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Drought Impact on Transpiration Dynamics of Common Deciduous Trees Growing at Contrasting Urban Sites

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ABSTRACT

Urban trees provide essential ecosystem services, notably air cooling through transpiration, which helps mitigate the urban heat island effect and enhances cities' climate resilience. However, the complex spatial variability within urban areas and extreme weather events like droughts can disrupt trees' ecohydrological dynamics. In a study conducted in Freiburg, Germany, we investigated transpiration processes in Norway maple (*Acer platanoides*) and small-leaved lime (*Tilia cordata*) across diverse urban locations, including parks, parking lots, grass verges and tree pits. We assessed the effects of four distinct drought periods on transpiration and compared differences between tree species and growing sites. Small-leaved lime exhibited a 5% greater reduction in transpiration during drought periods compared to Norway maple, which experienced a 34% decline in transpiration during peak sap flow compared to nondrought periods. Tree pits with 90% surface sealing induced the most significant drought-induced transpiration reduction for small-leaved lime (58%), with both species displaying the lowest transpiration to potential evapotranspiration ratio in these locations. Significant differences were observed in the diurnal sap velocity patterns for both species. We highlighted the site-specific impact of surface sealing on transpiration during droughts, as well as the significant relationship between soil water deficit and relative transpiration rates. This study provides crucial insights into common urban tree species' responses to drought-induced transpiration across varied urban settings, emphasising the role of surface sealing. Continuous monitoring of diverse urban tree species is essential for building extensive databases and enhancing our understanding of tree water relations in diverse urban landscapes.

1 | Introduction

The rapid pace of urbanisation has led to profound impacts on urban ecosystems, notably altering hydrological and meteorological processes (Fletcher et al. 2013). Among these impacts, trees emerge as pivotal actors, contributing significantly to the resilience and adaptability of urban areas to environmental changes through ecohydrological processes mainly like transpiration. Transpiration, a key ecosystem service provided by urban trees, plays a crucial role in mitigating the urban heat island effect (Qiu et al. 2013; Konarska et al. 2014; Norton et al. 2015),

thereby ensuring a safe and comfortable living environment for urban residents, especially during extreme weather events like heatwaves and droughts (Gillner et al. 2015b; Phung et al. 2016). Previous research has underscored the cooling potential of tree transpiration in urban settings, estimating significant reductions in city air temperatures ranging from 0.5°C to 4.0°C (Bowler et al. 2010; Qiu et al. 2013; Rahman et al., 2017b). The transpiration process in plants involves the diffusion of water vapour into the atmosphere, primarily driven by hydrometeorological parameters such as the absorption of radiant energy converting into latent heat flux. This mechanism not only reduces

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ambient air temperature but also improves substantially to local micrometeorological conditions (Oke 1989; Bowler et al. 2010; Rahman et al. 2017a; Chen et al. 2019).

The transpiration process of urban trees is dynamically influenced by various site-specific hydrometeorological factors, including air temperature (T_a), relative air humidity (H_a), vapour pressure deficit (VPD), gross precipitation (P_g) and incoming shortwave solar radiation (SR), as well as by edaphic parameters such as soil water content and nutrient availability on a seasonal to annual scale (Tang et al. 2006; Ewers et al. 2008; Tognetti et al. 2009; Rahman et al. 2017a; Hayat et al. 2021).

Furthermore, within highly heterogeneous urban ecosystems, anthropogenic factors such as surface sealing, soil compaction, shading effects from surrounding structures and elevated temperatures significantly affect tree transpiration processes (Nielsen et al. 2007; Drake et al. 2018), potentially inducing long-term physiological stress and compromising tree vitality. Additionally, biological factors including tree morphological characteristics, leaf properties and wood anatomical features influence transpiration rates, particularly through stomatal regulation (Köcher et al. 2009; Pataki et al. 2011).

Understanding how trees respond to extreme weather conditions within urban environments is imperative. Studies have indicated that rising air temperatures during hot and dry periods can elevate leaf temperature, leading to leaf damage (Kunert and Hajek 2022), while increased VPD negatively affects transpiration and photosynthesis rates through stomatal regulation (Lloyd and Farquhar 2008). Stomatal control mechanisms have been shown to lead to substantial reductions in transpiration rates during dry periods (Rötzer et al. 2021), with a strong correlation between stomatal conductance and VPD identified in certain tree species (Gillner et al. 2015a).

Despite the importance of understanding urban tree transpiration processes, studies based on direct field measurements remain scarce due to technical challenges and equipment requirements in urban environments (Rahman et al. 2017a; Ahongshangbam et al. 2023). However, research efforts such as those by Pataki et al. (2011) and Ponte et al. (2021) have begun to shed light on the environmental drivers influencing tree transpiration in urban contexts, revealing species-specific differences and highlighting the responsiveness of trees to factors such as VPD and surface sealing.

Yet, significant knowledge gaps persist in our understanding of urban tree transpiration processes, particularly regarding the effects of changing environmental conditions, such as heatwaves and droughts, on ecohydrological processes. Moreover, there is a pressing need to investigate the influence of urban infrastructure, such as pavements, on tree physiological processes and to explore the variability in hydraulic strategies among different urban tree species across diverse urban settings.

In this context, our study aims to address fundamental knowledge gaps in drought-induced transpiration processes of urban trees across contrasting sites. Specifically, our objectives are as follows:

- i. Investigate differences in the diurnal patterns of sap velocity between tree species and study sites throughout the growing season, including selected periods such as droughts.
- ii. Assess the sensitivity of sap velocities and transpiration rates to drought periods compared to high sap flow periods.
- iii. Estimate transpiration rates for both tree species during selected weather periods and compare transpiration differences between contrasting urban growing sites.
- iv. Conduct a comparative analysis of the ratios between actual daily tree transpiration and potential reference evapotranspiration during selected periods.

2 | Methodology

2.1 | Tree Selection and Site Description

We focused our study on two commonly planted deciduous tree species, Norway maple (*Acer platanoides*) and small-leaved lime (*Tilia cordata*), within the urban environment of Freiburg, Germany. Both species exhibit similar levels of drought tolerance, with small-leaved lime scoring at 2.75 and Norway maple at 2.73 on a relative scale where five represents the maximum (Niinemets and Valladares 2006). Additionally, their shade tolerance is nearly identical, with small-leaved lime at 4.18 and Norway maple at 4.2 (Niinemets and Valladares 2006).

Freiburg is located in a warm and humid temperate climatic region, characterised by an average total annual precipitation of 896 mm and an annual mean air temperature of 11°C, based on data for the period 1991–2020 obtained from the climate station of the German Weather Service, DWD. Monthly average rainfall is from May to August, ranging from 80 to 100 mm, with July typically experiencing the highest temperatures, averaging 20.1°C.

We carefully selected four contrasting growing sites for each tree species, representing varying degrees of surface sealing underneath the tree crown, including parks, parking lots, grass verges and tree pits (see Table 1). The degree of surface sealing was quantified as the relative amount of the crown projection area (CPA) that is completely paved and impermeable. Specific sealing degrees for various surface types within the CPA were obtained from Schaffitel et al. (2020) and were used to calculate weighted averages (%) of the totally impermeable area within the CPA of each tree per study site (Table 1).

At each study site, we monitored three trees, except for ‘Hermann-Herder-Straße’ (HHS), where only two trees could be equipped, and at ‘Technische Universität Freiburg’ (TUF), where two trees were studied due to vitality issues affecting the third tree. In total, 11 trees of each species were selected for our study.

All study sites were strategically chosen within a radius of 2 km from the climate station (DWD) (refer to Figure 1 for geographical distribution). For Norway maple, study sites were predominantly situated in the southern part of the city, specifically along streets such as ‘Schwimmbadstraße’

TABLE 1 | Overview of study sites and urban conditions of investigated tree species.

Study sites	ID	Tree species	Number of trees	Urban condition	Degree of sealed surface in crown projection area (%)
Goethestraße	GTS	Norway maple	3	Grass verge	75
Hermann-Herder-Straße	HHS	Small-leaved lime	2	Parking lot	45
Institutsviertel-Mensa	IVM	Small-leaved lime	3	Park	5
Jacobistraße	JCS	Small-leaved lime	3	Grass verge	75
Stefan-Meier-Straße	SMS	Small-leaved lime	3	Tree pit	90
Schwimmbadstraße	SWB	Norway maple	3	Tree pit	90
Technische Universität Freiburg	TUF	Norway maple	2	Park	0
Urachstraße	URS	Norway maple	3	Parking lot	40



FIGURE 1 | Map of the city of Freiburg with study sites (yellow), urban climate station (orange star) and the location of Freiburg in Germany (red point). The geodata of Germany originates from the Federal Agency for Cartography and Geodesy, while the city of Freiburg provided the geodata of Freiburg. Norway maple sites: GTS=grass verge; SWB=tree pit; TUF=park; URS=parking lot. Small-leaved lime sites: HHS=parking lot; IVM=park; JCS=grass verge; SMS=tree pit.

(SWB), ‘Goethestraße’ (GTS) and ‘Urachstraße’ (URS), with one station located at the technical campus of the university (TUF). Conversely, monitoring sites for small-leaved lime were primarily located on the university campus (HHS, ‘Institutsviertel-Mensa’ - IVM and ‘Stefan-Meier-Straße’

- SMS), with one plot positioned on ‘Jacobistraße’ (JCS). Most of the selected trees were planted in tree alleys along streets, although exceptions existed (HHS, IVM and TUF). The study site HHS, featuring a surface sealing degree of 45%, represented a typical parking lot scenario with a combination of

lawn, grass pavers and an asphalted street between the two monitored trees. In contrast, IVM and TUF were located in urban parks with lawns beneath the tree crowns. Streets such as GTS, HHS, SMS and SWB, characterised by north–south orientation, were flanked by four-story buildings on their eastern and western sides, creating narrow urban canyons. Along GTS and JCS, where trees grew in grass verges, and SMS and SWB (tree pit locations with a surface sealing degree of approximately 90%), front yards bordered the monitoring sites, partially extending into the CPA. Moreover, sidewalks in GTS, SMS and SWB were fully impermeable, while in JCS, the sidewalk was paved with natural paving stones (sealing degree of 81%). The Norway maple plot URS comprised a fully paved road, a parking lane to the north and a lawn with a 1-m-high hedge to the south.

2.2 | Tree Morphology

Main tree morphological traits were measured in August 2021 (refer to Table A1 in the Supporting Information). Stem diameter at breast height (DBH) was measured at a height of 1.3 m. Tree heights (TH) and crown lengths (CL), measured from the lowest primary branch to the top of the crown, were assessed using a Vertex Forester. To determine crown radii, we measured the distances of eight intercardinal directions from the most remote tree shoot projected onto the surface to the trunk using a laser distance metre (Leica DISTO A2). The average crown radius (CR) was defined as the quadratic mean of eight measured crown radii, including the stem radius. Crown volume (CV) was calculated for each tree, referring to the equations for respective crown shape types according to Lawrence (1985), namely, ovoid, half-ellipsoid and spherical. CPA was determined using the CR of each tree. Tree ages were estimated using equations by Herzog (2021) for Norway maple and Lukaszkiwicz and Kosmala (2008) for small-leaved lime, based on DBH.

Leaf area index (LAI) was measured monthly for each tree using a plant canopy analyser (LAI-2200C LI-Cor). Four individual measurements were conducted per tree on each measurement date, and average LAI values were calculated (refer to Table A2 and Figure A1 in the Supporting Information). Additionally, leaf area (LA) and leaf area density (LAD) were calculated for each vegetation period following Baptista et al. (2018).

2.3 | Leaf Water Potential (LWP) Measurements

Throughout the study period, midday (from 12:30 to 2:00 PM LT) and predawn (from 03:00 to 05:00 AM LT) LWP were measured. Measurement dates were selected during stable hot and dry weather conditions (drought periods) in each growing season (refer to Figure 2). At least two twig samples per tree were used for LWP measurements, and an average was estimated for each tree and measurement date. Midday LWP measurements were conducted on fully sun-exposed twigs at mid-crown height, mostly on the southern side, using a telescopic pruner and a Scholander pressure chamber as per the protocol by Scholander et al. (1964). Predawn LWP measurements were taken from twigs of similar crown sides.

2.4 | Sap Velocity Measurements and Transpiration Calculation

We employed sap flow sensors (East 30 Sensors, Washington, US) to gauge sap velocity within the xylem utilising the heat ratio technique, comprising a central heater needle and a thermistor needle positioned upstream and downstream of the heater. To accurately monitor sap flow across different depths of the sapwood, three thermistors were embedded at depths of 5, 17.5 and 30 mm within the thermistor needles. Temperature differences between thermistors were recorded at 30-min intervals after 60 s of heating. Higher sap velocities in the xylem correspond to faster heat transport, resulting in lower temperature differences. The sensors were fixed to the north side of the trunk beneath the crown base, positioned 2–4 m above the surface to prevent accessibility and potential damage. Approximately 5 cm² of bark and phloem was removed to expose the cambium and mount the probes securely to the trunk. Following installation, the probes were shielded with aluminium caps to safeguard against external factors such as rain, fluctuations in air temperature and SR. Due to the variability in wood anatomy, particularly branching or bulges resulting from cut branches, the installation position on the trunk side was carefully selected to ensure proper detection of xylem flow, permitting deviations from the north side as necessary. All sensors were removed over the winter season to minimise the risk of frost damage. In 2022, before the commencement of the second growing season, all sensors were repositioned within the trunk to ensure a proper fit within the intact sapwood. Consequently, the comparison of absolute sap velocities and transpiration rates between trees and study sites is restricted in this study. Therefore, relative (normalised) transpiration rates (T_{rel}) were calculated.

Sap velocities (V_{sap} , m s⁻¹) for each sensor per tree were computed from the temperature differences measured at the corresponding thermistor pairs, following Equation (1) proposed by Campbell et al. (1991).

$$V_{sap} = \frac{2 * k}{C_w * (r_u + r_d)} * \ln \left(\frac{\Delta T_u}{\Delta T_d} \right) \quad (1)$$

where C_w represents the specific heat capacity of water (J m⁻³ K⁻¹), r denotes the distance (m) from the heater needle to the thermistor needle (6 mm) and ΔT indicates the temperature difference measured before and after the 60-s heating pulse. The subscripts u and d denote the positions upstream and downstream of the heater needle, respectively. The thermal conductivity of sapwood k for both tree species, Norway maple and small-leaved lime, was determined following the method outlined by Pappas et al. (2022), resulting in calculated values of 0.656 and 0.733 W m⁻¹ K⁻¹, respectively. Given the wounding of xylem tissue caused by drilling, all sap velocities were subsequently corrected (V_c) using the numerical model solution recommended for our sap flow measurement technique (Equation (2)) as proposed by Burgess et al. (2001).

$$V_c = b * V_{sap} + c * V_{sap}^2 + d * V_{sap}^3 \quad (2)$$

For the 2-mm wounds, we applied correction coefficients as follows: $b = 1.8558$, $c = 0.0018$ s m⁻¹ and $d = 0.0003$ s² m⁻², as outlined in Burgess et al. (2001). The corrected sap velocities from

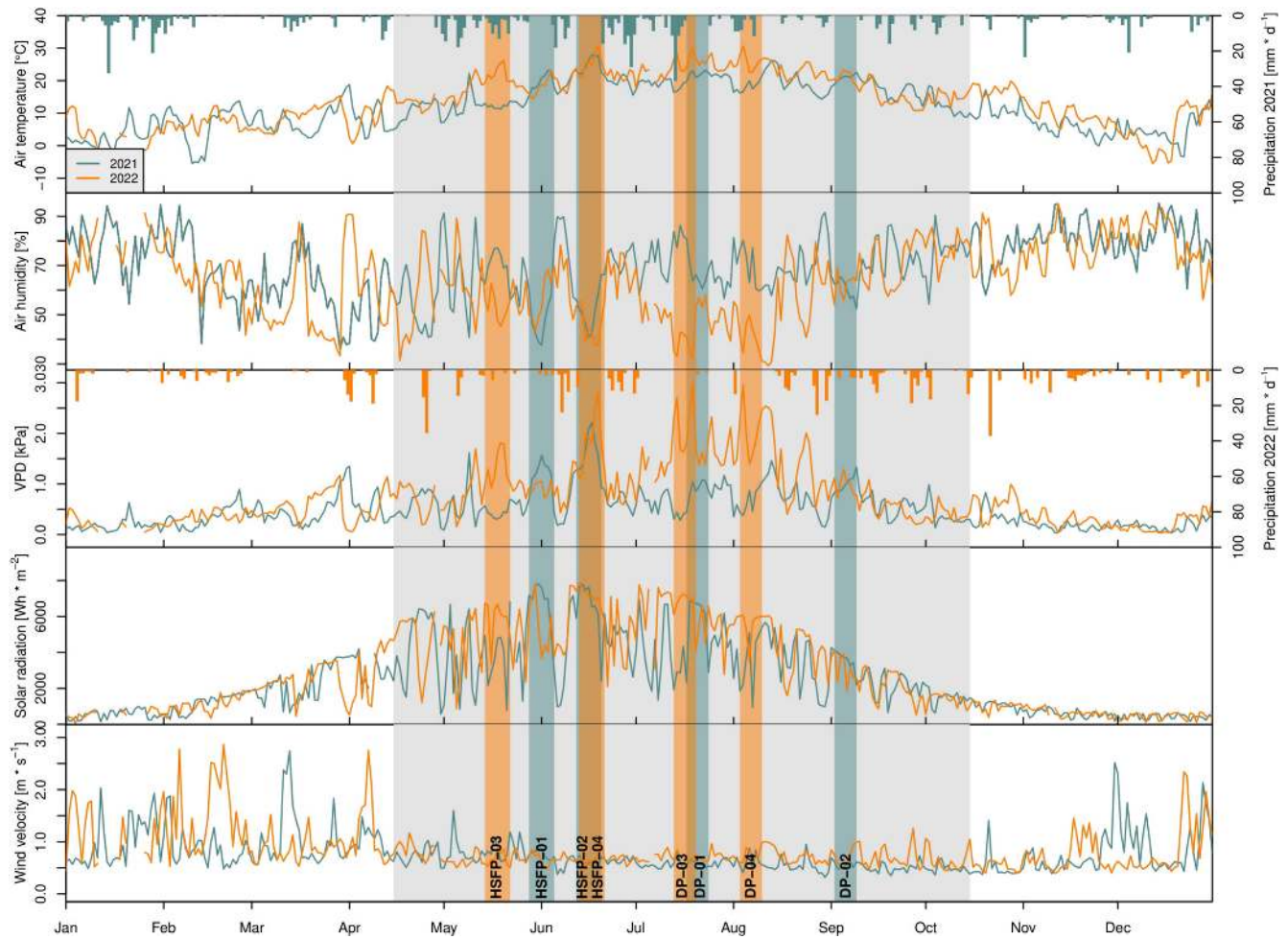


FIGURE 2 | Average daily weather conditions recorded at DWD for both observation years (2021 and 2022). Green and orange lines mark data of 2021 and 2022, respectively. The grey marked area represents the selected vegetation period, whereas green and orange strips are selected high sap flow periods (HSFP01 to HSFP04) and drought periods (DP01 to DP04) of the respective year.

each sapwood depth were then averaged for each sensor and utilised for sap flow calculation. Sap flow rates were determined by multiplying the total sapwood depth of each tree (as indicated in Table A3 in the Supporting Information) by the averaged sap velocities of the sensor. To ascertain the sapwood depth, tree cores were extracted from both the north and south sides of the trunk and examined using a flashlight to discern the sapwood–heartwood boundary based on differences in light transmissivity through the wood, achieved by slowly moving the core sample back and forth across the light beam. Bark depth was also measured and considered in the analysis. The measured bark and sapwood depths, along with the estimated sapwood area for each tree, are provided in Table A3 in the Supporting Information. It is worth noting that a decline in sap velocities across the sapwood was not factored into these calculations; thus, absolute transpiration rates should be interpreted with caution.

Absolute daily transpiration rates (T_{abs} in mm day^{-1}) were computed by dividing the total daily sap flow rate by the CPA of each individual tree. Given that absolute values may vary within a tree species due to factors such as morphological traits (e.g., tree height, LA and age), wood physiological properties and xylem hydraulic conductivity, normalised values were utilised for inter-tree comparisons.

2.5 | Meteorological Data Collection and Selected Weather Periods

We used meteorological data from the urban climate station operated by the German Weather Service (DWD), situated at Stefan-Meier-Straße 4 (elevation: 274 m a.s.l., WGS84-latitude: 48.000625, WGS84-longitude: 7.845948) (refer to Figure 1). DWD collects various meteorological parameters including air temperature (T_a , °C), relative air humidity (H_a , %), air pressure (hPa), VPD (hPa), wind speed (ms^{-1}) and direction (°), solar irradiance (SR, Wm^{-2}) and gross precipitation (P_g , mm). The dataset, provided upon request, features a temporal resolution of 10 min. It is important to acknowledge that recorded meteorological conditions may slightly differ at our study sites due to the influence of surrounding urban structures and vegetation, contributing to spatial meteorological variability within the city (Cristiano et al. 2017). Additionally, we conducted continuous measurements of air temperature and relative air humidity at each tree and SR measurements beneath tree crowns (detailed information are provided in Appendix S1).

In our analysis of drought effects on transpiration dynamics, we identified four distinct drought periods based on LWP measurements conducted on specific dates: 2021-07-21,

2021-09-07, 2022-07-20 and 2022-08-09. For each designated drought period (DP) (see Figure 4 and Table 2), we selected eight consecutive days during which LWP measurements (predawn and midday) were taken. Additionally, we identified four periods characterised by the highest transpiration rates (HSFP) observed throughout the vegetation periods for our analysis (see Figure 3 and Table 2). These periods represent optimal transpiration conditions (no droughts) for all trees under investigation.

2.6 | Data Processing and Statistical Analysis

We defined the period from 15 April to 15 October as the main growing season (study period) for each year, 2021 and 2022. Sap velocity datasets underwent thorough quality checks and outlier screening. We implemented a zero-flow baseline correction for all sap flow sensors by scrutinising the 30-min meteorological dataset for instances of rainfall lasting at least 3 h during nighttime, between 22:00 and 05:00 h LT, for a minimum of five nights during each study period. The lowest value obtained for each study period served as the baseline, following the approach by Pfautsch et al. (2010).

In 2022, due to the reinstallation of sap flow sensors for the growing season, normalised transpiration values were used for comparisons between trees and study sites to identify significant tree-specific differences. At JCS-T1, a second sap flow sensor was installed on the eastern side of the trunk, as the northern sensor exhibited lower data quality. Subsequently, sap velocities (m h^{-1}) and daily transpiration rates (both normalised and absolute) of each tree ($n=22$) and averages of study sites were employed in our study. Study sites were included in the analysis if at least two trees recorded sap velocities during defined periods. For instance, HHS was excluded for HSFP-01 when comparing diurnal sap velocities between study sites. We compared average peak sap velocities among different study sites and tree species, which we calculated based on the five highest average sap velocities of the 30-min dataset recorded per tree throughout each day during selected periods (e.g., drought period).

Additionally, we computed potential reference evapotranspiration (ET_{pot}) using the meteorological datasets from DWD, adhering to the guidelines of FAO56 (Allen et al. 1998) and employing the standardised Penman–Monteith equation from the Environmental Water Resources Institute of the American Society of Civil Engineers (Allen et al. 2005).

We conducted Tukey's pairwise comparison tests to identify significant differences between trees and study sites for parameters such as diurnal sap velocities, transpiration rates and ratios between absolute daily transpiration rates (T_{abs}) and ET_{pot} . Linear regression analysis was employed to examine the relationships between LWP (predawn and midday), surface sealing, relative soil water deficit and T_{rel} for selected drought periods. The relative soil water deficit was computed for individual soil depths (10, 30 and 50 cm) and for the entire soil profile by utilising the hourly dataset of soil water content measurements. This involved dividing the mean hourly values of each soil depth and the averaged soil profile by the highest observed value recorded during the observation period. The resulting values ranged between 0 and 1, which were then multiplied by 100 to express the relative soil water deficit percentage. Subsequently, daily averages of soil water deficit were calculated. The standard significance level was set at the 95% confidence level ($p\text{-value} \leq 0.05$) for all investigations. Data processing and statistical analyses were performed using the software package R, version 4.3.2 (R Core Team 2023).

3 | Results

3.1 | Weather Conditions Throughout Both Growing Seasons and During Selected Periods

DWD recorded a mean average annual air temperature (T_a) of 11.74°C in 2021, with a notable positive deviation of 2.6°C in 2022. In 2022, the gross precipitation (P_g) was 158 mm lower compared to the previous year, which registered a total annual precipitation depth of 871 mm. (see also Figure 2) Furthermore, the average relative air humidity (H_a) in 2022 was 6% lower than in 2021, with H_a measuring at 70.0% in 2021. During the first growing season, the

TABLE 2 | Average meteorological conditions recorded at DWD in selected periods of eight consecutive days each, with averages (MEAN) and standard deviations ($\pm$; SD).

Selected periods (date)	T_a ($^\circ\text{C}$)	H_a (%)	VPD (kPa)	Wind speed (m s^{-1})	P_g (mm)	SR (kW m^{-2})
HSFP-01 (21-05-28 to 21-06-04)	19.8 ± 2.8	48.0 ± 8.3	1.23 ± 0.25	0.77 ± 0.09	5.2	7045 ± 853
HSFP-02 (21-06-12 to 21-06-19)	25.2 ± 2.5	49.8 ± 6.2	1.66 ± 0.36	0.61 ± 0.07	0.1	6958 ± 759
HSFP-03 (22-05-14 to 22-05-21)	22.4 ± 2.6	52.6 ± 5.8	1.34 ± 0.36	0.68 ± 0.13	7.2	5986 ± 1098
HSFP-04 (22-06-13 to 22-06-20)	25.4 ± 3.3	44.6 ± 6.8	1.90 ± 0.57	0.69 ± 0.13	0.2	7184 ± 440
HSFP: MEAN $\pm$ SD	23.2 ± 2.3	48.7 ± 2.9	1.53 ± 0.26	0.69 ± 0.06	3.2 ± 3.1	6793 ± 473
DP-01 (21-07-17 to 21-07-24)	21.9 ± 1.2	67.2 ± 6.4	0.89 ± 0.21	0.57 ± 0.05	5.7	5619 ± 1877
DP-02 (21-09-02 to 21-09-09)	20.9 ± 1.1	60.1 ± 4.4	1.01 ± 0.17	0.55 ± 0.06	0.2	3535 ± 609
DP-03 (22-07-13 to 22-07-20)	26.2 ± 2.6	39.3 ± 6.9	2.15 ± 0.51	0.71 ± 0.08	2.4	6543 ± 1036
DP-04 (22-08-03 to 22-08-10)	26.0 ± 2.7	40.4 ± 6.3	2.09 ± 0.50	0.76 ± 0.13	0.0	5562 ± 881
DP: MEAN $\pm$ SD	23.9 ± 2.4	51.8 ± 12.1	1.54 ± 0.59	0.65 ± 0.09	2.1 ± 2.3	5315 ± 1099

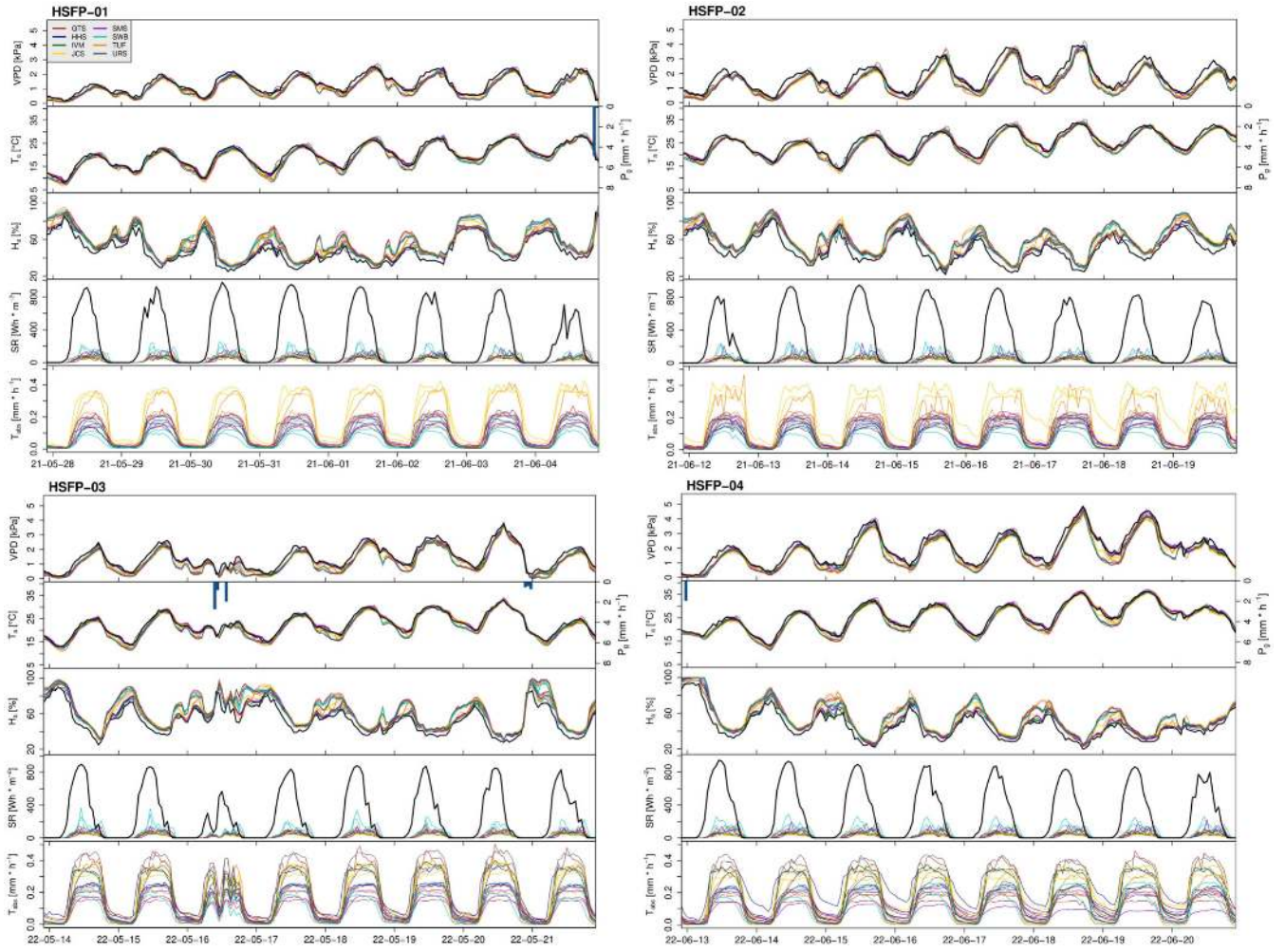


FIGURE 3 | Vapour pressure deficit (VPD), air temperature (T_a), relative air humidity (H_a), gross precipitation (P_g), solar radiation (SR), and absolute transpiration (T_{abs}) during high sap flow periods (HSFP-01 to HSFP-04). The bold black line represents meteorological data from DWD, and coloured lines represent recorded data at each investigated tree per study site. Norway maple sites: GTS=grass verge; SWB=tree pit; TUF=park; URS=parking lot. Small-leaved lime sites: HHS=parking lot; IVM=park; JCS=grass verge; SMS=tree pit.

average T_a was 17.2°C, H_a averaged at 67.2% and total P_g amounted to 516 mm. The average VPD was 0.701 kPa, while the mean total SR per day reached 3813 Whm⁻². In contrast, the second growing season experienced a mean daily T_a of 19.9°C, H_a averaged 58.6% and recorded 93.1 mm less precipitation. Additionally, VPD and SR were higher by 0.386 kPa and 667 Whm⁻², respectively. The average daily wind speed was 0.62 and 0.70 ms⁻¹ during the vegetation periods of 2021 and 2022, respectively.

The average daily meteorological conditions recorded at DWD for each selected weather period (HSFP and DP) are summarised in Table 2. Moreover, Figures 3 and 4 illustrate the hourly course of meteorological conditions within each tree crown for each period, spanning eight consecutive days. Across all selected weather periods, tree crown temperature and VPD were 0.74°C and 0.30 kPa lower, respectively, compared to the data recorded at DWD. Relative air humidity was on average 8% higher during these periods. The average daily air temperature ranged between 14.0°C and 20.8°C during HSFPs and between 18.1°C and 21.3°C during DPs, while the mean VPD was 1.24 kPa for both contrasting weather periods, with a slightly higher relative humidity of 59.7% during DPs.

3.2 | Diurnal Sap Velocity Differences Among Tree Species and Study Sites

Throughout the vegetation period in 2021, both tree species exhibited the highest sap velocities in park locations TUF and IVM (Figure 5), with averaged peak values of 0.266 and 0.257 m h⁻¹, respectively. Similar diurnal values (0.260 m h⁻¹) as IVM were found in the small-leaved lime plot JCS, where trees grow along a grass verge. In contrast, diurnal courses at HHS and SMS were significantly lower than those of IVM and JCS, with average peaks of 0.109 and 0.137 m h⁻¹, respectively, throughout the day. Comparing Norway maple plots of 2021, sap velocities at TUF were significantly higher than those at GTS, SWB and URS, which showed similar diurnal patterns. Notably, no significant differences in diurnal sap velocity were observed between Norway maple sites during the drier growing season in 2022. As in 2021, TUF showed the highest sap velocities in 2022, followed by GTS, URS and then SWB, where trees exhibited the lowest peak sap velocities in both years with 0.095 m h⁻¹ for 2021 and 0.180 m h⁻¹ for 2022. Unlike Norway maple sites in 2022, small-leaved lime showed significant differences in the magnitude of the diurnal course of sap velocity between JCS, with

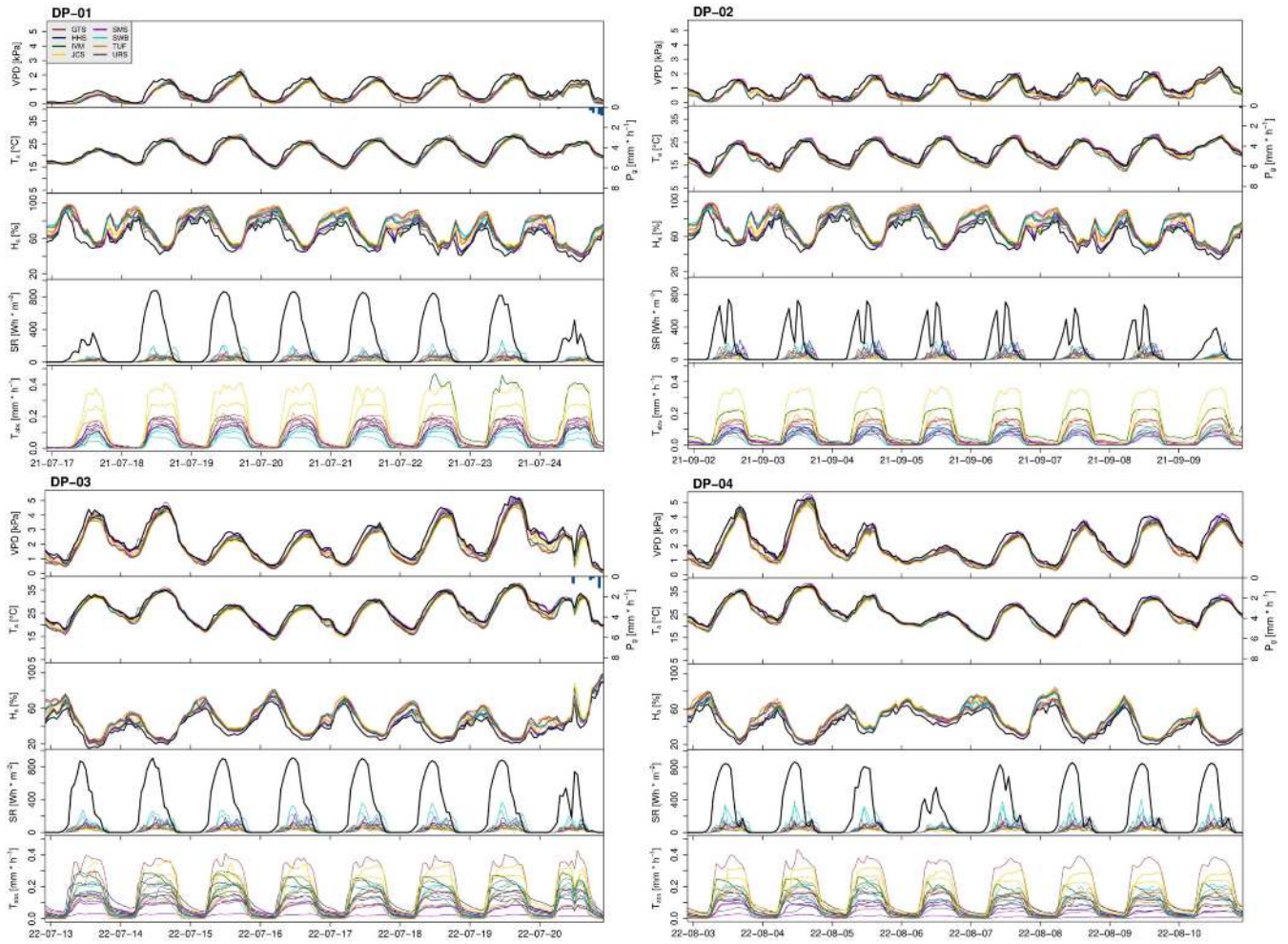


FIGURE 4 | Vapour pressure deficit (VPD), air temperature (T_a), relative air humidity (H_a), gross precipitation (P_g), solar radiation (SR) and absolute transpiration (T_{abs}) during drought periods (DP-01 to DP-04). The bold black line represents meteorological data from DWD, and coloured lines represent recorded data at each investigated tree per study site. Norway maple sites: GTS = grass verge; SWB = tree pit; TUF = park; URS = parking lot. Small-leaved lime sites: HHS = parking lot; IVM = park; JCS = grass verge; SMS = tree pit.

the highest averaged maximum sap velocity of 0.258 m h^{-1} , and SMS, with an average of 0.162 m h^{-1} , occurring between 12:00 and 16:00 h. Although HHS and IVM did not exhibit significant differences between each other in 2022, the park location IVM did not record the highest values relative to 2021, whereas JCS demonstrated such an increase. Sap velocity increases at approximately 05:30 h, peaks throughout the day between 12:30 and 15:00 h, when SR, VPD and air temperatures are highest (Figure 3), decreases in the late afternoon and the most active time ending between 20:30 and 21:30 h. Thereafter, sap velocity decreases minimally and reaches the minimum between 04:00 and 05:00 h. Overall, study sites of both tree species with comparable sealing degrees underneath tree crowns revealed similar magnitudes of diurnal patterns, such as SWB and SMS or HHS and URS.

3.3 | Comparison of Diurnal Sap Velocity Patterns Among Study Sites of Selected Periods

Throughout the HSFPs (Figure 6), the park site TUF indicated the highest average daytime sap velocities with peaks ranging from 0.344 to 0.416 m h^{-1} between 12:00 and 16:00 h. During

HSFP-01 and HSFP-02, sap velocities recorded at TUF were significantly higher than all other Norway maple sites and during HSFP-03, higher than SWB. For HSFP-04, no significant differences in diurnal sap velocity courses were observed among Norway maple sites. Focusing on SWB with the highest degree of surface sealing (90%) indicated reduced diurnal courses across all HSFPs with maximum daytime peaks ranging from 0.160 to 0.249 m h^{-1} . Over these four periods, GTS and URS did not vary significantly. When looking at small-leaved lime plots, major significant differences were observed between trees growing along a grass verge (JCS) and trees planted in tree pits (SMS) for all HSFPs except HSFP-03, which showed no significant differences in diurnal courses among growing sites. Interestingly, IVM differed significantly from JCS in HSFP-04 but showed a similar pattern with SMS. Throughout all HSFPs, JCS displayed peak sap velocities ranging from 0.356 to 0.423 m h^{-1} between the same timespan (12:30 and 15:00 h) as Norway maple sites.

Compared to HSFPs, the magnitudes of diurnal sap velocities were reduced during drought periods (DP-01 to DP-04) (Figure 7). Across all investigated trees of both species, average peak sap velocities occurring throughout the day were 28.7% lower than during HSFPs. Furthermore, during drought periods,

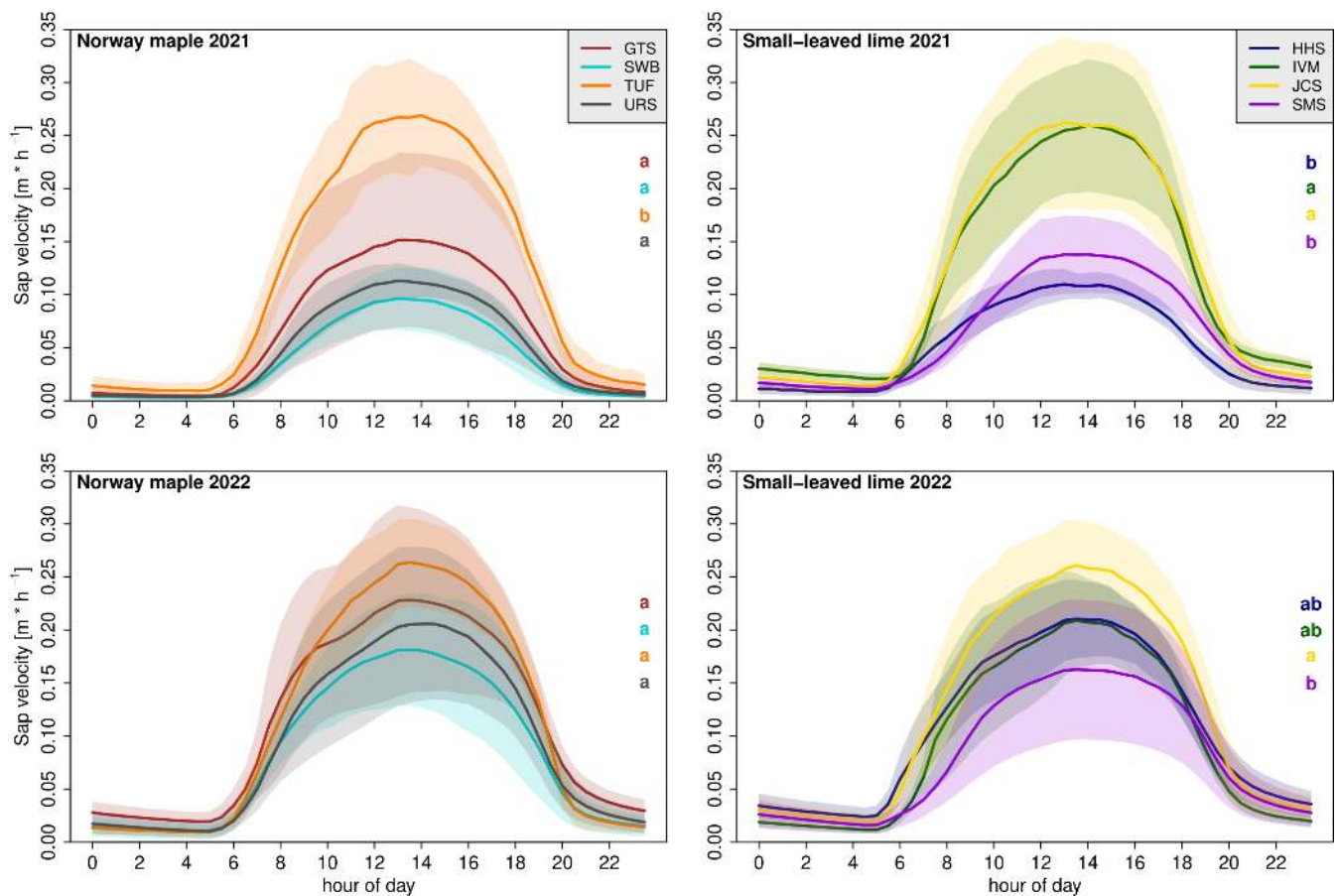


FIGURE 5 | Averaged diurnal sap velocities per study site throughout each vegetation period represented as coloured lines and the coloured area above and below lines showing standard deviations. Coloured letters refer to study sites and indicate significant differences (p -value < 0.05) among study sites. GTS = grass verge; HHS = parking lot; IVM = park; JCS = grass verge; TUF = park; URS = parking lot; SMS = tree pit; SWB = tree pit.

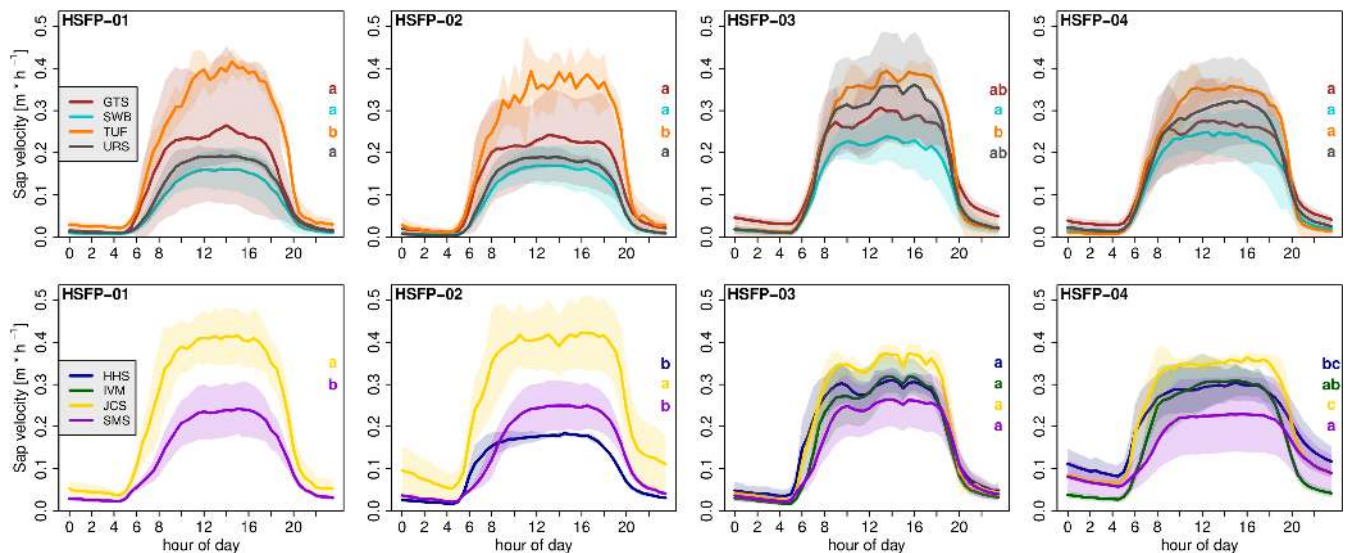


FIGURE 6 | Average diurnal pattern of sap velocity during selected high sap flow periods (HSFP) for each study plot. Lines are the average course of diurnal sap velocity of all trees per study site and the coloured area above and below lines showing standard deviations. Coloured letters indicate significant differences (p -value < 0.05) among study sites. Norway maple sites: GTS = grass verge; SWB = tree pit; TUF = park; URS = parking lot. Small-leaved lime sites: HHS = parking lot; IVM = park; JCS = grass verge; SMS = tree pit.

a delayed morning increase and an earlier afternoon decrease in transpiration rates occurred compared to HSFPs (Figures 6 and 7). On average, Norway maple exhibited a decrease of 25.3%

in highest sap velocities, while small-leaved lime experienced a reduction of 32.1%. The strongest drought-induced restriction was observed at SMS with 51.2% significantly lower peak

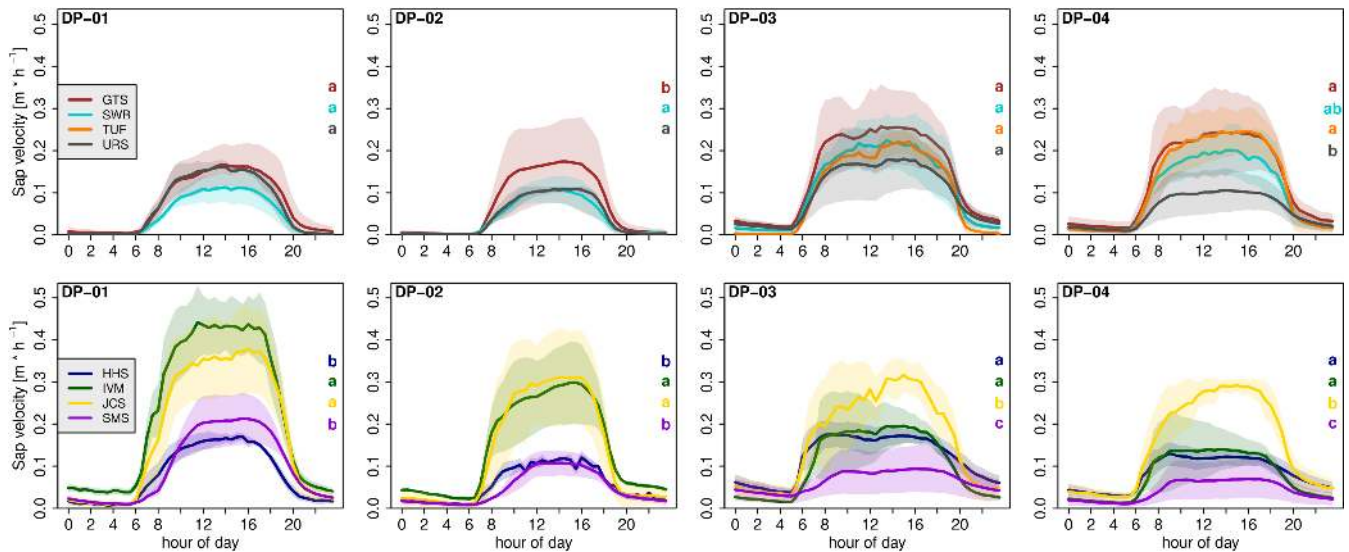


FIGURE 7 | Average diurnal pattern of sap velocity during selected drought periods (DP) for each study plot. Lines are the average course of diurnal sap velocity of all trees per study site and the coloured area above and below lines showing standard deviations. Coloured letters indicate significant differences (p -value < 0.05) among study sites. Norway maple sites: GTS=grass verge; SWB=tree pit; TUF=park; URS=parking lot. Small-leaved lime sites: HHS=parking lot; IVM=park; JCS=grass verge; SMS=tree pit.

sap velocities (p -value < 0.05) during the most active diurnal transpiration period from 12:00 to 16:00h. Additionally, SMS showed significant differences in diurnal trends from all other study plots (Figure 7), except for DP01 and DP-02, where similar patterns were observed with HHS, and trees at SMS exhibited a delayed increase of sap velocities compared to other trees. In contrast to SMS, the Norway maple study site SWB, where trees were also planted in tree pits, exhibited an average reduction of about 21.8% in daily maximum sap velocities, which ranged between 0.104 and 0.113 m h^{-1} . Throughout the selected drought periods, significant differences of Norway maple sites were observed between GTS and URS in DP-02 and between URS to GTS and TUF in DP-04. Sap velocities at the small-leaved lime plot JCS were significantly higher compared to all other sites of the same species during DP-03 and DP-04, and these trees exhibited an average reduction of 18.1% in maximum sap velocities, which was similar to the 18.6% reduction observed at the Norway maple site GTS.

3.4 | Daily Transpiration Characteristics During Selected Periods

Relative transpiration rates (T_{rel}) of each tree were compared based on four periods during which the highest sap flow values were recorded throughout both vegetation periods (HSFP-01 to HSFP-04) (Figure 8). In HSFP-01, HHS-T1 exhibited the lowest average daily T_{rel} with 0.77 compared to all other trees, which had similar values ($T_{\text{rel}} > 0.80$). Additionally, HHS-T1 was significantly lower than GTS-T2, which indicated the highest T_{rel} of 0.95 and both trees at TUF (average $T_{\text{rel}} = 0.94$).

During HSFP-02 to HSFP-04, similar patterns were observed among trees and species, with some exceptions. For example, during HSFP-02, T_{rel} of TUF-T3 was significantly lower (12%) compared to the average of all other investigated trees ($T_{\text{rel}} = 0.94$). Furthermore, normalised daily transpiration rates

of SWB-T3 were significantly lower during HSFP-03 (35%) compared to the averages of all other trees. SWB-T3 also exhibited significantly reduced T_{rel} in HSFP-04, although similar to GTS-T1, SMS-T3 and URS-T3. All other trees had similar T_{rel} values, and the average T_{rel} throughout all periods and trees was 0.90.

We also compared absolute daily tree transpiration rates (T_{abs}) with potential reference evapotranspiration (ET_{pot}) for each HSFP (Figure 9). Generally, a similar pattern was observed between HSFP-01 and HSFP-02 and between both periods in 2022. The selected periods in 2021 exhibited the highest daily transpiration rates for trees growing along a grass verge (JCS), with a range from 0.92 to 1.14. Following this, TUF-T3 displayed an average ratio of 0.76 over the first two periods. In HSFP-01 and HSFP-02, all other trees showed slight variations among each other, with various significant differences between trees. However, they showed ratios ranging from 0.23 for SWB-T2 to 0.59 for GTS-T1. Patterns of HSFPs in 2022 differed slightly from those in 2021, with average $T_{\text{abs}}/ET_{\text{pot}}$ ratios across all trees being 22.7% higher. On average, GTS-T3, HHS-T1 and URS-T1 exhibited slightly higher daily transpiration rates (> 1.0) than ET_{pot} in both periods in 2022. Throughout all HSFPs, small-leaved lime indicated a higher ratio with 0.71 compared to Norway maple with a ratio of 0.55, and there were several significant differences between trees and study sites. Notably, trees at the same study site also exhibited significant differences in $T_{\text{abs}}/ET_{\text{pot}}$ ratios from each other, especially GTS and IVM. Furthermore, highly sealed study sites SMS and SWB had the lowest ratios throughout these periods, 0.51 and 0.39, respectively. In contrast, unlike SMS and SWB, JCS for small-leaved lime and TUF for Norway maple had the highest $T_{\text{abs}}/ET_{\text{pot}}$ ratios of 0.97 and 0.64, respectively.

We compared average T_{rel} values between trees and study sites throughout four selected drought periods (DP-01 to DP-04) (Figure 10). During the first drought period in 2021 (DP-01), small-leaved lime displayed the highest transpiration rates

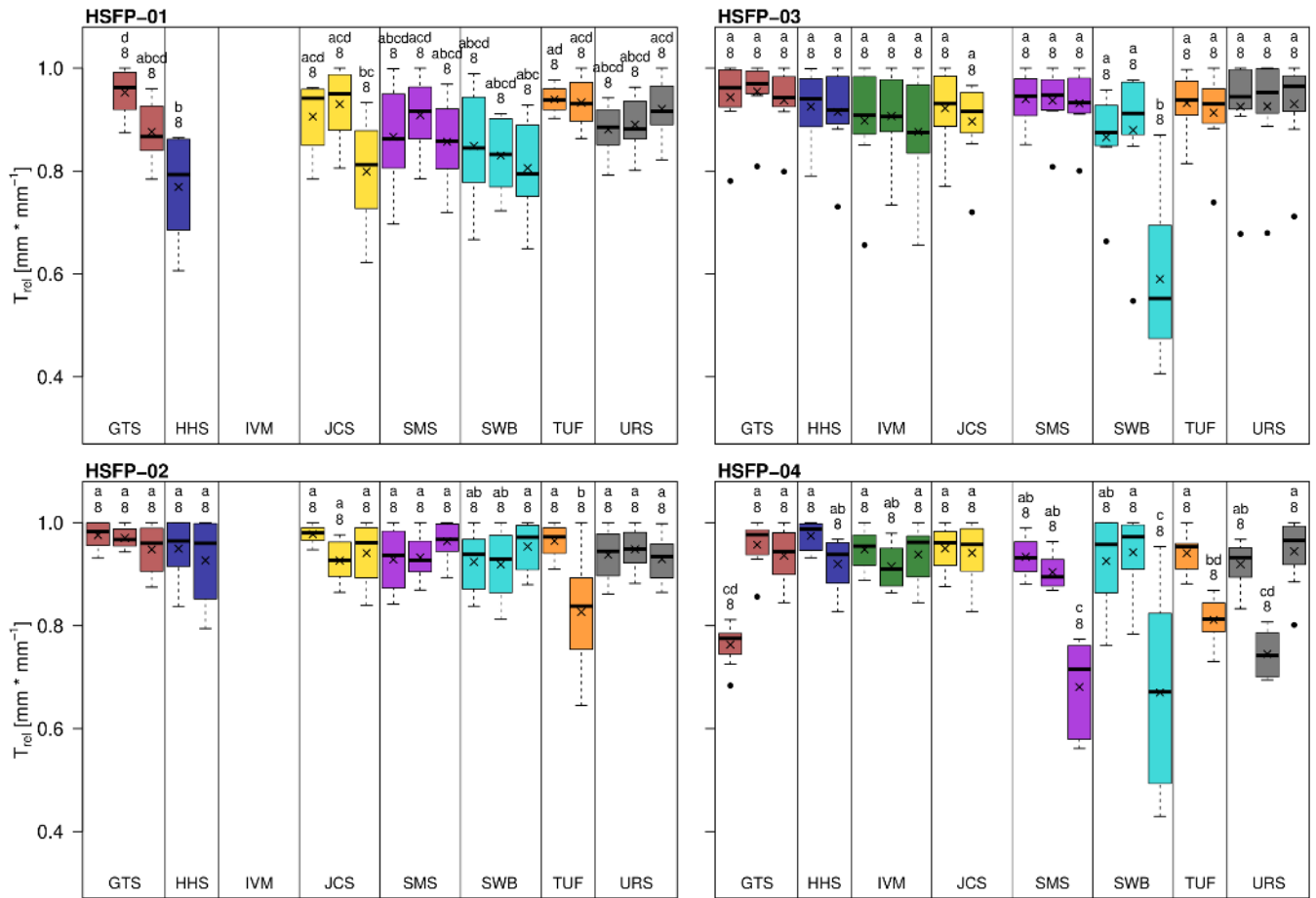


FIGURE 8 | Relative daily transpiration of each investigated tree during high sap flow periods. Values above the upper whisker represent the number of measured days during the selected period (HSFP), and letters indicate significant differences (p -value < 0.05) among trees for each period. Norway maple sites: GTS=grass verge; SWB=tree pit; TUF=park; URS=parking lot. Small-leaved lime sites: HHS=parking lot; IVM=park; JCS=grass verge; SMS=tree pit.

averaging 0.80 ± 0.09 compared to the other three drought periods and Norway maple averages. Throughout this period, park trees at IVM exhibited the highest T_{rel} values, ranging from 0.88 to 1.00, and were significantly elevated from trees planted in tree pits at SWB, which had the lowest T_{rel} , averaging 0.53. In comparison to DP-01, a similar pattern occurred in DP-02, but T_{rel} of both tree species was reduced by 39% for small-leaved lime and by 25% for Norway maple. In the study year 2022, both selected drought periods showed a similar pattern, although slightly different from the DPs of 2021. Interestingly, small-leaved lime trees at IVM did not experience the highest T_{rel} as in 2021, while trees at JCS were still at a high transpiration level, indicating the lowest transpiration reduction among other small-leaved lime sites with an average of 25% reduction compared to HSFPs, comparable to the 24% reduction indicated by GTS. Noteworthy, trees at SMS had the strongest reduction in transpiration across all drought periods at 58% compared to HSFPs, while Norway maple trees with similar growing conditions at SWB indicated a 28% transpiration reduction. There was a similar transpiration reduction at both parking lots HHS and URS, which had an average T_{rel} of 0.53 (transpiration reduced by 42%) and 0.48 (transpiration reduced by 47%) across all DPs, respectively. Our comparative analysis revealed a greater reduction in daily transpiration rate of 39% for small-leaved lime than for Norway maple with 34%.

We also examined ratios between absolute daily tree transpiration rates (T_{abs}) and potential reference evapotranspiration (ET_{pot}) for each drought period (Figure 11), similar to our analysis for HSFPs (Figure 9). In DP-01 and DP-02, the small-leaved lime plots IVM and JCS indicated significantly higher T_{abs} - ET_{pot} ratios than all other tree growing sites, reaching average ratios of 0.96 and 0.88, respectively. Additionally, IVM-T1, IVM-T3 and JCS-T1 had even higher T_{abs} than ET_{pot} in DP-01. Due to the higher ratios at IVM and JCS, small-leaved lime sites showed a higher ratio of 0.67 than Norway maple with 0.34 for both drought periods in 2021, while our selected tree species indicated similar average ratios of 0.40 for Norway maple and 0.37 for small-leaved lime during both droughts in 2022. Additionally, the highest average T_{abs} - ET_{pot} ratio per study site occurred at JCS with 0.58, and the lowest exhibited SMS with 0.17. However, the significantly highest ratio per investigated tree was GTS-T3 with 0.87, while SMS-T3 indicated the significantly lowest ratio of 0.06 throughout DP-03 and DP-04. Across all four drought periods, the average ratio of each study site is as follows, in declining order: JCS with $0.73 > IVM$ (0.65) $> GTS$ (0.47) $> TUF$ (0.39) $> HHS$ (0.39) $> URS$ (0.34) $> SWB$ (0.30) $> SMS$ with 0.25. In contrast to the T_{abs} - ET_{pot} ratios at HSFPs, the reduction in average ratio throughout all DPs was lowest at IVM with 3.5%, followed by GTS (20.4%), SWB (22.2%), JCS (24.7%), TUF (39.1%), HHS (42.5%), URS (43.0%) and SMS with the highest reduction of 51.0%.

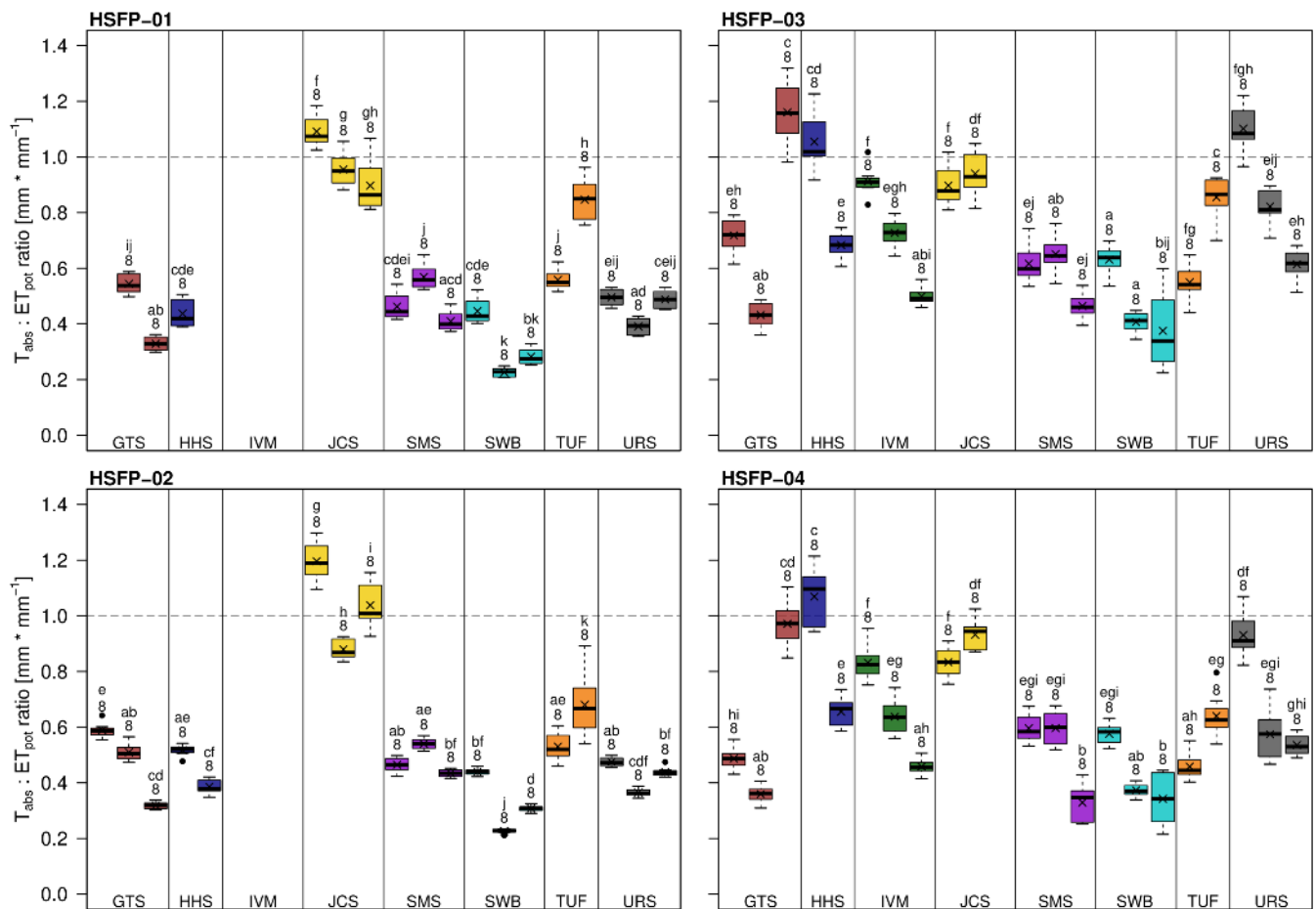


FIGURE 9 | Ratio between absolute daily transpiration (T_{abs}) and potential reference evapotranspiration (ET_{pot}). Values above the upper whisker represent the number of measured days during high sap flow period (HSFP), and letters indicate significant differences (p -value < 0.05) among trees. Norway maple sites: GTS=grass verge; SWB=tree pit; TUF=park; URS=parking lot. Small-leaved lime sites: HHS=parking lot; IVM=park; JCS=grass verge; SMS=tree pit.

3.5 | LWPs and Site Characteristics Influencing Transpiration During Drought Periods

Predawn and midday LWPs were assessed on each tree during 2 days of each growing season during hot and dry weather conditions (Figure 12). Both predawn and midday LWPs exhibited variations across the selected measurement dates in 2021 and 2022. On average, midday LWPs were lower across all measured trees, indicating an average of -2.13 ± 0.23 MPa in the second vegetation period, coinciding with a higher VPD recorded at DWD, averaging 2.12 kPa during DP-03 and DP-04, compared to the average midday LWP of -1.58 ± 0.16 MPa for 2021, which experienced a lower average VPD of 0.95 kPa recorded during DP-01 and DP-02 (see also Table 2 and Figure 4). In 2021, midday LWP across all trees ranged from -1.80 measured at URS to -1.36 measured at the park site IVM. Furthermore, Norway maple exhibited a slightly lower midday LWP of -1.64 MPa compared to small-leaved lime with -1.51 MPa. During the second growing period, the same study sites IVM and URS (green and grey bars in Figure 12) had the highest and lowest midday LWPs with -1.71 and -2.41 MPa, respectively, which were reduced by 20% at IVM and by 25% at URS, aligning with the higher VPD recorded in 2022. In the same year, predawn LWP was lowest at SMS with -1.79 MPa and highest at JCS with -0.58 MPa. In 2021, the average of both predawn LWP

measurements across all investigated trees was -0.54 ± 0.17 MPa, with the lowest value of -0.86 MPa measured at SMS, where trees were planted in tree pits (violet bars in Figure 12), and the highest values of -0.34 MPa at JCS.

During the selected drought periods (DP-01 to DP-04), predawn and midday measurements of LWPs were conducted on each study tree (Figure 12), allowing us to explore relationships between average T_{rel} of DPs and LWPs (Figure 13). We observed a strong significant linear correlation (p -value < 0.05) between predawn LWPs and T_{rel} for both tree species combined for drought periods in 2021 (green) and 2022 (orange), with an adj. R^2 of 0.43 and 0.79, respectively. Additionally, the predawn LWP measured during each DP correlated with the respective average T_{rel} of both tree species combined (see Table A5 in the Supporting Information). Moreover, when considering both tree species together, there we found a notable rise in T_{rel} as midday LWPs increased, with an adj. R^2 of 0.11 observed during drought periods in 2021. However, we did not find any significant relationships for both tree species combined during drought periods in 2022. Nonetheless, for small-leaved lime, midday LWP values were significantly correlated with T_{rel} in DP-02, indicating an adj. R^2 of 0.84, DP-04, and across all drought periods combined (adj. R^2 =0.48). Conversely, Norway maple did not exhibit any

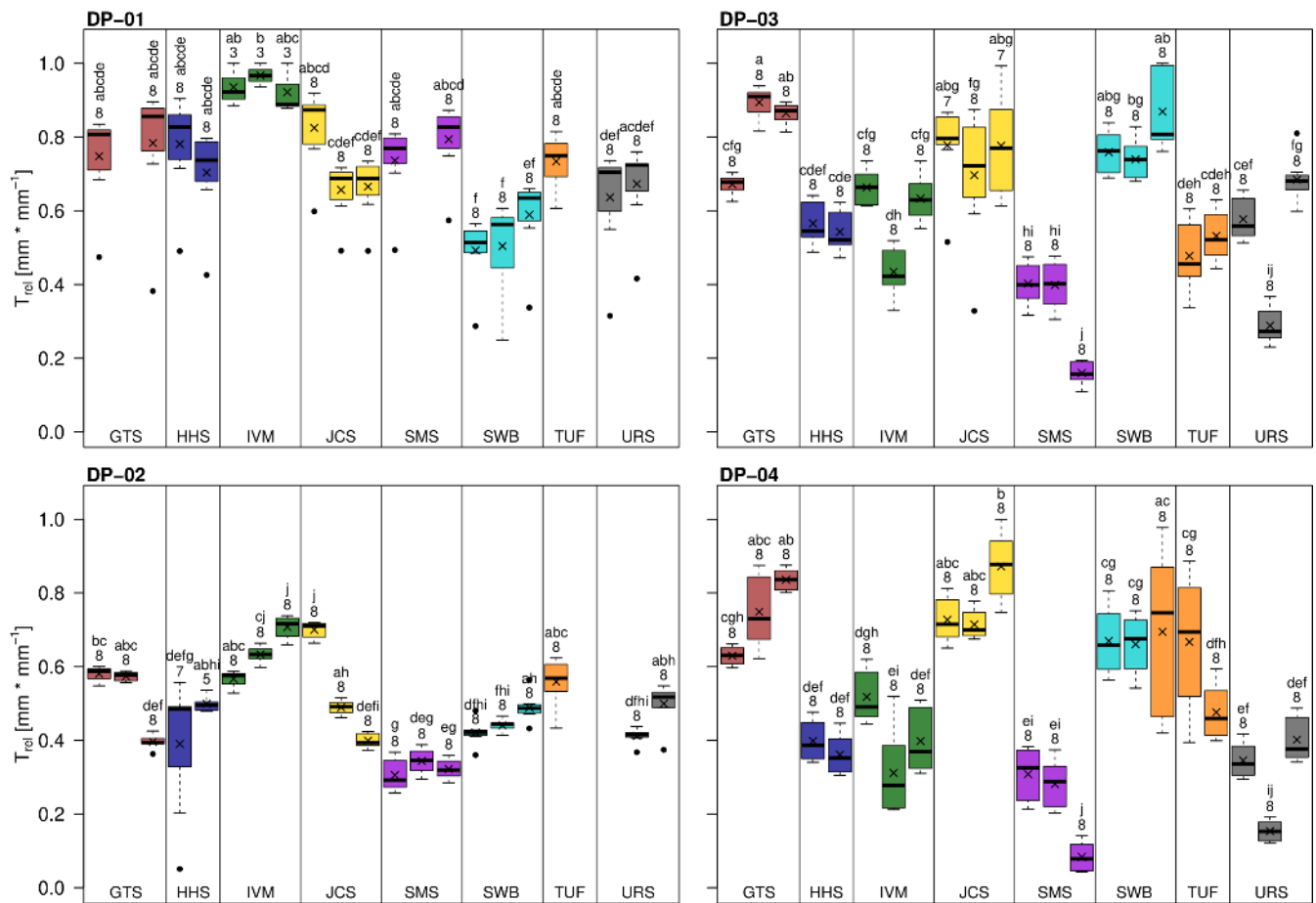


FIGURE 10 | Relative transpiration of each investigated tree during drought periods (DP-01 to DP-04). Values above the upper whisker represent the number of measured days during the selected DP, and letters indicate significant differences (p -value < 0.05) among trees. Norway maple sites: GTS=grass verge; SWB=tree pit; TUF=park; URS=parking lot. Small-leaved lime sites: HHS=parking lot; IVM=park; JCS=grass verge; SMS=tree pit.

significant correlations with midday LWPs. Detailed information on significance levels, correlation coefficients and adj. R^2 values is presented in Table A5 in the Supporting Information.

Furthermore, we investigated the influence of the relative surface sealing on LWP (predawn and midday) and identified contrasting responses between both tree species. Norway maple demonstrated that a higher degree of surface sealing within the CPA led to a significant increase in predawn LWP during DP-02, DP-03 and both drought periods in 2022 (p -value < 0.05), with the highest estimated adj. R^2 of 0.59 observed for DP-02. Conversely, small-leaved lime exhibited a decrease in predawn LWP (higher negative LWP values) with higher surface sealing degrees during DP-01, with an adj. R^2 of 0.33. A similar and more pronounced pattern emerged for midday LWP (refer to Figure A2). Small-leaved lime showed a decrease in LWP with higher surface sealing degrees during droughts in both growing seasons, whereas Norway maple displayed a contrasting behaviour, demonstrating a significant linear correlation for both droughts in 2021, indicating an increase in LWP with higher surface sealing.

Addressing site-specific growth conditions, we conducted a linear correlation analysis examining the relationship between the degree of surface sealing beneath tree crowns and relative daily transpiration (T_{rel}) during drought periods, identifying

significant relationships. We observed a clear association between the degree of surface sealing and T_{rel} for both tree species collectively, as well as for small-leaved lime individually during droughts in 2021 (refer to Figure 14 and Table A6 in the Supporting Information). We estimated adj. R^2 ranging from 0.18 to 0.55, with the highest adj. R^2 observed for small-leaved lime during DP-01. These findings indicate that during drought periods, surface sealing negatively impacts T_{rel} , resulting in reduced tree transpiration in highly sealed urban areas. In contrast, Norway maple exhibited divergent behaviour, showing an increase in T_{rel} as the sealing degree increased, observed during drought periods in 2022, supported by an adj. R^2 of 0.30 for both droughts combined and with 0.47 for DP-03 explicitly.

Regarding the soil water status during both drought periods (DP) and high sap flow periods (HSFP), we observed robust linear correlations between relative soil water deficit (%) and relative daily transpiration (T_{rel}) among several investigated trees (refer to Figure 15). Notably, as soil water deficit increased, there was a pronounced reduction in T_{rel} observed for trees situated at HHS, IVM, SMS, TUF and URS. Particularly significant correlations were identified for soil water deficit in the upper soil layer (10 cm) as well as when considering the entire averaged measured soil profile. However, no significant relationships were discerned for trees growing at GTS, SWB, and JCS. These

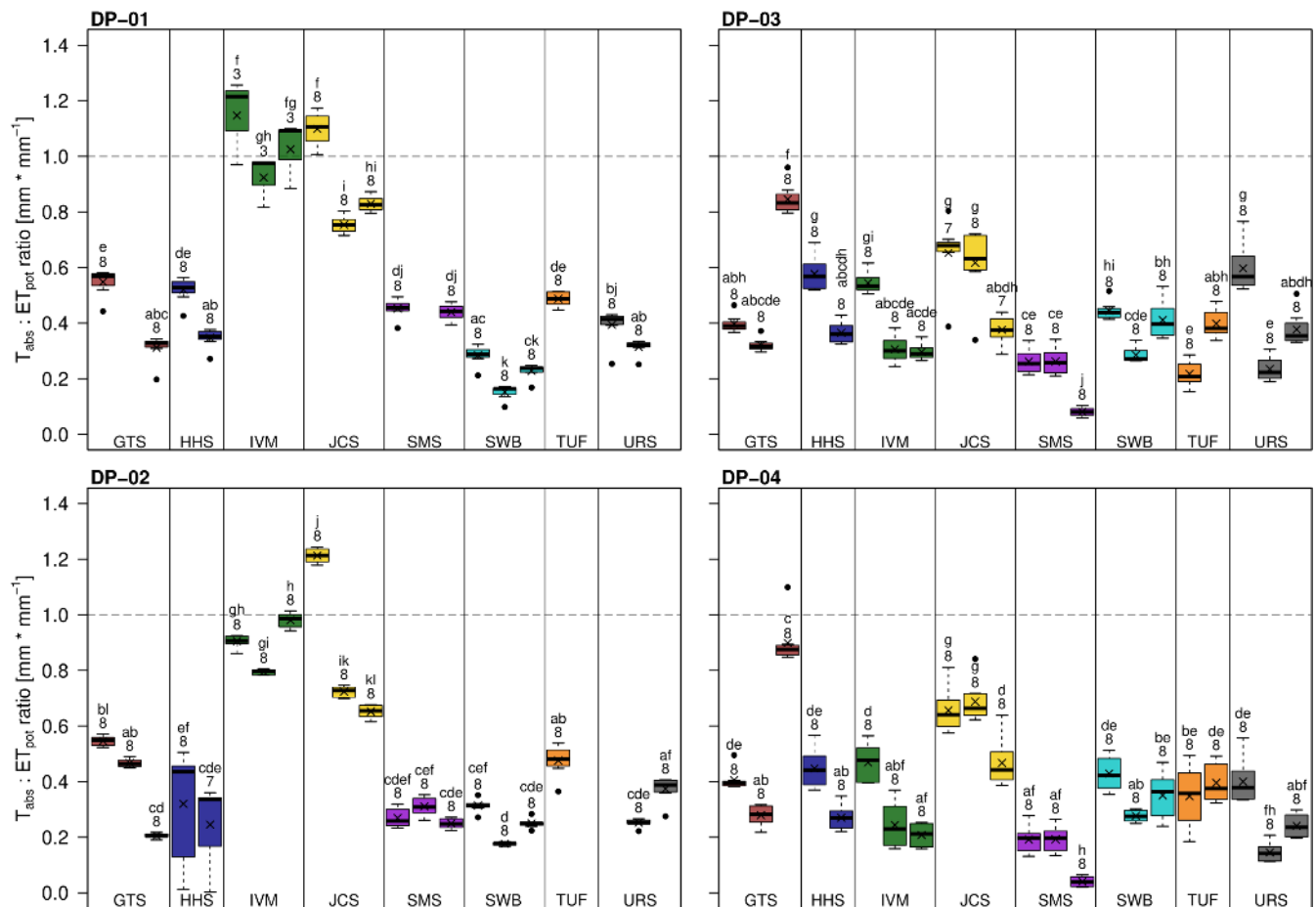


FIGURE 11 | Ratio of absolute day transpiration (T_{abs}) and potential reference evapotranspiration (ET_{pot}). Values above the upper whisker represent the number of measured days during drought period (DP), and letters indicate significant differences (p -value < 0.05) among trees. Norway maple sites: GTS=grass verge; SWB=tree pit; TUF=park; URS=parking lot. Small-leaved lime sites: HHS=parking lot; IVM=park; JCS=grass verge; SMS=tree pit.

findings offer insights in distinct site-specific (tree-specific) pattern in soil–plant interplay and highlight the heterogeneous behaviour of trees planted across various urban environments.

4 | Discussion

Our investigation highlights a notable gap in the literature regarding the study of drought impact on transpiration processes in urban trees, particularly in terms of direct field measurements using sap flow sensors on trees of the same species across diverse urban environments (Konarska et al. 2016; Rahman et al. 2017a). Despite this scarcity, we endeavour to contextualise our findings by drawing comparisons with previous studies on urban trees. It is important to clarify the sap flow measurement technique employed in our study, utilising HPV sap flow temperature sensor probes from East-30 Sensors. These probes record sap velocity (m h^{-1}), a metric numerically equivalent to sap flux density ($\text{g m}^{-2} \text{h}^{-1}$) obtained from measurements with thermal dissipation probes (TDPs) (Granier 1985; Burgess et al. 2001; Fuchs et al. 2017). This equivalence ensures the comparability of diurnal courses and magnitudes of sap velocities presented in our study.

Regarding the absolute values of transpiration (T_{abs}) depicted in our study, we did not address radial variations of sap velocity along

the entire sapwood depth (Cermak and Nadezhdina 1998). Our primary focus was to compare contrasting growing sites and tree species, a task facilitated by examining normalised transpiration rates (T_{rel}), as depicted in Figures 8 and 10. While active xylem sapwood area tends to be less variable in diffuse-porous species like Norway maple and small-leaved lime (Gebauer et al. 2008), caution is warranted when linking absolute transpiration rates shown in our study (e.g., in Figures 9 and 11) to other studies, as different sap flow methods may lead to over- or underestimation (Steppe et al. 2010; Fuchs et al. 2017). Additionally, slight deviations in sap velocity magnitude may have occurred due to sensor reinstallation in March 2022, impacting sensor placement within the xylem and variations in xylem properties. Nonetheless, efforts were made to maintain consistent and appropriate sensor placement similar to that of 2021.

4.1 | Diurnal Sap Velocity Differences Between Tree Species and Study Sites

To facilitate a comprehensive comparison of species-specific transpiration dynamics across various urban environments, we deliberately selected four contrasting growing sites for each tree species: parks, parking lots, grass verges and tree pits, with varying degrees of surface sealing within the canopy projection area

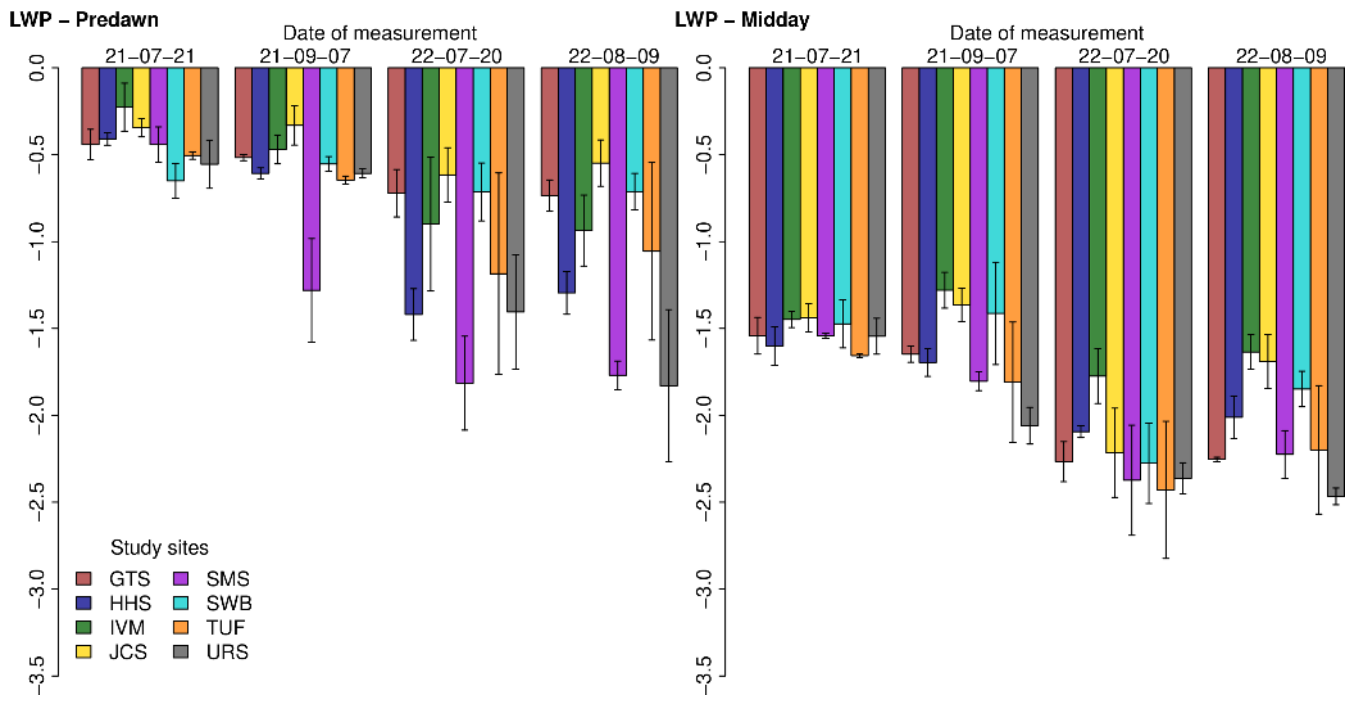


FIGURE 12 | Average leaf water potential (LWP) with standard deviations of each study site during predawn (left plot) and midday conditions (right plot).

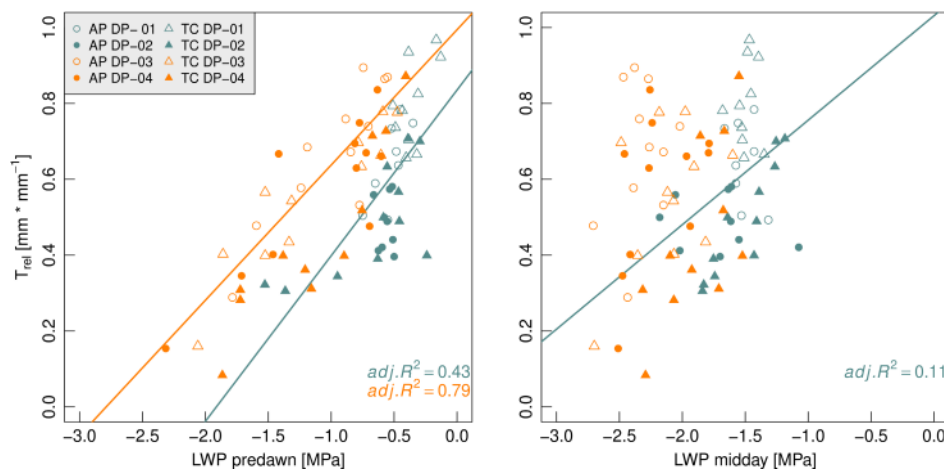


FIGURE 13 | Predawn and midday leaf water potentials (LWPs) versus relative daily transpiration rates of each investigated tree across drought periods (DP-01 to DP-04). AP=Norway maple, TC=small-leaved lime, green=both drought periods in 2021 and orange=both drought periods in 2022. Norway maple sites: GTS=grass verge; SWB=tree pit; TUF=park; URS=parking lot. Small-leaved lime sites: HHS=parking lot; IVM=park; JCS=grass verge; SMS=tree pit.

(CPA), as detailed in Table 1. It is essential to note that achieving a homogeneous microclimate and edaphic conditions is imperative for accurately comparing tree transpiration characteristics (Larcher 2001; Fini et al. 2009; Stokes et al. 2010), considerations that were meticulously integrated into our study design (see Figures 3 and 4 and Table A4 in the Supporting Information). Notably, despite slight variations, averages of air temperature (T_a), humidity (H_a) and VPD across high sap flow periods (HSFPs) and drought periods (DPs) remained relatively similar, with only minor differences observed in precipitation amount and SR, as outlined in Table 2. Importantly, none of the investigated trees received irrigation throughout the study period.

Examining the average diurnal courses of sap velocity throughout each growing season, we consistently observed higher sap velocities for both tree species in parks (TUF and IVM), while trees growing in tree pits exhibited the lowest values (see Figure 5). These findings are congruent with Rahman et al. (2017a), who reported a 44% higher average daytime sap flux density for small-leaved lime (*T. cordata*) in an open green square with vegetated soil compared to a circular paved square. Conversely, Ahongshangbam et al. (2023) observed an 18.6% higher average daily sap flux density for lime trees (*Tilia europaea*) growing along a road compared to small-leaved lime trees in an urban park. Interestingly, our estimated mean sap velocity for trees at JCS in 2021 aligned closely with

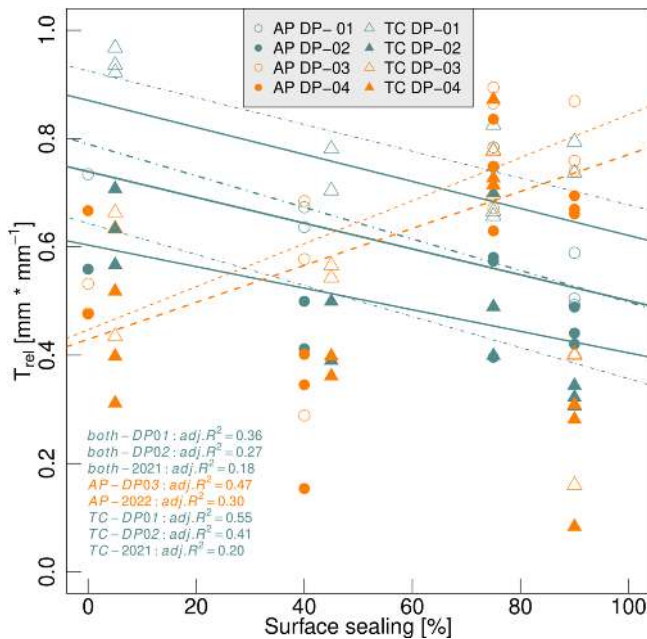


FIGURE 14 | Surface sealing vs. relative daily transpiration rates during drought periods (DP-01 to DP-04). AP=Norway maple, TC=small-leaved lime, green = droughts in 2021 and orange = droughts in 2022, thick solid line=both tree species and drought periods of a growing season, solid line=both tree species for a single drought period, bold solid line=both tree species for both drought period during a growing season, dot-dashed line=small-leaved lime for both a periods of a growing season, dashed line=Norway maple lime for a drought periods of a growing season.

those at IVM, yet notably differed from other small-leaved lime sites, exhibiting the highest values in 2022 (see Figure 5). These variations underscore the significant variability in transpiration dynamics among different urban green areas and tree species, attributed to species-specific stomatal characteristics as highlighted by Rahman et al. (2015). For instance, Rahman et al. (2019) found a threefold difference in water use between *T. cordata* and *Robinia pseudoacacia* (common locust) in Munich, Germany.

Our observations revealed a consistent diurnal pattern of sap velocities for both tree species, characterised by an increase at approximately 05:30h coinciding with the opening of leaf stomata, peaking between 12:30 and 15:00h and diminishing with stomata closure between 20:30 and 21:30h (see Figure 5). These trends align with previous studies (e.g., Stratópoulos et al. 2019; Chen et al. 2022b; Huang et al. 2022), attributing the highest sap flux to the most radiation-intensive hours and highest air temperatures of the day. Additionally, nocturnal stem sap velocities were detected at study sites GTS, HHS, IVM, and JCS (see Figure 5, 6, and 7), attributed to the replenishment of water storage in trees, a phenomenon also observed by Konarska et al. (2016) and Chen et al. (2022b) for *R. pseudoacacia*. This replenishment occurs during periods of strong daily sap flow rates, resulting in an imbalance between water supply and consumption, prompting root water uptake during nighttime, influenced by environmental drivers such as VPD (Fang et al. 2018).

Our comparative analysis of average diurnal sap velocity between HSFPs and DPs revealed significant differences between

study sites for both tree species (see Figures 6 and 7), consistent with prior research (e.g., Liu et al. 2018; Chen et al. 2022b). While slight differences in sap velocities were observed between study sites during HSFPs, particularly notable differences emerged during DPs (see Figure 7). Sites with trees growing in tree pits exhibited the most pronounced reduction in average maximum sap velocity during DPs, such as a 51.2% reduction at SMS compared to HSFPs. These findings are consistent with the notion that trees growing in tree pits with extensive sealed surfaces may experience more frequent and severe drought stress due to restricted access to soil water, leading to lower sap velocities and transpiration rates (Konarska et al. 2016). On average, small-leaved lime sites exhibited a stronger reduction in sap velocities (32.1%) compared to Norway maple sites (25.3%) in our study, consistent with previous research (Whitlow et al. 1992; Stratópoulos et al. 2019). This underscores the species-specific sensitivity of transpiration to drought conditions.

4.2 | Drought Impact on Transpiration Process

We conducted an analysis of T_{rel} and $T_{rel} \cdot ET_{pot}$ ratios during both high sap flow periods (HSFPs) and drought periods (DPs) for each tree, comparing study sites and tree species (Figures 8 to 11). Throughout all HSFPs, we observed similar T_{rel} values among trees and tree species ($T_{rel} > 0.9$), with only a few exceptions, such as significantly reduced T_{rel} recorded at SMS and SWB during HSFP-04 (see Figure 8). Additionally, during HSFPs in 2021, JCS and TUF-T3 exhibited the highest $T_{rel} \cdot ET_{pot}$ ratios, while other trees ranged between 0.23 (SWB-T2) and 0.59 (GTS-T1). On average, we observed a 22.7% higher $T_{rel} \cdot ET_{pot}$ ratio across all trees in 2022 compared to the previous year. Small-leaved lime consistently exhibited a higher ratio of 0.71 compared to Norway maple with a ratio of 0.55, and trees growing in tree pits showed the lowest $T_{rel} \cdot ET_{pot}$ ratios (e.g., 0.51 at SMS). These findings align with numerous studies reporting high variability in transpiration rates among different urban green spaces within the same tree species (e.g., Ferrini and Baietto 2007; Pataki et al. 2011; Rahman et al. 2015; Ahongshangbam et al. 2023). For instance, Konarska et al. (2016) investigated common lime trees (*T. europaea*) and reported twice the transpiration rate of park trees compared to street trees, consistent with studies by Cregg (1995) and Kjelgren and Clark (1992). However, a study on *Fraxinus pennsylvanica* and *A. platanoides* conducted in Utah showed no differences in water use between trees growing over asphalt and turf (Kjelgren and Montague 1998), which is also reflected in our observations of $T_{rel} \cdot ET_{pot}$ ratios. However, other studies (e.g., Kjelgren and Montague 1998; Litvak et al. 2012; Peters et al. 2010) reported higher transpiration rates for trees growing at sites surrounded by extended sealed surfaces due to higher irradiances and increased temperature compared to more vegetated habitats (e.g., parks and urban forests). In our study, this phenomenon was observed primarily for trees growing along the grass verge at JCS and for GTS-T3 (see Figure 9).

We also examined the effect of drought periods on the transpiration process (Figures 10 and 11), crucial for understanding trees' ecophysiological behaviour during stress periods (Korn 2016). Our analysis revealed a reduction in T_{rel} during drought periods compared to T_{rel} measured during HSFPs.

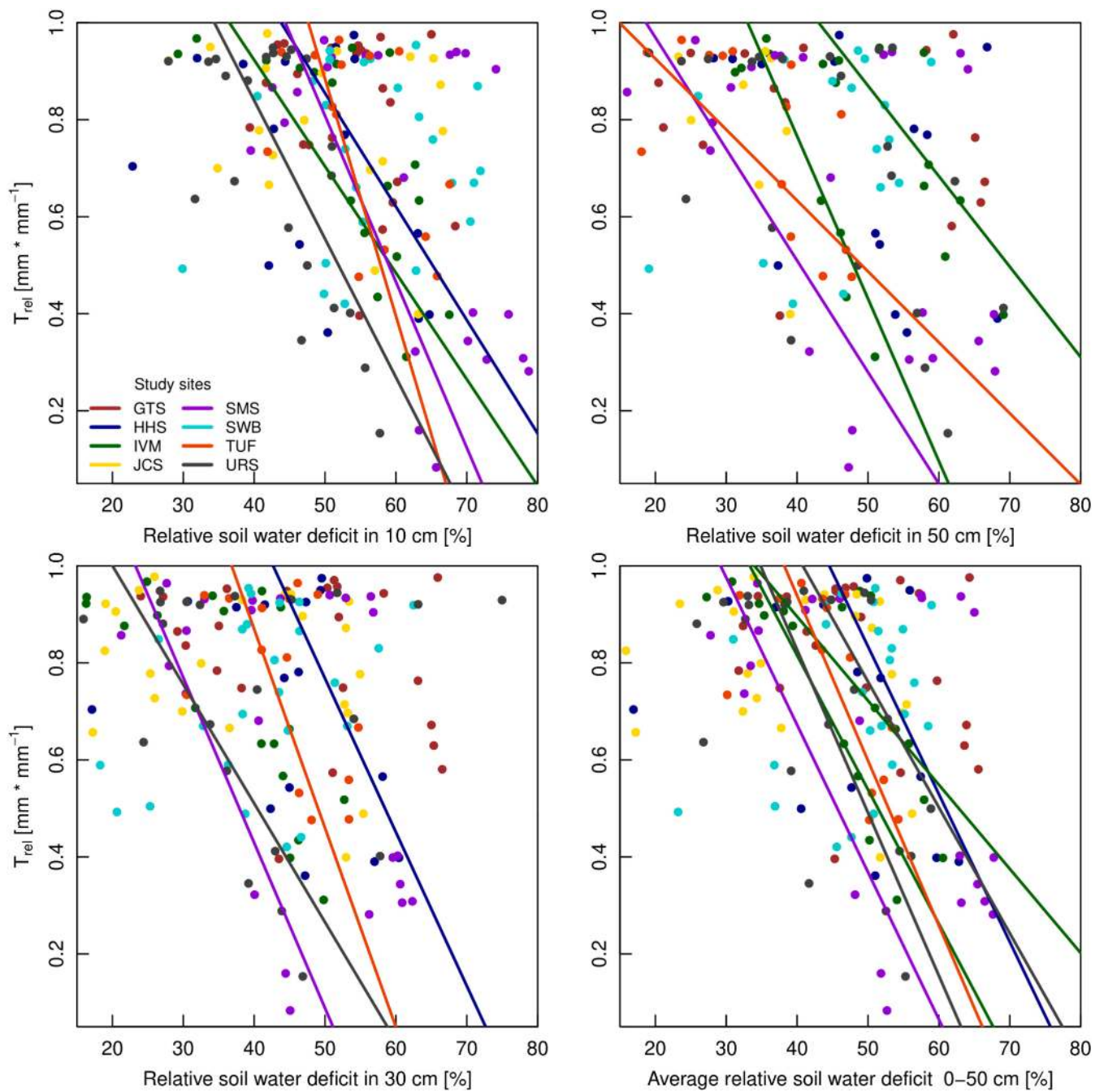


FIGURE 15 | Relative soil water deficit (normalised) versus relative averaged tree transpiration values recorded throughout all eight periods (HSFP and DP); each line represents significant linear correlation of one tree. Norway maple sites: GTS=grass verge; SWB=tree pit; TUF=park; URS=parking lot. Small-leaved lime sites: HHS=parking lot; IVM=park; JCS=grass verge; SMS=tree pit.

Small-leaved lime exhibited a 5% larger reduction across all study sites compared to Norway maple, which experienced a 34% reduction across all sites. These findings are consistent with the study by Rötzer et al. (2021), reporting a significant 63% reduction in transpiration rates of *T. cordata* and *R. pseudoacacia* during the European drought in 2018. Additionally, Stratópoulos et al. (2019) and Kunz et al. (2016) reported reinforced water use efficiency and resistance in maintaining sap flow of Norway maple during periods of high evaporative demand compared to small-leaved lime. Fini et al. (2009) and Gillner et al. (2015a) found lower drought sensitivity of

broad-leaved lime (*Tilia platyphyllos*) compared to Norway maple, with higher water use efficiency and gas exchange observed in broad-leaved lime under dry soil conditions, as reported by Gillner et al. (2015a). Moreover, Moser et al. (2017) highlighted the mildly isohydric behaviour of small-leaved lime trees during heat and dry periods, resulting in maintained or even increased transpiration rates under such conditions, consistent with our observations for trees at JCS. However, Leuzinger et al. (2005) reported a fivefold decrease in stomatal conductance during drought, demonstrating the drought sensitivity of broad-leaved lime.

Furthermore, Kjellgren and Montague (1998) elucidated that deciduous tree species from temperate forests exhibited reduced stomatal conductance, transpiration, and higher leaf surface temperatures in highly sealed urban sites. This observation aligns with the findings of Forrai et al. (2012), who reported decreased photosynthesis rates and reduced transpiration rates for several tree species, including Norway maple and small-leaved lime. Additionally, Thomsen et al. (2020) found that common oak (*Quercus robur*) maintained transpiration rates that closely followed ET_{pot} , comparable to small-leaved lime in our study, during droughts in 2021 (see Figure 11). In 2022, both tree species in our study indicated similar average ratios across all sites.

Examining transpiration reduction across study sites, we observed the most pronounced reduction of T_{rel} at SMS, with a 58% decrease, while the comparable study site for Norway maple exhibited a reduction of 28% relative to HSFPs. Remarkably, JCS exhibited the highest T_{rel} with the smallest reductions (25%), similar to GTS. Restricted transpiration rates can be attributed to impeded infiltration processes due to extensive impermeable surfaces, which reduce soil water availability, thereby subjecting trees to more frequent and severe drought stress (Rahman et al. 2011; Chen et al. 2022a). This relationship is supported by our findings of a strong linear relationship between the degree of surface sealing and T_{rel} during DPs (see Figure 14 and Table A6 in the Supporting Information) as well as between soil water deficit and T_{rel} (refer to Figure 15).

Further analysis comparing $T_{abs}-ET_{pot}$ ratios during drought periods between study sites indicated the lowest reduction in the average ratio at IVM (3.5%), followed by GTS (20.4%), SWB (22.2%), JCS (24.7%), TUF (39.1%), HHS (42.5%), URS (43.0%) and SMS with the highest reduction of 51.0% (see Figure 11). These results likely stem from insufficient water supply and reduced sensitivity to VPD and SR for trees planted in tree pits compared to park trees, which experience less water stress and maintain transpiration, thereby potentially offering higher cooling potential at those sites (Leuzinger et al. 2010; Rahman et al. 2017a; Chen et al. 2022a).

During the course of the 2022 growing season, we observed early leaf senescence in trees growing in tree pits, especially after DP-03 at SMS, with an early abscission recorded and a reduced LAI (see Table A1 and Figure A1 in the Supporting Information). This observation is consistent with the findings of Dantec et al. (2000) and Poyatos et al. (2013), who highlighted the lower suitability of tree species during droughts, indicating these processes. Moreover, maintaining open stomata under dry conditions increases the risk of damage or dieback due to cavitation, as well as the early onset of leaf wilting and abscission (Roloff et al. 2013; Stratópoulos et al. 2019). Additionally, Stratópoulos et al. (2019) suggested that tree species exhibiting drought-induced leaf senescence and abscission may reduce ecosystem services such as shading and transpirational cooling.

Considering the LWPs measured on each tree during drought periods, both predawn and midday LWPs decrease with higher drought stress intensity at all study sites, particularly at HHS and SMS for small-leaved lime and at URS for Norway maple during predawn conditions. These results are consistent with Gillner et al. (2017), who observed a similar

pattern for small-leaved lime during dry conditions, along with an increasing VPD, categorising small-leaved limes as an anisohydric tree species. Korn (2016) elucidated the decline of predawn LWP values as a drought tolerance mechanism aimed at exploiting the soil moisture reservoir under low soil water potentials and maintaining transpiration, thereby preventing water loss alongside reduced photosynthesis rates (Sperry 2000; Gillner et al. 2015a). These explanations support our findings of significant correlations between predawn LWP values and T_{rel} of both tree species (see Figure 13), which showed an increase in T_{rel} with higher predawn LWPs, as also observed for midday LWPs for both droughts combined in 2021. Furthermore, we emphasised the impact of surface sealing on LWP values (refer to Figure A2), highlighting the site-specific effects on tree ecophysiology. However, to advance our understanding of drought impact on tree water relations, intensive diurnal LWP measurements should be conducted during stress periods due to the high complexity of species-specific stomatal aperture regulation, as mentioned by Larcher (2001) and Gillner et al. (2017). Additionally, leaf anatomical characteristics influence tree transpiration dynamics (Roloff et al. 2013).

Gillner et al. (2017) summarised that small-leaved lime as a street tree exhibits a high capability to provide ecosystem services even in hot and dry periods and recommended planting trees at stressed urban sites (e.g., with soil restrictions). However, we do not fully agree with this, as we observed a high reduction in sap velocity and transpiration rates at SMS. In contrast, Stratópoulos et al. (2019) highlighted the higher drought resilience of Norway maple compared to small-leaved lime and recommended planting Norway maple in drought-prone urban sites and small-leaved lime more in urban parks, with a higher probability of sufficient water supply, thereby sustaining tree physiological processes. Furthermore, Bühler et al. (2006) and Nielsen et al. (2007) recommended increasing the proportion of permeable surfaces around urban trees and decreasing soil compaction to enhance the amount of available soil water instead of establishing an irrigation management plan. Based on our results, we tend to agree with Bühler et al. (2006), Nielsen et al. (2007) and Stratópoulos et al. (2019).

In common with the few previous studies, the number of trees per study site investigated in our study was limited to only three and two individuals, respectively, due to the high demand for measurement equipment and the challenge in maintaining such a service-intensive monitoring network within a city. Therefore, additional field research for long-term observations is necessary to develop a solid database for various tree species and to understand species-specific responses to urban environmental stress effects on trees' ecosystem services.

5 | Conclusion

The investigation of drought impact on the transpiration process of two common deciduous tree species in contrasting urban environments in the City of Freiburg, Germany, forms the core of our study, supported by direct field measurements on 11 trees per species. Over two growing seasons, we delved into site-specific and species-specific differences in diurnal patterns of sap velocity,

transpiration rates and the ratios between actual daily transpiration rates (T_{abs}) and potential reference evapotranspiration rates (ET_{pot}), particularly during high sap flow periods (HSFP) and drought periods (DP). Throughout our study period from 2021 to 2022, we meticulously measured sap flow, soil water content in the rhizosphere, LAI and LWP at all trees, which were strategically planted in urban parks, parking lots, grass verges, and tree pits.

Our findings revealed significant differences (p -value < 0.05) in the diurnal pattern of sap velocities across both growing seasons. Notably, in 2021, park trees of both species exhibited the highest sap velocities throughout the day ($\sim 0.262 \text{ m h}^{-1}$) compared to trees growing in tree pits. Additionally, our comparative analysis of sap velocity characteristics during HSFPs and DPs among study sites unveiled significant reductions in maximum sap velocities, averaging 25.3% for Norway maple and 32.1% for small-leaved lime, with the most pronounced drought-induced reduction observed at SMS with 51.2%.

Moreover, we observed a slight difference in transpiration levels between growing seasons, with a 22.7% higher average $T_{\text{abs}}/ET_{\text{pot}}$ ratios for all trees in 2022. Small-leaved lime exhibited a ratio of 0.71 compared to Norway maple with 0.55, with trees growing in tree pits showing the lowest ratios. Additionally, our analysis revealed a drought-induced reduction in T_{rel} compared to T_{rel} during HSFPs, with small-leaved lime experiencing a 5% higher reduction across all study sites compared to Norway maple, which saw a reduction of approximately 34% across all sites. A grass verge site with a sealing degree of 75% exhibited the highest T_{rel} during drought periods. Furthermore, we established a strong linear relationship (p -value < 0.05) between the degree of surface sealing and drought-induced T_{rel} for both tree species in 2021. We also uncovered a significant correlation between LWPs and T_{rel} , with the lowest predawn LWP (-1.5 MPa) observed at sites with a 90% degree of surface sealing within the CPA (tree pits). Additionally, we emphasised the site-specific influence of surface sealing on T_{rel} during droughts, along with the significant interaction between soil and tree evidenced by strong relationships between soil water deficit and transpiration characteristics.

Our study has generated a vital dataset for small-leaved lime and Norway maple, contributing to an enhanced understanding of drought-induced transpiration responses in trees within highly anthropogenically influenced ecosystems. We emphasised the substantial impact of surface sealing on tree transpiration processes during stress periods. However, we advocate for further continuous monitoring of various urban tree species to build a comprehensive database for modelling approaches and to deepen our understanding of the drought-induced impacts on trees' ecosystem services, such as transpiration cooling ability. This will ultimately aid urban architects and planners in making informed decisions regarding the selection of tree species for optimal urban living environments.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.