1. Figure S1. Seasonal variations of daily values of leaf area index (*LAI*). Figure S2. The frequency distribution of stem diameters at breast height (*DBH*) for T1P0, T1P1, T1P2, T2P0, T2P1, and T2P2 is presented in figures (a), (b), (c), (d), (e), and (f) respectively. Figure S3. Logarithmic function of canopy conductance (g_c) and vapor pressure deficit (*VPD*) before BLA. Figure S4 Response relationship between transpiration rate per unit leaf area (E_L) and air temperature (a, T_{air}), wind speed at 2 m height (b, W_s), soil water content (c, θ) at the depths of 20 cm soil layer for different treatments. Figure S5. Response relationship between canopy conductance (g_c) and photosynthetic active radiation (*PAR*) for different treatments. Table S1. Linear regression functional equation for transpiration rate per unit leaf area (E_L) and vapor pressure deficit (ln*VPD*). Table S2. Linear regression functional equation for transpiration rate per unit leaf area (E_L) and photosynthetic active radiation (ln*PAR*). Table S3. Linear regression functional equation for transpiration rate per unit leaf area (E_L) and reference evapotranspiration (lnET_0). Table S4. Linear regression functional equation for transpiration rate per unit leaf area (E_L) and air temperature (T_{air}). Table S5. Linear regression functional equation for transpiration rate per unit leaf area (E_L) and wind speed (W_s). Table S6. Linear regression functional equation for transpiration rate per unit leaf area (E_L) and soil water content (θ). Table S7. Logarithmic function of canopy conductance (g_c) and vapor pressure deficit (*VPD*) and their function after the boundary line analysis (BLA). Table S8. Linear regression functional equation for canopy conductance (g_c) and photosynthetic active radiation (*PAR*).

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