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Characteristics of Changes in Sap Flow-Based Transpiration of Poplars, Locust Trees, and Willows and Their Response to Environmental Impact Factors

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Abstract: The sap flow and transpiration of three typical tree species (poplar, locust tree, and willow) in Ningxia are crucial for sustaining the ecosystem in the Ningxia Yellow River Irrigation area. However, there is a lack of clarity regarding the variations in sap flow and transpiration of these trees and their corresponding responses to environmental factors. From February to December 2021, this study selected 30 samples representing the three typical trees in the irrigation area and monitored their tree sapwood sap flow continuously and dynamically using the Thermal Diffusion Probe method. This study yielded several key findings: (1) Variations exist in sap flow density and transpiration among the three typical trees, with willows exhibiting higher sap flow density and transpiration than poplars and locust trees. (2) Tree transpiration showed a highly significant positive correlation with net radiation, temperature, and vapor pressure deficit, along with a highly significant negative correlation with relative humidity. (3) Soil moisture content undergoes changes under precipitation and artificial drip irrigation, but its correlation with tree transpiration is limited. (4) The primary environmental factors influencing poplars, locust trees, and willows are temperature, soil moisture content at a depth of 30 cm, and soil moisture content at a depth of 60 cm.

Keywords: meteorological factors; Ningxia Yellow River Irrigation area; sap flow; soil moisture content

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1. Introduction

Transpiration, recognized as one of the most crucial physiological activities in plants [1], plays a vital role in plant physiological processes and ecosystem functioning [2] and constitutes a significant component of the hydrological cycle. Acting as the regulatory mechanism for water transport between the plant and its external environment through stomata, transpiration manifests as sap flow in the xylem layer, facilitating the movement of water from the roots to the leaves. Consequently, assessing plant sap flow emerges as an effective means of measuring transpiration. Contemporary research underscores that the measurement of tree sap flow serves as a pivotal indicator of plant transpiration rate [3–7]. Widely adopted in this context, the Thermal Diffusion Probe (TDP) technique has proven instrumental [8–11]. This method calculates sap flux density by leveraging temperature differences between two TDPs mounted along the stem. It further extrapolates transpiration for an individual tree by scaling point measurements within the tree to the total cross-sectional area of the sapwood. Notably, this technique combines applicability and repeatability, making it a valuable tool for accurate and replicable measurements. This technique proves valuable for analyzing sap flow density (SFD) and transpiration patterns in three typical tree species within the Ningxia Yellow River Irrigation area (NYRIa) [12].

The NYRIa is a crucial ecological barrier in the western region of China, ensuring the ecological security of the upper and middle reaches of the Yellow River, North China, and Northwest China [13]. Poplar (*Populus tomentosa*), willow (*Salix matsudana*), and locust tree (*Robinia pseudoacacia* Linn.) are the primary tree species used for protective forests and urban greening in the NYRIa [14], playing a significant role in restoring vegetation cover and enhancing the ecological environment within this region [15,16]. With the implementation of the policy to return farmland to forests and an increase in planting density [17,18], the total water consumption demand for normal tree growth is increasing year by year [19], which is bound to further impact the irrigation area's water supply and demand. It is necessary to design a suitable irrigation management system for the unique climatic and geographic conditions of the irrigation area to promote the healthy growth of arbor in the NYRIa [20]. An essential foundation for the establishment of effective irrigation systems is the precise estimation of the SFD and transpiration patterns in the region [19]. Given the markedly distinct physiological characteristics exhibited by the three typical trees, it follows that variations in sap flow and transpiration patterns are inevitable. Unraveling the intricacies of this variability, alongside comprehending water consumption patterns, presents a significant challenge for all stakeholders, encompassing the scientific community, management entities, and policymakers.

Plant sap flow is significantly influenced by the meteorological environment, which includes factors such as temperature, relative humidity, wind speed, net radiation, atmospheric pressure, and vapor pressure deficit (VPD) [21–26]. Furthermore, it has been verified that the meteorological drivers of the SFD can change with tree species [27]. Therefore, it is very important to evaluate the changes in the SFD of different tree species and their response to meteorological factors to understand and predict the response of tree growth to climate change. Meanwhile, the soil properties also affect tree transpiration to some extent [28,29]. Soil water is essential for plant sap flow and growth, prompting the common practice of using irrigation to enhance these processes [30]. Additionally, precipitation plays a pivotal role in momentarily augmenting soil water content (SWC) [31], thereby amplifying vegetation transpiration [32,33]. In the NYRIa, both precipitation and irrigation stand out as primary factors contributing to fluctuations in SWC—an influential factor shaping vegetation transpiration [34,35]. However, the effect of soil moisture conditions on the transpiration of arbor in the NYRIa has often been neglected. The response of plant sap flow to environmental factors is an extremely complex one, with sap flow characteristics varying widely across different tree species, meteorological conditions, groundwater depths, and SWC [36]. Currently, most studies focus on the response of specific plant transpiration to meteorological factors, but there is a lack of research on the transpiration of various typical tree species within a region and on the relationship between SWCs [37–39]. Hence, the discernment of the correlation between water consumption in vegetation transpiration and SWC holds significant value for the effective execution of water-saving irrigation practices in the NYRIa.

Artificial neural networks serve as potent non-linear statistical tools, mimicking the functionality of human nerve cells. These independent algorithmic learning systems are adept at incorporating artificial intelligence techniques [40]. Artificial neural network-based models have been effectively employed in understanding the relationships among meteorological factors, stomatal conductance, SFD, and vegetation growth [41,42]. However, there is a noticeable gap in the existing literature concerning the comprehensive assessment of the diverse effects of various environmental factors on distinct typical arbor trees, particularly through the lens of artificial neural networks. Employing the multilayer perceptron (MLP) model offers a novel perspective for evaluating the impact of 12 environmental factors on the transpiration of three typical arbors.

In conclusion, variations exist in sap flow and transpiration among different tree types, along with distinct responses to environmental factors. Nevertheless, a quantitative evaluation of the differences among the three typical trees in the NYRIa remains elusive. Therefore, the four main sections of this paper focus on (a) exploring sap flow and transpiration characteristics in three typical trees within the NYRIa, (b) examining their response to meteorological factors and unique traits in transpiration water consumption, (c) analyzing their response to different soil moisture conditions (precipitation and drip irrigation) in transpiration water consumption, and (d) evaluating the key factors influencing transpiration variations in various tree species.

2. Materials and Methods

2.1. Study Area

Ningxia is situated within the middle and upper reaches of the Yellow River Basin, sharing borders with Gansu, Inner Mongolia, Shaanxi, and other provinces. It boasts a long and narrow north–south border, encompassing a total area of 66,400 km^2 [43]. The climate is characterized as dry, falling under the category of continental monsoon climate [44]. The NYRIa typifies an arid region with an average precipitation of only 192 mm. Notably, the majority of the annual precipitation occurs between May and September, constituting 82.0% of the total annual precipitation. The remaining months witness comparatively low precipitation rates but are characterized by higher levels of evaporation [45]. The NYRIa experiences an average evaporation capacity of 1122 mm, approximately six times higher than the precipitation. Evaporation is concentrated mainly from April to August, accounting for 67% of the total annual evaporation. The average temperature in the NYRIa ranges from 8 to 9 °C, with daily temperature differences typically spanning 12 to 15 °C. Among the common tree species in the NYRIa are poplars, willows, and locust trees.

This study reveals an uneven distribution of groundwater depth (GD) in the NYRIa due to prolonged irrigation. This GD variable significantly influences the SWC, subsequently affecting the growth and transpiration of local vegetation. To explore this relationship effectively, this study identifies five monitoring stations, each with varying GDs and thriving arbor (Figure 1): Shizuishan station, Huinongqu station, Ningxia central station, Forestpark station, and Suyukou station. These stations exhibit GDs of 1.1 m, 1.8 m, 4.4 m, 10 m, and >100 m, respectively.

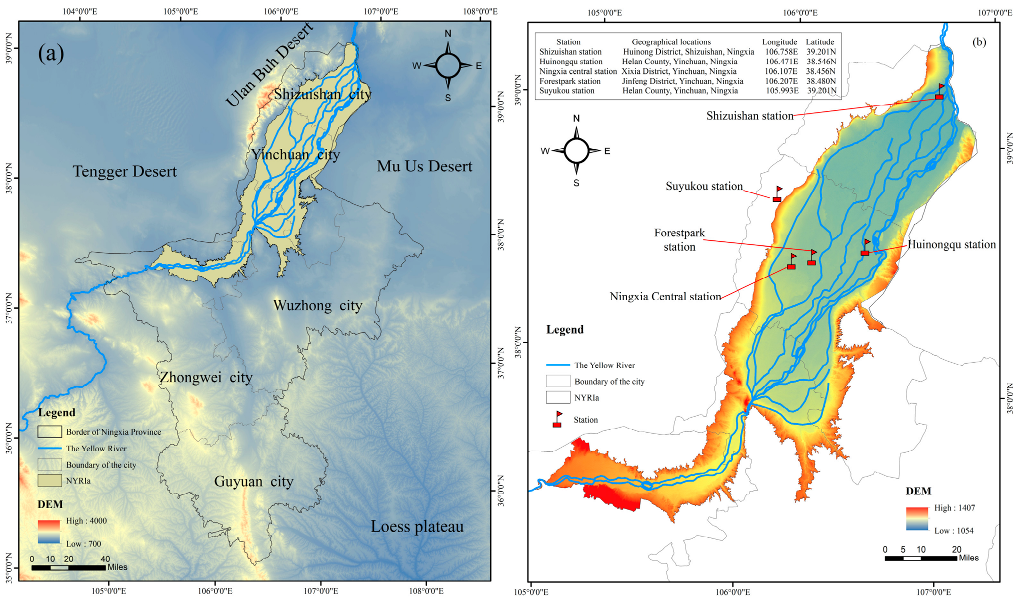

Figure 1. Location of the study area and hydrological station sites: (**a**) Ningxia; (**b**) Ningxia Yellow River Irrigation area.

2.2. Measurement of Sapwood Area of Trees and Biological Characteristics

The sapwood area plays a critical role in determining thermal diffusion flux. Typically, the correlation between tree diameter at breast height (DBH) and sapwood area (A_S) is employed for A_S calculations. In this study, we determine A_S by selecting trees of the same species and growth environment as the target trees. We establish the relationship between A_S and DBH for different tree types. Finally, we calculate the corresponding A_S using the fitted curve and the observed DBH of the target trees. This approach minimizes damage to the observed sample trees, ensures data accuracy, and meets the requirements for long-term observation of sap flow data. The equation describing the relationship between A_S and DBH for the three trees is:

$$\text{Poplar: } As = 0.820DBH^{1.809}\ (\mathrm{R}^2 = 0.9328, \mathrm{n} = 10) \tag{1}$$

$$\text{Locust tree: } As = 0.466DBH^{1.824}\ (\mathrm{R}^2 = 0.9205, \mathrm{n} = 25) \tag{2}$$

$$\text{Willow: } As = 1.370DBH^{1.682}\ (\mathrm{R}^2 = 0.9834, \mathrm{n} = 6) \tag{3}$$

To study the effects of soil moisture and meteorological conditions on vegetation transpiration, in situ experiments were conducted at the five mentioned sites. Our study utilized TDP thermal diffusion technology to monitor the sap flow process of 30 trees, considering factors such as tree species, DBH, tree height, drip irrigation, and crown width (CW). Table 1 presents monitored vegetation information from each site. Additionally, a soil moisture monitoring system was installed both horizontally (0.5 to 1 m from the root system) and within the root system to track moisture levels.

Table 1. Statistical table for monitoring tree samples. Abbreviations: DBH, diameter at breast height; CW, crown width.

State	Number	Varieties of Trees	DBH (cm)	Height (m)	CW (m × m)	TDP (mm)
Ningxia central station	NC-H1	locust tree	7.8	5.7	2.9 × 3.7	TDP30
	NC-H2	locust tree	7.9	5.9	3.4 × 4.7	TDP30
	NC-Y1	poplar	16.8	16.5	2.2 × 2.4	TDP50
	NC-Y2	poplar	22.7	18.8	2.9 × 3.6	TDP 80
	NC-L1	willow	14.5	10.1	4.7 × 6.3	TDP 50
	NC-L2	willow	22.6	11.7	9.2 × 10.8	TDP 50
	NC-H3	locust tree	8.8	16.2	3.6 × 4.1	TDP 30
	NC-H4	locust tree	12.8	9.5	3.2 × 4.5	TDP 30
	NC-Y3	poplar	24.2	18.7	2.5 × 4.5	TDP 80
	NC-Y4	poplar	32.3	23.5	3.1 × 2.8	TDP 80
	NC-Y5	poplar	33.8	29.4	3.3 × 2.2	TDP 80
	NC-Y6	poplar	42	29.6	5.5 × 4.4	TDP 100
Huinongqu station	HN_L1	willow	14.9	8.9	3.4 × 4.3	TDP 50
	HN_L2	willow	11.0	6.8	1.8 × 2.4	TDP 30
	HN_Y1	poplar	12.5	12.1	2.5 × 4.5	TDP 50
	HN_Y2	poplar	7.9	8.9	2.1 × 3.0	TDP 30
Suyukou station	SY_Y1	poplar	13.8	8.9	2.5 × 4.5	TDP 50
	SY_Y2	poplar	16.0	9.1	2.7 × 4.3	TDP 50
	SY_H1	locust tree	7.0	6.3	2.2 × 2.7	TDP 30
	SY_H2	locust tree	7.2	6.4	2.0 × 2.8	TDP 30
Forestpark station	FP_Y1	poplar	18.0	7.1	3.4 × 3.0	TDP 50
	FP_Y2	poplar	12.0	7.2	3.3 × 2.9	TDP 50
	FP_H1	locust tree	12.4	6.5	3.7 × 4.3	TDP 30
	FP_H2	locust tree	10.0	6.3	2.9 × 3.1	TDP 30
Shizuishan station	SZS_Y1	poplar	22.9	13.4	2.7 × 4.3	TDP 80
	SZS_Y2	poplar	30.9	16.0	3.4 × 3.0	TDP 80
	SZS_H1	locust tree	12.4	6.0	3.8 × 4.2	TDP 50
	SZS_H2	locust tree	13.7	8.2	3.6 × 4.4	TDP 50
	SZS_L1	willow	35.7	12.6	7.6 × 9.3	TDP 80

2.3. Sap Flow

Different-size thermal dissipation probes (Dynamax Inc., Houston, TX, USA) were used to monitor the tree sap flux density from February to December 2021. To ensure measurement accuracy, the probe length was selected based on the sapwood width of different trees. After probe installation, the probe and tree were sealed with silicone adhesive to prevent rainwater entry. The probe area was wrapped in aluminum foil to mitigate heat radiation impact. Cling film was then wrapped around the tree and the upper part of the reflective bubble insulator to prevent water ingress from the tree surface.

All data were automatically recorded by a data collector, averaged every 10 min, and stored. According to Granier's empirical formula [46], the measured temperature difference between the two probes was converted into the SFD of the tree sapwood:

$$SFD_i = 0.0119\left(\frac{\Delta T_{max} - \Delta T}{\Delta T}\right)^{1.231} \tag{4}$$

where SFD_i is the sap flux density (g cm^{-2} s^{-1}), ΔT is the probe temperature difference between the two needles (°C), and ΔT_{max} is the maximum value of ΔT recorded in the non-transpiration period when SFD_i is near zero (°C).

The hourly evapotranspiration ET_i (g/h) for a sample tree was calculated using the formula:

$$ET_i = 3600 \times A_s \times SFD_i \tag{5}$$

where A_s represents the sapwood area and 3600 is a time conversion coefficient that extends the instantaneous sapwood density to hourly sapwood flow. The total transpiration for the entire tree in a single day can be obtained by accumulating these hourly values.

2.4. Meteorological and Soil Moisture Measurements

Meteorological factors, including temperature (T) (°C), relative humidity (RH) (%), wind speed (WS) (m/s), precipitation (P) (mm), net radiation (Rn) (MJ·m^{-2}/day), and VPD (kPa), were selected. These were measured by a Weatherhawk 232 automatic weather station placed on the open ground around the trees, with a data collection interval of 10 min. VPD was calculated based on RH and T data using the formula [29]:

$$VPD = 0.611e^{(17.502T/(T+240.97))}(1 - RH) \tag{6}$$

where VPD is the water vapor pressure deficit (kPa), T is the temperature (°C), and RH is the relative humidity (%).

The soil moisture monitoring profile, positioned 0.5~1 m horizontally from the tree roots, consisted of a vertically excavated 2 m deep soil pit (2 m × 1 m). Probes were inserted into six soil layers at depths of 30 cm, 60 cm, 90 cm, 120 cm, 160 cm, and 200 cm. Volumetric water content, soil temperature, and soil conductivity in these layers were monitored, with the data collector recording measurements every 10 min.

Drip irrigation was applied twice during the growing season, first on 10–11 May with a total water volume of 3.92 L, and then on 11–13 July with a total water volume of 4.89 L.

2.5. MLP Model

In order to identify patterns in various experimental datasets, artificial neural network models have been widely implemented as a practical tool [46]. The MLP model is a biologically inspired computational network consisting of at least 3 layers (input, hidden, and output) along with connecting neurons and nodes arrayed in each layer (Figure 2). The model consists of 12 independent variables as inputs (T, P, RH, Rn, WS, VPD, SWC_{30cm}, SWC_{60cm}, SWC_{90cm}, SWC_{120cm}, SWC_{160cm}, and SWC_{200cm}) and only the dependent variable Y as an output, which is tested by trial and error on the hidden layers (1–12) and the neurons in each of the hidden layers to find the best topology of each artificial neural network system's optimal topology.

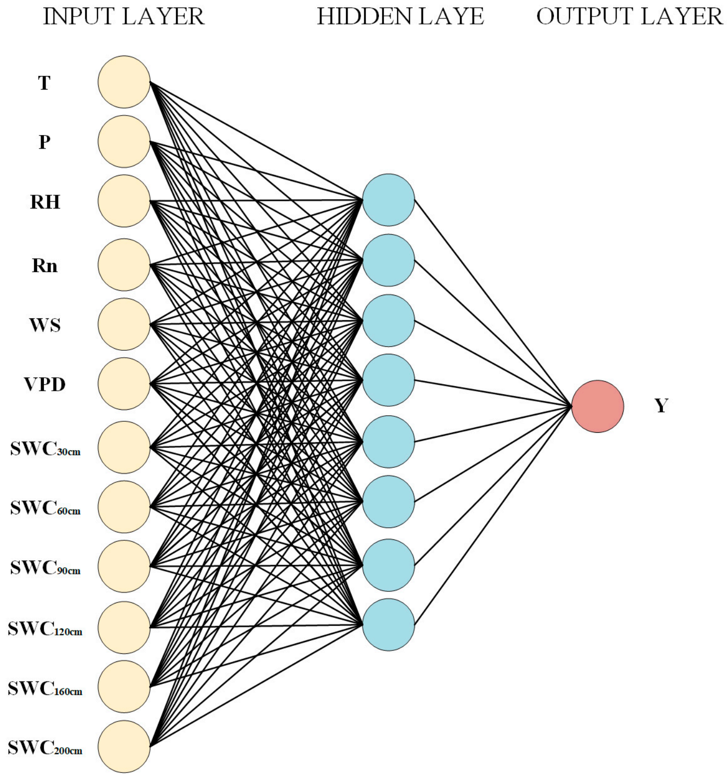

Figure 2. Architecture of the MLP model feed-forward network used in this study. Abbreviations: T, temperature; P, precipitation; RH, relative humidity; Rn, net radiation; WS, wind speed; VPD, vapor pressure difference; SWC_{30cm}, soil moisture content at 30 cm underground.

3. Results

3.1. Trend Analysis of Meteorological Factors

In this study, we analyzed the T, precipitation (P), Rn, RH, WS, and VPD trends in the NYRIa from March to December 2021 (Figure 3).

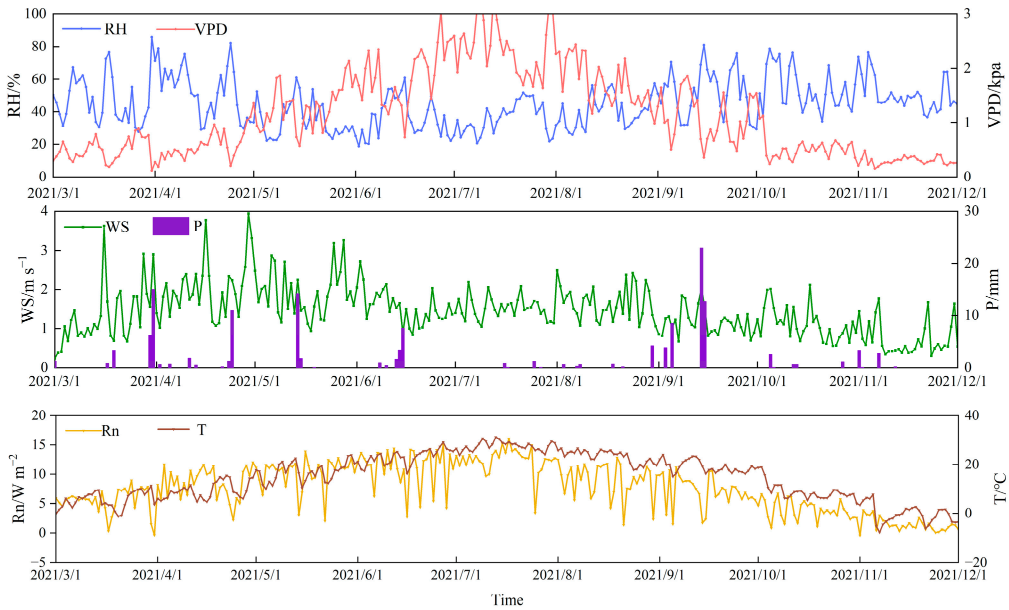

Figure 3. Changes in meteorological factors. Abbreviations: RH, relative humidity; VPD, vapor pressure difference; WS, wind speed; P, precipitation; Rn, net radiation; T, temperature.

The average annual RH was 45.28%, characterized by high temperatures and low precipitation from May to August, resulting in decreased air humidity. In 2021, the RH ranged from a maximum of 85.69% with 6.2 mm of precipitation to a minimum of 20.19%. VPD exhibited a lower level during the growing season (May–October) and a higher level during the non-growing season, contrasting the trend of relative humidity. WS showed no distinct seasonal pattern, with maximum speeds occurring mainly in spring (March–June). Precipitation was concentrated in spring and fall, totaling 141.7 mm in 2021, less than the 2020 drought year. The maximum daily precipitation for the year was 35.7 mm. Rn followed the temperature trend, increasing and then decreasing from February to July, with a subsequent cooling phase from August to December. The average annual temperature was 11.83 °C.

3.2. Characterization of Changes in Sap Flow and Transpiration in Typical Trees

3.2.1. Characteristics of Daily Variation in Sap Flow of Typical Trees

In the Ningxia central station, six trees were selected: two poplars (NC-Y3 and NC-Y4), two locust trees (NC-H1 and NC-H2), and two willows (NC-L1 and NC-L2). This helped characterize the changes in tree SFD among the different species.

The growing season, based on sap flow initiation, spans from May to October for poplars and locust trees and from April to October for willows (Table 2). Poplars consistently initiate sap flow earliest, followed by willows and then locust trees. Sap flow initiation times progressively delay each month, ranging from 70 to 160 min. The tree SFD of the three typical trees exhibited distinct diurnal patterns, with the peak sap flow consistently occurring at a similar time. During the night to early morning, characterized by weak solar radiation, low air temperature, and high relative humidity, SFD remained small and relatively stable. As solar radiation increased, air temperature rose, and relative humidity decreased, the initiation of tree sap flow typically commenced between 6 and 8 a.m.

Table 2. Starting time of three typical arbor sap flows during the growing season. Abbreviations: DBH, diameter at breast height; CW, crown width.

Number	DBH (cm)	CW (m × m)	April	May	June	July	August	September	October
NC-Y3	24.2	2.5 × 4.5	\	5:30	5:50	6:10	6:30	7:00	7:50
NC-Y4	32.3	3.1 × 2.8	\	\	5:40	5:50	6:10	6:50	7:30
NC-H1	7.82	2.9 × 3.7	\	6:20	6:50	7:10	8:00	8:30	9:00
NC-H2	7.95	3.4 × 4.7	\	6:10	6:30	6:50	7:10	7:50	8:10
NC-L1	15.45	4.7 × 6.3	6:50	6:10	6:00	6:00	6:20	7:20	8:10
NC-L2	22.60	9.2 × 10.8	6:40	6:10	6:00	6:00	6:20	7:10	7:50

For poplars, the start time shifts from 5:30 a.m. in May to 7:50 a.m. in October, while locust trees' start time moves from about 6:20 a.m. in May to around 9:00 a.m. in October. Willows exhibit a 'late–early–late' pattern, initiating sap flow gradually earlier (from 6:50 to 6:00 a.m.) from April to June and later (from 6:00 to about 8:00 a.m.) from July to October.

Throughout the growing season, the daily variation in tree SFD for the three typical trees exhibited an inverted 'U' shape, featuring single or double peaks (Figure 4). Willows displayed the highest peak mean SFD (4.24×10^{-3} cm/s), followed by locust trees (3.75×10^{-3} cm/s), and poplars with the smallest (2.55×10^{-3} cm/s). Conversely, during the growing season, SFD increases slowed down around 9:00 a.m., while in the non-growing season, decreases in SFD commenced around the same hour, albeit to a lesser extent.

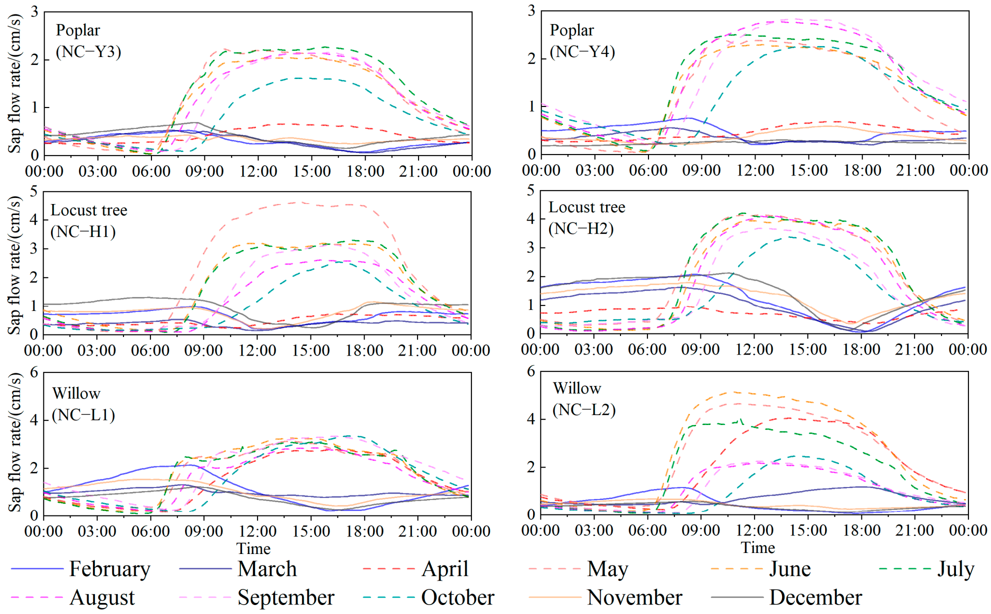

Figure 4. Month-by-month sap flow change curves of different types of trees. Abbreviations: SFD, sap flow density.

3.2.2. Typical Tree Transpiration Pattern

In this study, we calculated the cumulative SFD over the sapwood area as a proxy for single-plant transpiration, converting the units to L/d for ease of presentation and description. Figure 5 presents the month-by-month transpiration process of the three typical arbors. The three typical arbors exhibited distinct patterns of transpiration water consumption during the growing and non-growing seasons.

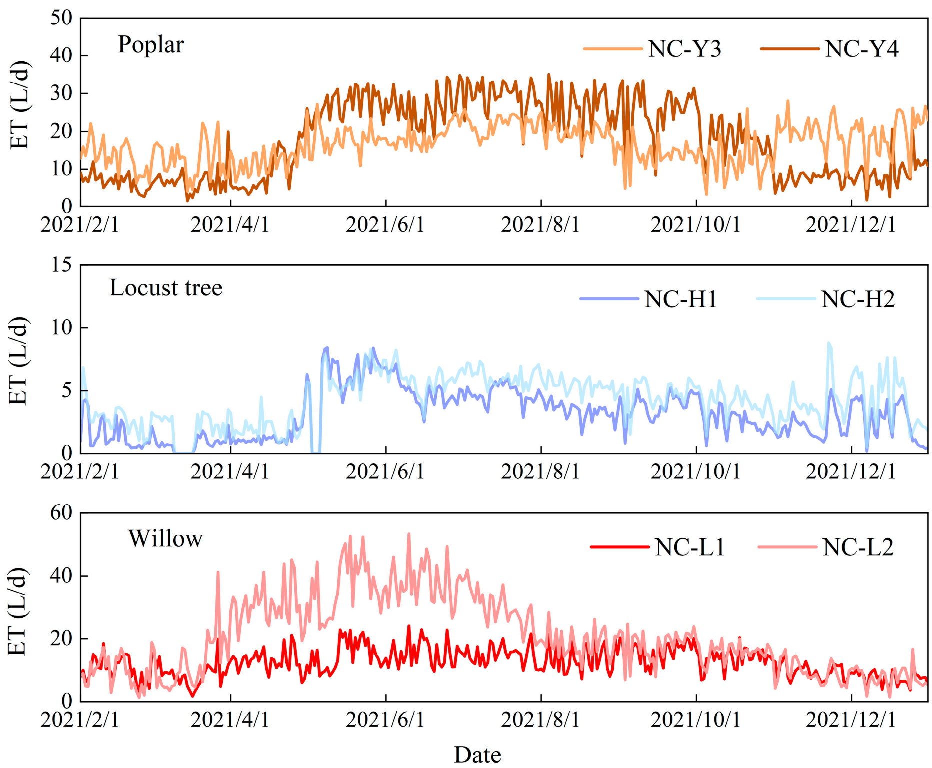

Figure 5. Transpiration water consumption process of three typical trees. Abbreviations: ET, evapotranspiration.

Significant differences in transpiration were observed between the growing and non-growing seasons for the three typical trees (Figure 5). The average transpiration of poplars, locust trees, and willows during the growing season was 21.4 L/d, 11.4 L/d, and 24.11 L/d, respectively, while during the non-growing season, the transpiration decreased to 11.68 L/d, 2.32 L/d, and 12.2 L/d, respectively. Transpiration sharply increased at the start of the growing season and remained high. Poplars and locust trees showed rapid transpiration growth in May, peaking from May to June, while willows' sap flow increased gradually in April, peaking in water consumption from April to June. In contrast, water consumption was relatively low during the non-growing period.

Differences in transpiration characteristics were noted among trees of the same species: $ET_{NC\text{-}Y4} > ET_{NC\text{-}Y3}$, $ET_{NC\text{-}H2} > ET_{NC\text{-}H1}$, and $ET_{NC\text{-}L2} > ET_{NC\text{-}L1}$, aligning with the DBH and SFD of the trees. NC-Y4 had a larger DBH and SFD than NC-Y3, resulting in greater evapotranspiration from Y4 than Y3 during the growing season. DBH and sap flow density jointly determine the difference in transpiration between two willow trees. NC-L2 (22.6 cm) had a larger DBH than NC-L1 (14.5 cm). The average sap flow density of NC-L2 (2.28×10^{-3} cm/s) was significantly larger than that of NC-L1 (1.74×10^{-3} cm/s) from April to August, leading to significantly greater transpiration for NC-L2 during the same period.

Distinct transpiration characteristics were observed among different tree types. Willow (24.11 L/d) transpiration was the highest, followed by poplars (21.4 L/d), and locust trees (11.4 L/d) exhibiting the lowest.

3.3. Differential Analysis of Sap Flux Density Response Characteristics of Typical Trees to Meteorological Factors

Table 3 presents Pearson correlation coefficients between daily SFD and five factors (Rn, T, RH, VPD, and WS). The analysis included 344 sets of SFD and meteorological data collected during the growing period.

Table 3. Correlation of SFDs of three typical trees with Rn, T, RH, VPD, and WS. Abbreviations: GD, groundwater depth; Rn, net radiation; T, temperature; RH, relative humidity; VPD, vapor pressure difference; WS, wind speed.

GD	Varieties of Trees	Rn	T	RH	VPD	WS
1.1 m	poplar	0.854 **	0.735 **	−0.622 **	0.819 **	0.135 *
	locust tree	0.502 **	0.294 **	−0.559 **	0.407 **	0.053
	willow	0.891 **	0.813 **	−0.501 **	0.754 **	0.034
4.4 m	poplar	0.319 **	0.185 *	−0.155 *	0.151 *	−0.145 *
	locust tree	0.703 **	0.535 **	−0.646 **	0.621 **	0.105
	willow	0.435 **	0.148 *	−0.262 **	0.175 *	0.103
>100 m	poplar	0.813 **	0.683 **	−0.609 **	0.774 **	0.040
	locust tree	0.807 **	0.765 **	−0.417 **	0.752 **	−0.036

** represents $p < 0.01$ level of significance, * represents $p < 0.05$ level of significance.

Common correlation patterns emerged across the three representative tree species and meteorological factors. SFD showed a highly significant positive correlation with Rn, T, and VPD ($p < 0.01$). Conversely, a highly significant negative correlation existed between SFD and RH. However, the correlation between SFD and WS was not significant ($p > 0.05$).

Differences in correlation magnitudes appeared between the three tree species and various meteorological factors. For instance, at a depth of 1.1 m, poplars showed significant positive correlations with Rn, VPD, and T (0.854/0.819/0.735, respectively), along with a significant negative correlation with RH (−0.622). Locust trees displayed Rn as the most influential positive factor (correlation coefficient: 0.891), with a stronger correlation with T than VPD (correlation coefficient: 0.891 vs. 0.559). Furthermore, locust trees had lower correlations with Rn and VPD compared to poplars and willows (0.502 and 0.407, respectively), and their correlation with T was even lower at 0.294.

The correlation between SFD and meteorological factors was significantly affected by GD. Stations at varying GDs (1.1 m to 4.4 m) revealed that the correlation between the SFD of poplars and willows and meteorological factors decreased with increasing GD. However, for locust trees, the correlation improved significantly, indicating stronger ties between poplar and willow SFDs and meteorological factors under shallow GD conditions. The correlation of poplars slightly decreased after an increase from 1.1 m to >100 m, while the correlation of locust trees increased significantly.

3.4. Analysis of Changes in Transpiration Water Consumption Characteristics of Typical Trees in Response to Soil Moisture

3.4.1. Effect of Precipitation and Drip Irrigation on SWC

Precipitation and drip irrigation effectively boost SWC in the NYRIa. This study assesses the impact of the maximum rainfall event and two drip irrigation sessions on SWC (Table 4). The peak precipitation occurred on 14–15 September, with 23 mm and 12.7 mm of precipitation, constituting 25.2% of the total annual precipitation. The two drip irrigation events transpired on 10–11 May and 11–13 July, delivering 3.92 L and 4.89 L of water, respectively.

Table 4. Changes in SWC after precipitation and drip irrigation.

Water Source	Soil Depth (cm)	Soil Moisture Content before Precipitation (%)	Maximum Moisture Content after Precipitation (%)	Increment in Moisture Content (%)
Precipitation	30	4.75	15.09	10.34
	60	4.12	8.65	4.53
	90	0.55	0.77	0.22
	120	0	0	\
	160	2.03	2.03	\
	200	0.20	0.20	\
First drip irrigation	30	4.64	18.35	13.71
	60	4.12	17.74	13.62
	90	0.45	14.35	14.13
	120	0	8.30	8.08
	160	4.76	16.23	11.47
	200	0.51	8.95	8.45
Second drip irrigation	30	4.60	17.43	12.83
	60	4.07	16.61	12.54
	90	0.63	12.17	11.54
	120	0	8.69	8.69
	160	1.83	15.29	13.46
	200	0	7.74	7.74

Precipitation notably affected the topsoil, especially SWC30cm, resulting in a 10.34% increase. However, its influence on other soil layers, particularly below 90 cm, was minimal. In contrast, drip irrigation significantly raised SWC throughout the entire (0–200 cm) soil profile. Both drip irrigation events caused an over 11% increase in SWC from 30 to 90 cm in both instances.

Figure 6 shows ET changes in three trees under precipitation conditions. Before the precipitation occurred, the ET of the trees declined. After the precipitation occurred, the ET of the trees rose. This phenomenon is reflected at different depths. Figure 7 shows ET changes in locust trees and willows under drip irrigation conditions. After the drip irrigation occurred, the ET of the willows was relatively obvious, and the ET of the locust trees exhibited a smaller change.

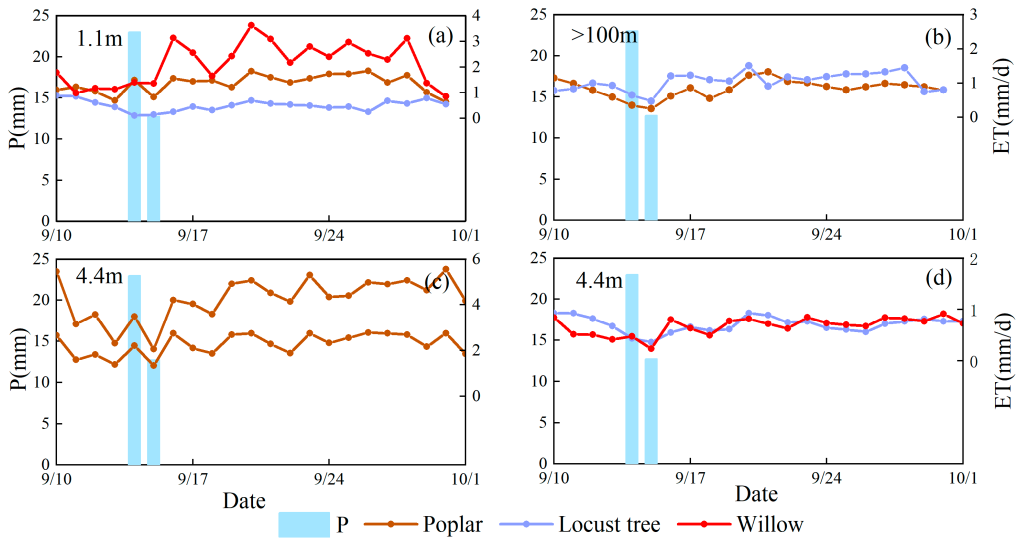

Figure 6. Changes in transpiration during precipitation. (**a**) changes in transpiration of poplar, locust tree and willow at a GD 1.1m. (**b**) changes in transpiration of poplar and locust tree at a GD exceeded 100 m. (**c**) changes in transpiration of poplars at a GD 4.4m. (**d**) changes in transpiration of locust tree and willow at a GD 4.4m. Abbreviations: P, precipitation; ET, evapotranspiration.

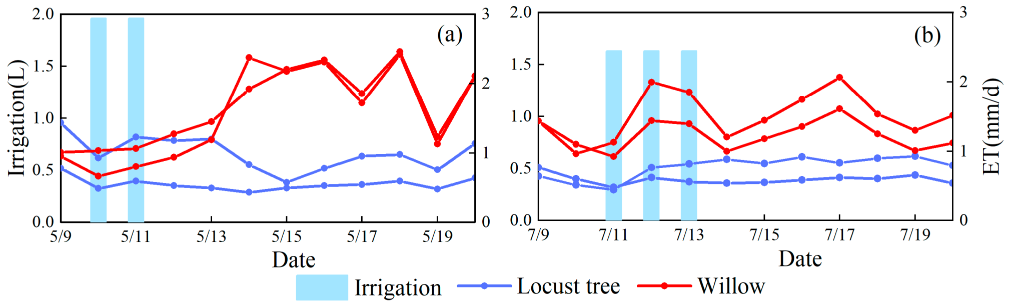

Figure 7. Changes in transpiration during drip irrigation. (**a**) changes in transpiration of locust tree and willow during the first drip irrigation. (**b**) changes in transpiration of locust tree and willow during the second drip irrigation. Abbreviations: ET, evapotranspiration.

3.4.2. Correlation between Tree Transpiration and SWC

Table 5 illustrates the correlation between the transpiration of three typical trees and SWC under precipitation conditions. At monitoring points at 1.1 m GD, poplars and willow trees predominantly utilized moisture at SWC60cm during precipitation, with a significant correlation ($p < 0.01$), while locust tree transpiration did not exhibit a significant correlation with soil water in any layers. At monitoring points at 4.4 m GD, poplar trees showed significant correlations with moisture at SWC_{30cm}, SWC_{60cm}, and SWC_{200cm} during precipitation ($p < 0.05$). Locust trees were significantly correlated with SWC_{120cm} and SWC_{200cm}, and willows exhibited a more significant correlation with SWC_{160cm} ($p < 0.05$). When the GD exceeded 100 m, poplars and locust trees were significantly correlated with SWC_{60cm} during precipitation, while there was no significant relationship between SWC and transpiration in the remaining layers.

During the drip irrigation water retention period, the transpiration of poplars and locust trees did not show a significant correlation with the SWC of each layer, as indicated in Table 6. Poplars exhibited a negative correlation with SWC_{30cm}, while locust tree transpiration showed a negative correlation with SWC_{30cm} to SWC_{160cm}.

Table 5. Correlation between transpiration and SWC (under precipitation conditions) of three typical trees. Abbreviations: GD, groundwater depth; SWC_{30cm}, soil moisture content at 30 cm underground.

GD	Varieties of Trees	SWC_{30cm}	SWC_{60cm}	SWC_{90cm}	SWC_{120cm}	SWC_{160m}	SWC_{200cm}
1.1 m	poplar	0.501 *	0.550 **	−0.131	0.192	0.111	−0.150
	locust tree	0.168	−0.099	−0.046	0.261	−0.032	−0.050
	willow	0.588 **	0.740 **	0.068	0.226	−0.016	−0.120
4.4 m	poplar	0.480 *	0.514 *	−0.273	−0.157	0.353	0.583 **
	locust tree	0.171	0.122	−0.351	−0.535 *	−0.031	−0.706 **
	willow	0.236	0.391	0.173	0.167	0.525 *	−0.101
>100 m	poplar	0.041	0.784 **	0.476	−0.412	−0.148	0.154
	locust tree	0.187	0.491 *	0.145	−0.035	−0.097	0.437

** represents $p < 0.01$ level of significance, * represents $p < 0.05$ level of significance.

Table 6. Correlation between transpiration and SWC (under drip irrigation) of three typical trees. Abbreviations: GD, groundwater depth; SWC_{30cm}, soil moisture content at 30 cm underground.

GD	Varieties of Trees	SWC_{30cm}	SWC_{60cm}	SWC_{90cm}	SWC_{120cm}	SWC_{160m}	SWC_{200cm}
4.4 m	locust tree	−0.014	0.033	0.069	0.193	0.218	0.097
	willow	−0.293	−0.304	−0.186	−0.152	−0.146	0.100

3.5. Comprehensive Analysis of Factors Influencing Transpiration Impacts on Arbor

Twelve environmental factors, including air temperature, precipitation, relative humidity, net radiation, wind velocity at 2 m, VPD, SWC_{30cm}, SWC_{60cm}, WC_{90cm}, SWC_{120cm}, SWC_{160cm}, and SWC_{200cm}, were selected for analysis using an artificial neural network MLP model. The objective was to identify the ranking of importance of these factors, quantifying the degree of influence of SWC and meteorological factors on vegetation transpiration.

The MLP model for the three typical trees revealed varying responses to environmental factors (Figure 8). For the poplar, T, VPD, and RH were the most influential meteorological factors, with SWC_{30cm} to SWC_{120cm} having a limited impact on transpiration. The poplar exhibited higher sensitivity to changes in meteorological factors under irrigation-deficient conditions, and its root system tended to concentrate water absorption in deeper soil layers, making it less responsive to shallow soil moisture changes. For the locust tree, SWC_{30cm} emerged as the most crucial factor affecting transpiration, followed by SWC_{60cm} and SWC_{90cm}. Meteorological factors like P, RH, and WS showed low sensitivity. Locust tree transpiration responded significantly to irrigation and surface soil moisture, with drip irrigation playing a more vital role than precipitation. The shallow depth of precipitation infiltration (<30 cm) had a limited effect on locust tree transpiration. For the willow, SWC_{60cm} was identified as the primary environmental factor influencing transpiration, followed by T and SWC_{90cm}. Meteorological factors like WS, VPD, and RH had limited effects. This suggested that the water content of surfaces SWC_{30cm} to SWC_{90cm} and SWC_{200cm} had a more substantial impact on willow transpiration. Among meteorological factors, only temperature significantly controlled willow transpiration compared to others.

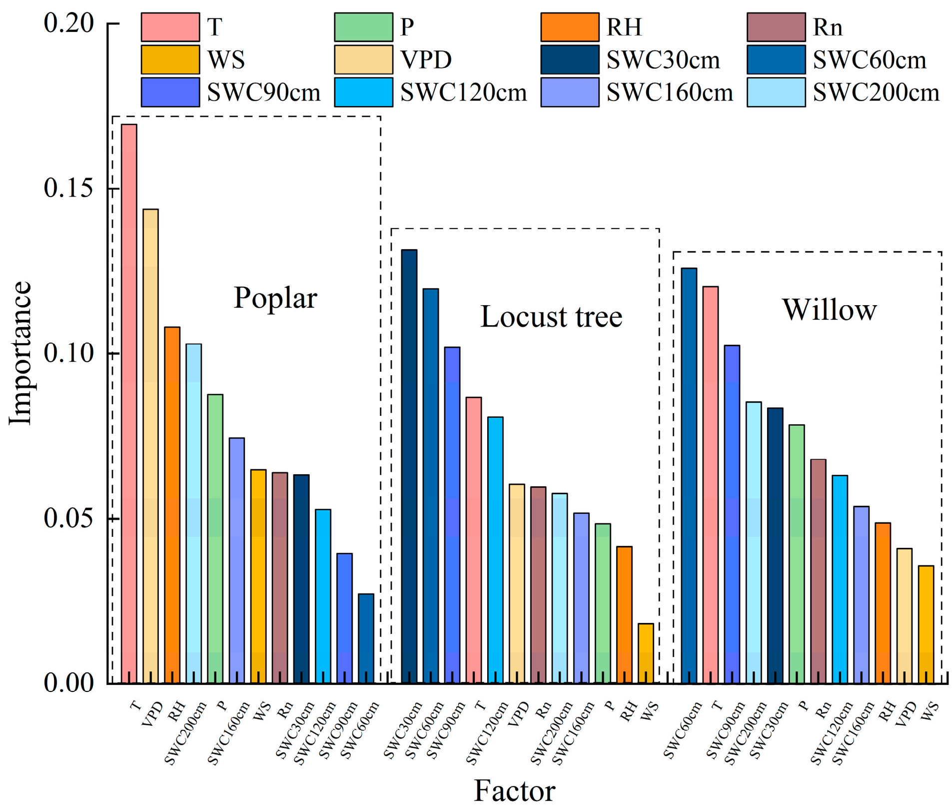

Figure 8. Ranking of importance of environmental factors for three typical tree MLP models. Abbreviations: T, temperature; P, precipitation; RH, relative humidity; Rn, net radiation; WS, wind speed; VPD, vapor pressure difference; SWC_{30cm}, soil moisture content at 30 cm underground.

4. Discussion

4.1. Relationship between Tree Sap Flow and Meteorological Factors

This study has revealed a strong correlation between SFD and meteorological factors in three typical arbors, especially Rn, T, VPD, and RH. Current research in arid regions of northern China has consistently highlighted the significant impact of temperature, net radiation, relative humidity, and VPD on tree transpiration [22–24,26,47,48]. While variations in physiological anatomy and DBH among the different tree species influenced SFD characteristics, the response patterns to daily environmental changes were remarkably similar (Table 3). Notably, the three tree types exhibited positive correlations with Rn, T, and VPD, with VPD and Rn showing particular significance [24,49]. Our experiment indicated a significant influence of Rn on sap flow, supporting the idea that solar radiation induces stomatal opening, providing energy for sap flow and enhancing tree transmittance [47]. A positive feedback loop was observed between sap flow and VPD [50]. A logarithmic decrease in stomatal conductance is associated with rising VPDs, subsequently reducing transpiration [51]. Under general conditions, the increase in temperature will promote an increase in vegetation steaming. However, when a drought occurs, high temperatures and low precipitation can cause plants to be coerced by water limitations and restrict the steaming effect of trees [52]. Simultaneously, the transpiration of the three typical trees exhibited a significant negative correlation with RH. An increase in RH resulted in decreased water evaporation from the tree leaves' surface area, thereby reducing tree transpiration [24]. Compared with previous research [22,24], it has been confirmed that, in the NYRIa, the transformation of the three typical trees has a strong correlation with Rn, T, VPD, and RH.

While the response relationships of the three typical trees to various meteorological factors remained consistent, the degree of response varied. The close relationship between tree SFD and the tree's own biostructure characteristics under the same climatic conditions is evident. In addition to differences in DBH among the sample trees, variations in water transport organization were observed. Willows and locust trees, being ring-porous, displayed greater SFD compared to bulk-porous poplars, consistent with existing research [53]. This study also confirms the following phenomenon: willows exhibited the highest SFD, followed by locust trees, and poplars recorded the smallest SFD.

4.2. Relationship between Transpiration and SWC

In many tree species, the relationship between transpiration and SWC varies, with some studies suggesting no direct correlation in certain species [54]. Our study, however, revealed a significant impact of soil moisture on tree transpiration in the NYRIa. Despite varying soil moisture levels under different conditions, such as precipitation and artificial drip irrigation, tree transpiration consistently changed across all three typical vegetation types (Figures 6 and 7). Precipitation and drip irrigation increase transpiration over a short period of time, which affects poplars more significantly. This finding emphasizes the significance of soil moisture in influencing tree transpiration, particularly in the NYRIa. These results align with prior research [24,54]. With a GD of 1.1 m, willows and poplars exhibit a notable increase in transpiration. Precipitation, in this scenario, primarily influences surface soil moisture content. Consequently, poplar trees demonstrate a strong correlation with SWC_{30cm} and SWC_{60cm} (Table 5). In contrast, locust trees show a minimal correlation with soil moisture content, and the influence of precipitation is limited. During drip irrigation, while there is a certain increase in willow tree transpiration, there is no significant correlation between transpiration and SWC (Table 6).

Hölscher et al. explored the linear relationship between sap flow and SWC in three tree species—Eurasian maple, European gooseberry, and European small-leaved linden. While a functional relationship exists, the coefficient of determination (R^2) is only 0.26–0.41. Notably, there is no direct correlation between the sap flow of European ash trees and SWC [54]. Studies on sand willow in the Mu Us Desert indicate that it is predominantly influenced by meteorological factors during the growth period, utilizing deeper soil water (50–100 cm) only when subjected to winter water stress [55]. In the Minqin Oasis Desert transition zone, tamarisks' daily sap flow showed no significant correlation with shallow soil moisture (0–40 cm) but did with middle soil (40–160 cm) [56]. Previous research in arid regions has suggested that vegetation sap flow is primarily driven by meteorological factors, with weak or no influence from soil moisture [14,57].

In our study, poplars and willows exhibited a significant positive correlation with shallow soil moisture content (SWC_{30cm} and SWC_{60cm}) under precipitation conditions. In the arid environment of the NYRIa, poplars and willows demonstrated a preference for absorbing shallow soil moisture, as indicated in Table 4. However, a noteworthy association between Poplars and SWC_{200cm} was observed at 4.4 m, suggesting plants also absorb deep water during drought [21,58,59]. The water content in various soil layers plays a crucial role in ensuring the stable growth of trees [60]. The impact of SWC on transpiration was more pronounced for poplars and willows and less significant for locust trees in the NYRIa. This phenomenon is influenced by various factors, including meteorological conditions and GD.

5. Conclusions

This study assessed sap flow and transpiration patterns, as well as responses to environmental factors, in three typical tree species (poplar, locust tree, and willow) in the NYRIa. Variations in sap flow and transpiration characteristics among the tree species were identified. Monitoring revealed higher sap flow density and transpiration volume in willows compared to locust trees and poplars. Additionally, the sap flow density of the three tree types consistently responded to meteorological factors, showing positive correlations with Rn, T, and VPD, a negative correlation with RH, and an unclear correlation with WS. While transpiration in the three tree types changed under precipitation and drip irrigation, the correlation with SWC was limited. In conclusion, there are certain differences in the main factors affecting the transpiration of different types of trees.

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