Water Consumption Characteristics of Typical Tree Species and Environmental Impact Factors in the Rocky Mountainous Areas of Northern China (Postprint)

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Abstract

Investigating the water consumption characteristics of plants and environmental influencing factors in the northern rocky mountainous region is of great significance for constructing stable vegetation ecosystems and can provide scientific guidance for local vegetation restoration strategies. At the Xishan Experimental Forest Farm of Beijing Forestry University, transpiration observations and analyses were conducted on a mixed plantation of Robinia pseudoacacia and Pinus tabuliformis from July to October 2016 using the thermal diffusion probe method, combined with synchronously observed soil moisture content and meteorological factors. The results showed that: (1) Although the diurnal variation patterns of transpiration for Robinia pseudoacacia and Pinus tabuliformis were similar, their seasonal variation patterns differed; (2) The transpiration of both species exhibited clockwise hysteresis with VPD (vapor pressure deficit). The transpiration of Robinia pseudoacacia showed clockwise hysteresis with solar radiation, whereas that of Pinus tabuliformis showed counterclockwise hysteresis; (3) Both species were highly coupled with the atmospheric environment ($\Omega < 0.1$), and their stomatal activities could effectively control transpiration; (4) The main environmental factors affecting plant transpiration were solar radiation ($P < 0.01$), VPD ($P < 0.01$), and wind speed ($P < 0.01$), with VPD-induced transpiration being greater than that induced by solar radiation; (5) The moisture condition of shallow soil (0–50 cm) may not be an important factor affecting plant transpiration. The study suggests that in practical management, regulating stomatal conductance could be adopted to reduce water consumption in Robinia pseudoacacia and Pinus tabuliformis plantations, thereby mitigating water as a limiting factor for plantation survival and consequently improving afforestation survival rates.

Full Text

Preamble

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Title: The Effect of Environmental Factors on Plant Water Consumption Characteristics in a Northern Rocky Mountainous Area

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Keywords: northern rocky mountainous area; plant transpiration; environmental variables; coupling

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Abstract

Understanding plant water consumption characteristics and environmental impact factors in the rocky mountainous areas of northern China is crucial for constructing stable vegetation ecosystems and provides scientific guidance for local vegetation restoration strategies. We conducted transpiration observations and analyses in a mixed plantation of *Robinia pseudoacacia* and *Pinus tabuliformis* at the West Mountain Experimental Forest of Beijing Forestry University from July 11 to October 31, 2016, using thermal dissipation probe (TDP) methods combined with synchronous monitoring of soil moisture content and meteorological factors. The results showed that: (1) The two species exhibited different seasonal transpiration patterns, with *R. pseudoacacia* transpiration decreasing in autumn while *P. tabuliformis* maintained relatively stable transpiration throughout the growing season; (2) Both species showed similar diurnal transpiration patterns, but *R. pseudoacacia* had much higher transpiration rates in the morning than in the afternoon, displaying a clockwise hysteresis loop with vapor pressure deficit (VPD), whereas *P. tabuliformis* showed a counterclockwise hysteresis loop with solar radiation; (3) The main environmental factors influencing transpiration were solar radiation, VPD, and wind speed ($P < 0.01$), with VPD inducing higher transpiration than solar radiation; (4) Both species were well coupled to the atmospheric environment ($P < 0.1$), and their stomatal activity could effectively control transpiration; (5) Shallow soil moisture (0–50 cm) was not a major influencing factor on plant transpiration. In practical management, transpiration of these species could be reduced through regulating canopy conductance, thereby alleviating water limitations on plantation survival and improving afforestation success rates.

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Introduction

Tree transpiration represents the primary component of tree water consumption and constitutes the core of water physiological ecology research [1]. In forest ecosystems, transpiration results from the combined effects of multiple environmental factors [2], with solar radiation, vapor pressure deficit (VPD), and soil moisture being the main environmental factors affecting plant transpiration. Solar radiation primarily influences transpiration by inducing stomatal opening and shows a linear correlation with sap flow [3], though high levels can lead to decreased sap flow [4]. Soil moisture affects transpiration by limiting root water uptake [5]. The influence of environmental factors on plant transpiration is also related to stomatal activity, and the coupling degree between trees and the atmospheric environment can be quantitatively expressed through the parameter Ω [6]. Jia et al. [7] studied the transpiration characteristics of *Quercus variabilis* in Beijing and found that transpiration rates were correlated with both solar radiation intensity and VPD. Zhang et al. [8] investigated diurnal variation patterns of sap flow in typical tree species in Jinyun Mountain and found that soil moisture had the greatest impact on nighttime sap flow. Sun et al. [9] examined canopy stomatal conductance of *Larix principis-rupprechtii* in North China and found that stomatal conductance responded differently to environmental factors such as solar radiation and soil moisture, exhibiting nonlinear characteristics. The rocky mountainous areas of northern China have thin soil layers, and as vegetation restoration progresses, the transpiration characteristics of these areas have received increasing attention [10–11]. This study aims to investigate the water consumption characteristics of typical plantations in the mountainous areas of Beijing, explore the mechanisms and extent of environmental factor effects on transpiration, and ultimately provide scientific basis for ecological vegetation construction and management in these regions.

1. Study Area and Materials

The study area is located at the West Mountain Experimental Forest of Beijing Forestry University (116°5 45 E, 40°3 46 N). This region belongs to the warm temperate sub-humid zone, within the Yanshan Mountain deciduous broad-leaved forest and *Pinus tabuliformis*-*Platycladus orientalis* forest zone. The multi-year average precipitation is 610.1 mm, the annual average temperature is 8.5–9.5°C, the multi-year average sunshine duration is 2565.8 hours, and the average frost-free period is 151 days. Precipitation in July–August generally accounts for 70% of the annual total. The study site is situated on a low mountain semi-sunny slope with colluvial cinnamon soil. Soil depth is approximately 50 cm, and rocky land accounts for about half of the area [7].

The experimental plot is a mixed plantation of *P. tabuliformis* and *R. pseudoacacia* with stand age of 56 years. The site was prepared with horizontal terraces, with a north-facing slope of 18°.

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2. Sap Flow Measurement and Calculation

2.1 Sample Tree Selection and Probe Installation

Healthy, disease-free trees were randomly selected from each diameter class as sample trees for sap flow monitoring. Sap flow was measured using thermal dissipation probe (TDP) technology. Probe length was determined based on sapwood width. Customized drills were used to install probes at breast height (DBH = 1.30 m) along the vertical direction with 40 mm spacing, ensuring the heated probe was positioned above and that all probes were fully embedded in the sapwood. After installation, the thermal dissipation sap flow measurement system (TDP, Dynamax Inc., Houston, USA) was set up, with probe tails connected to a data logger (CR1000, Campbell Scientific, Logan, USA) via cables. The junction between probes and tree trunk was sealed with silicone to prevent rainwater intrusion. As TDP is sensitive to environmental thermal radiation, the probe area was wrapped with aluminum foil. The entire data acquisition system was solar-powered and operated continuously, recording data every 30 minutes.

2.2 Calculation Methods

The empirical formula for calculating sap flow density (Js, g cm^{2} h^{1}) is:

$$J_s = 0.0119 \times \left(\frac{\Delta T_M - \Delta T}{\Delta T}\right)^{1.231}$$

where ΔT_M is the maximum daily temperature difference between upper and lower probes, and ΔT is the instantaneous temperature difference.

Whole-tree hourly transpiration (E, g/h) was calculated as:

$$E = J_s \times A_s \times 3600$$

where A_s is sapwood area (cm^2), and 3600 is the time conversion coefficient to extend instantaneous sap flow density to hourly values. Daily whole-tree transpiration was obtained through accumulation.

After obtaining sap flow for individual sample trees, stand transpiration (E_c) was calculated through scaling by sapwood area:

$$E_c = \sum_{i=1}^{n} \bar{J}_{s,i} \times A_{s,i}$$

where $\bar{J}_{s,i}$ is the mean sap flow rate for the i-th species and diameter class, and $A_{s,i}$ is the total sapwood area for that species and diameter class.

Sapwood area was determined by extracting tree cores at breast height using an increment borer. The color difference between sapwood and heartwood was distinct for both species, allowing measurement of sapwood thickness. Regression relationships between DBH and sapwood area were established for different species and diameter classes in the sample plot.

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3. Canopy Conductance (Gc) Calculation

Canopy conductance (G_c) was calculated based on the Penman-Monteith equation:

$$G_c = \frac{\gamma \lambda E G_a}{\Delta R_n + \rho C_p VPD G_a - (\Delta + \gamma)\lambda E}$$

where   is latent heat of vaporization (2465 J/g), C_p is specific heat at constant pressure (1.01 J g^{1} °C^{1}), Δ is the slope of saturation vapor pressure versus temperature curve (Pa/°C), R_n is net radiation above canopy (W/m^2),   is air density (kg/m^3), VPD is vapor pressure deficit (Pa),   is psychrometric constant (65.5 Pa/°C), G_a is aerodynamic conductance (m/s), and G_c is canopy conductance (m/s).

Aerodynamic conductance (G_a) was calculated as:

$$G_a = \frac{k^2 u}{\ln\left(\frac{Z-Z_h}{Z_0}\right)\ln\left(\frac{Z-Z_h}{Z_{0h}}\right)}$$

where k is von Karman constant (0.41), u is wind speed (m/s), Z is canopy height (m), Z_h is zero-plane displacement height (0.67Z), Z_0 is roughness length (0.1Z), and Z_{0h} is roughness length for heat transfer (0.1Z_0).

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4. Decoupling Coefficient

The decoupling coefficient (Ω) measures the coupling degree between trees and the atmospheric environment and was calculated using the formula:

$$\Omega = \frac{\Delta + \gamma}{\Delta + \gamma + G_a/G_c}$$

This coefficient quantifies the relative contributions of solar radiation and VPD to plant transpiration, where transpiration induced by solar radiation is ΩE and that induced by VPD is (1-Ω)E.

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5. Environmental Factor Observation

Given the horizontal terrace site preparation, soil volumetric water content (VWC) was monitored at both flat and slope positions using soil moisture sensors. Three replicates were established for flat positions and two for slope positions, with recording intervals set at 30 minutes. Temperature and relative humidity were monitored directly using sensors, and VPD was calculated as:

$$VPD = 0.611 \times \exp\left(\frac{17.27T}{T + 237.3}\right) \times (1 - RH)$$

where T is air temperature (°C) and RH is relative humidity (%).

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6. Statistical Analysis

Statistical analysis was performed using SPSS 16.0. Significant differences between samples were determined through paired t-tests and one-way ANOVA. Factors influencing tree sap flow were identified primarily through correlation analysis and regression fitting.

Results

1. Environmental Factors and Transpiration Changes During the Growing Season

Figure 1 [Figure 1: see original paper] shows the dynamic trends of environmental factors during the observation period. The region exhibited distinct seasonal climate patterns (2016). Solar radiation and VPD showed decreasing trends, while significant differences existed between months for different factors. Precipitation was concentrated in July–August (199.5 mm total), accounting for

70% of the rainfall during the four-month period. Surface soil water content (0-50 cm) varied significantly with terrain (F = 10.847, P = 0.000), and the rate of soil water content decline slowed as the season progressed.

Diurnal transpiration characteristics differed markedly between the two species and continuously declined as autumn approached, though they responded differently to seasonal changes. *R. pseudoacacia* transpiration intensity decreased with summer progression, while *P. tabuliformis* showed a slight increase in early autumn before declining similarly to *R. pseudoacacia*.

2. Daily Variation Patterns of Stand Transpiration and Response to Environmental Factors

The daily variation patterns of stand canopy transpiration (E_c) were similar for both species (Figure 2 [Figure 2: see original paper]), showing single-peak curves. However, canopy conductance (G_c) and the decoupling coefficient (Ω) played different roles in stand transpiration activity. In the morning, Ω remained at relatively high levels, indicating weak coupling between stand transpiration and the atmosphere, with solar radiation being the dominant factor. Stomata opened rapidly under solar radiation induction, causing increases in both G_c and E_c, though the rate of G_c increase was much lower than that of E_c.

As Ω began to decrease around 11:00, the coupling between stand transpiration and the atmosphere improved, and physiological control over transpiration gradually strengthened. G_c became the main factor influencing stand transpiration, with G_c and E_c showing a close quantitative relationship (Figure 4 [Figure 4: see original paper]), indicating that sample trees could effectively control transpiration through stomatal activity. Both species maintained Ω values below 0.4, demonstrating effective physiological regulation in response to environmental changes.

3. Response of Sap Flow to Environmental Factors in Different Species

Analysis of time-lag relationships revealed that both species had much higher sap flow rates in the morning than in the afternoon. *R. pseudoacacia* showed clockwise hysteresis with VPD, while *P. tabuliformis* showed counterclockwise hysteresis with solar radiation (Figure 5 [Figure 5: see original paper]). The hysteresis loops intensified with increasing daily VPD.

Correlation analysis between sap flow and environmental factors showed that solar radiation, VPD, and wind speed were significantly correlated with sap flow in both species (Table 3). Regression equations established using environmental factor data from August days provided accurate quantitative predictions of transpiration, with paired t-tests showing no significant differences between fitted and observed values (P > 0.05, Table 5).

Discussion

1. Time-Lag Effects Between Sap Flow and Environmental Factors

Many studies have observed time lags between sap flow and VPD [14–15]. The primary cause is trunk water storage, as trees continue nocturnal sap flow activity to replenish water lost during intense daytime transpiration [16–18]. This stored water is preferentially used when transpiration begins, causing sap flow to show counterclockwise hysteresis with solar radiation. Only *P. tabuliformis* exhibited this pattern in our study, possibly due to its use of internal water storage to buffer intense transpiration.

The time lag intensified with increasing VPD in both species, consistent with findings that increased resistance along the soil-to-leaf hydraulic pathway causes this phenomenon [19–20]. Murakami et al. [20] reported similar results for eucalyptus in northern Australian savannas under dry season conditions with declining soil moisture, analogous to the summer drought period in northern China' s rocky mountainous areas.

2. Mechanisms of Environmental Factor Effects on Stand Transpiration

Perennial plants possess extensive root systems that can access deep soil moisture, which may be the primary water source during dry seasons [11,14]. Our soil moisture monitoring was limited to 50 cm depth for two reasons: (1) the average soil depth in the study area is approximately 60 cm, and (2) the rocky soil medium easily causes poor contact between sensors and soil, leading to inaccurate measurements. The dense root network and rocky texture also limited excavation depth.

Despite not monitoring deep soil layers, our synchronous monitoring of shallow soil moisture (0–50 cm) and sap flow revealed that neither species showed significant response to shallow soil moisture, similar to findings in other studies [13,22]. This suggests that shallow soil is not the main root distribution zone, and deep soil moisture is likely an important water source for the stand. During periods with less rainfall, shallow soil moisture remained low, yet tree transpiration intensity could be maintained at levels similar to periods with more rainfall, indicating that deep water sources likely support plant transpiration during dry seasons.

On hourly or daily timescales, solar radiation is the main environmental factor regulating stomatal activity and the primary driver of transpiration [1]. However, the mechanism by which VPD affects stomata remains uncertain [1,22]. When atmospheric transpiration demand becomes excessive, stomata gradually close to prevent excessive water loss, maintain constant transpiration, or keep water potential within safe ranges, avoiding fatal xylem cavitation and embolism [24]. This mechanism increases hydraulic resistance along the soil-to-leaf pathway, ultimately determining the maximum transpiration rate trees can sustain.

Conclusion

This study investigated water consumption characteristics of typical tree species in the rocky mountainous areas of northern China and their environmental impact factors, revealing several key findings:

1. Due to phenological differences, *R. pseudoacacia* and *P. tabuliformis* showed different seasonal transpiration patterns, with the former decreasing water consumption gradually in autumn and the latter showing some increase in early autumn.
2. The two species exhibited similar diurnal patterns but different amplitudes, with *P. tabuliformis* showing higher transpiration intensity. Both species were well coupled with the atmospheric environment ($\Omega < 0.4$), indicating effective physiological control through stomatal activity, with transpiration maintaining a near-linear relationship with stomatal changes.
3. Among environmental factors, solar radiation primarily influenced transpiration before noon, while VPD contributed more to total transpiration. As atmospheric transpiration demand increased, sap flow started earlier to avoid xylem cavitation and embolism from intense transpiration.
4. Surface soil moisture (0–50 cm) did not significantly affect transpiration. Future research should monitor deeper soil layers to identify the main water supply layer for *P. tabuliformis* and *R. pseudoacacia* plantations.
5. Both species can effectively regulate transpiration through stomatal conductance, maintaining transpiration intensity within stable ranges to ensure normal physiological activities. In practice, water consumption of these plantations can be managed by reducing canopy conductance through pruning or selecting species with low canopy conductance, thereby alleviating water limitations and improving afforestation survival rates under limited water conditions.

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Note: Figure translations are in progress. See original paper for figures.