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RECEIVED 24 October 2024

ACCEPTED 06 May 2025

PUBLISHED 05 June 2025

CITATION

Larsen EK, Blanusa T, Tanner R, Barker J, Dunn N and Gush MB (2025) Impact of environmental drivers on ecosystem service-delivery of small garden trees in a temperate climate. *Front. Environ. Sci.* 13:1515809. doi: 10.3389/fenvs.2025.1515809

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Impact of environmental drivers on ecosystem service-delivery of small garden trees in a temperate climate

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Green infrastructure has an increasingly important role in mitigating urban environmental concerns such as heat island effect, localised flooding, pollution and biodiversity loss. Trees are a crucial element of that, and in the UK, around 25% of the urban tree canopy consists of trees within domestic gardens, which provide valuable ecosystem services. With the average UK garden size being only 188 m² and urban areas being under pressure from climate change, information on small garden trees, suitable for these spaces is increasingly important. To address this gap, we studied nine taxa of small-stature garden trees (representing a range of functional and structural tree characteristics) in a replicated outdoor experiment over two summers (2021 and 2022). In this paper, we focused on the sap flux patterns of selected taxa in response to measured environmental drivers (solar radiation, air temperature, relative humidity, wind speed and soil temperature), as well as trees' above-ground size and biomass growth. Results showed that the strongest driver of sap flux across all taxa was a reduction in relative humidity, followed by an increase in radiation and a rise in air temperature. The results depended on time of day and the specific taxon. Overall, *Malus* 'Scarlett' had the highest sap flux density in the morning, while *Crataegus* 'Prunifolia Splendens' averaged the highest sap flux density during afternoon and evening. Both taxa would be suitable garden trees to provide soil moisture reduction and cooling in smaller gardens during the growing season. Taxa with compact canopies in combination with high water demand such as *Cupressus*, *Ilex* and *Pyrus* in this study, provided the most transpirational cooling relative to size. This demonstrates how "the bigger the better" is not necessarily the case for transpirational cooling. Rather, the ratio between sapwood- and crown volume in combination with water demand, might be a better indicator of transpirational cooling efficiency.

KEYWORDS

climate resilience, evaporative demand, green infrastructure, sap flux, transpirational cooling, urban tree canopy

1 Introduction

Extreme heat events are increasing in frequency and severity as a consequence of climate change (IPCC, 2023; Harrington and Otto, 2020). By 2070 in the UK, summers are predicted to become up to 6°C warmer and 60% drier, but with 20% greater rainfall intensity, compared to pre-industrial levels (Met Office, 2025a). In addition, urban areas are typically warmer than surrounding rural areas due to the urban heat island (UHI) effect (Arnfield, 2003; Parsaee et al., 2019; Wang et al., 2019), caused by artificial, impervious and dark surfaces leading to increased sunlight absorption, short-wave radiation being trapped in street “canyons,” energy-intensive activities (industry, transport, etc.), and the lack of evaporating surfaces (Arnfield, 2003; Aram et al., 2019; Wang et al., 2019). Trees, due to their longevity and stature are one of the most efficient forms of urban planting to mitigate the UHI effect (Ellison et al., 2017; Hand et al., 2019; Wang et al., 2019). Globally, forest understory temperatures are on average 1.7°C cooler compared to open sites, a greater magnitude than the mean global warming of 1.0°C in the last century (De Frenne et al., 2015). However, the cooling effect differs significantly between taxa and the environments they grow in (Leuzinger et al., 2010; Smithers et al., 2018; Moss et al., 2019; Yarnvudhi et al., 2022). Appropriate selection of taxa is thus necessary to deliver positive and avoid negative (e.g., building subsidence; pollen allergies, etc.) impacts of tree planting in the built environment (Richter et al., 2022). Increasingly, considerations of appropriate tree taxa for green infrastructure are including multiple ecosystem services [e.g., the ability of trees to withstand the effects of gaseous and particulate air pollution but also mitigate it in light of decreasing air quality in cities (Oksanen and Kontunen-Soppela, 2021; Steinparzer et al., 2023)].

Domestic gardens are an often-overlooked urban resource. In the UK, they make up 30% of total urban area (Cameron, 2023). Furthermore, nearly 90% of the UK population is classed as urban/peri-urban and a similar percentage of urban households have access to domestic green spaces (Davies et al., 2009; Cameron et al., 2012). These spaces therefore have a unique potential to alter the microclimate in otherwise densely populated areas. While the average UK garden size is only 188 m², and 140 m² in London (Office for National Statistics, 2020), tree species diversity in domestic gardens is greater than in public green spaces (Vaz Monteiro et al., 2019; Mejita et al., 2024). However, available space for tree planting is a limiting factor in urban areas, where green and grey surfaces are “competing” for space. Furthermore, root restriction in confined spaces strongly limits urban tree survival and provision of ecosystem services such as ambient cooling, reduction of localised flood risks, and food and habitat provision for wildlife (Rahman et al., 2014; Gillner et al., 2015; North et al., 2017). Average UK garden sizes do not easily lend themselves to hosting large-stature landscape trees, so there is a knowledge gap on the extent to which smaller trees can effectively provide ecosystem services (Gillner et al., 2015; Rahman et al., 2015; Moss et al., 2019). To encourage tree planting in domestic gardens, there is a need to understand the cooling ‘performance’ of smaller trees. Plants cool down their surroundings in two main ways: through plant transpiration and through direct shading. Transpirational cooling occurs as liquid water within the plant is transformed to vapour in the atmosphere. This process absorbs solar energy/radiation at a rate of 2.45 kJ per gram of water, allowing the energy to be used for vaporisation without an increase in air temperature (Rockwell et al.,

2014; Vaz Monteiro et al., 2017). Plants’ physiological and morphological traits (extent of transpiration and canopy size/density) are therefore important determinants when deciding which trees are best equipped to grow in urban environments and to reduce ambient temperatures.

During an unparalleled heatwave in July 2022, UK air temperatures reached a historical record of 40.3°C (Kendon et al., 2023). These temperature extremes are predicted to become more frequent due to human-induced climate change (Christidis et al., 2020). To provide a wide selection of ecosystem services, garden trees need to thrive rather than just survive in the environment in which they are growing. When soil water is not a limiting factor, vapour pressure deficit (VPD) is the main driving force for plant/tree transpiration along with solar radiation (Priestley and Taylor, 1972). VPD is the difference between water holding capacity of the air and actual water content of the air and is determined by both RH and air temperature (Grossiord et al., 2020). However, transpiration is constrained by water availability and a plant’s physiological control of stomatal aperture, to avoid excessive water-loss and the risk of desiccation and hydraulic failure (Monteith, 1965; Dolman et al., 2014; Richter et al., 2022). Transpirational cooling provided by a tree is therefore linked to the trees’ regulation of water-loss. The capacity to cool down the leaves, and the ambient temperatures around leaves, differs between taxa, and some plants are better equipped than others to continue functioning under higher air temperatures (Leuzinger et al., 2010). On the other hand, ambient cooling through shading is directly linked to plant canopy size and density, with higher leaf area index (LAI) correlating to a greater cooling potential (Rahman et al., 2020).

Our study aimed to provide insight into how commonly planted garden tree taxa respond to high ambient temperatures and how much transpirational cooling small garden trees can provide, thereby informing tree choices appropriate for domestic gardens in a changing climate. We used a mixed model to understand the simultaneous influence of air temperature, relative humidity (RH), solar radiation, wind-speed and soil temperature on sap flux. The sap flux densities were further used to estimate the water uptake capacity and resultant transpirational cooling potential of each taxon relative to crown volume, thereby informing tree choices appropriate for domestic gardens in a changing climate.

In this paper we present 1) observations of transpiration rates (using a heat ratio sap flow method) of nine functionally and structurally different garden tree taxa, measured over peak summer periods (July) for two consecutive years, to understand how the water use of each taxon responded to meteorological fluctuations during the warmest and driest month of the year; 2) assessment of which meteorological variables were the strongest drivers of transpiration; 3) ambient cooling potential and cooling efficiency relative to crown volume for each taxon; and 4) conclusions on plant traits associated with greater cooling capacity of small stature garden trees.

2 Methodology

2.1 Tree selection and planting details

Tree taxa selected for the study represented a broad range of leaf- and growth characteristics, including evergreen/deciduous, needle-

TABLE 1 Key descriptors of the nine tree taxa used in the experiment.

Genus/Species	Epithet	Common name	Characteristics	Rootstock
<i>Crataegus persimilis</i>	'Prunifolia Splendens'	Plum-leaved hawthorn	DC, BR	<i>Crataegus monogyna</i>
<i>Cupressus sempervirens</i>	'Garda'	Mediterranean cypress	EV, SL	NG
<i>Ilex aquifolium</i>	'J.C. van Tol'	Common holly	EV, BR	NG
<i>Magnolia</i>	'Galaxy'	Magnolia	DC, BR	NG
<i>Malus</i>	'Scarlett'	Crab apple	DC, BR	Apple MM106
<i>Picea pungens</i>	'Erich Frahm'	Blue spruce	EV, NK	NG
<i>Prunus</i>	'Fugenzo'	Cherry	DC, BR	Colt
<i>Pyrus calleryana</i>	'Chanticleer'	Callery pear	DC, BR	<i>Pyrus kirchensaller</i>
<i>Sorbus ulleungensis</i>	'Olympic Flame'	Ulleung rowan	DC, BR	<i>Sorbus aucuparia</i>

Abbreviations: EV, evergreen; DC, deciduous; BR, broadleaved; NL, needle-leaved; SL, scale-leaved; NG, not grafted.

leaved, scale-leaved and broadleaved trees. The selected tree taxa had growth characteristics that represent commonly grown trees in UK gardens, and are moderately drought tolerant, without known "disservices" (e.g., allergenicity, emission of volatile organic compounds, or high susceptibility to invasive pests and diseases at the time of selection), according to peer-reviewed literature. An online tool ("My Garden"), managed by the Royal Horticultural Society (RHS), holds the data on over five thousand plant taxa registered by garden owners as being grown in their UK private gardens, and was used to obtain an overview of frequently planted tree taxa in domestic gardens. Advice on taxa was also sought from Frank P. Matthews's nursery (Tenbury Wells, UK), one of the UK's largest and oldest tree nurseries. This approach identified taxa within the genera *Magnolia*, *Malus* and *Prunus*, as important garden tree representatives in the UK. Additionally, *Pyrus calleryana* was chosen as it has been studied previously in an urban context for its cooling capacity (Rahman et al., 2014) and was considered a good reference. *Picea* and *Cupressus* were selected to represent two types of evergreen conifers with different morphological traits, one needle-leaved and another scale-leaved. The final selection comprised the following taxa: *Crataegus persimilis* 'Prunifolia Splendens', *Cupressus sempervirens* 'Garda', *Ilex aquifolium* 'J.C. van Tol', *Magnolia* 'Galaxy', *Malus* 'Scarlett', *Picea pungens* 'Erich Frahm', *Prunus* 'Fugenzo', *P. calleryana* 'Chanticleer' and *Sorbus ulleungensis* 'Olympic Flame' (Table 1). Because these garden trees are either cultivars or hybrids, none of them are classified as native.

As this study included nine different genera, and *Magnolia* 'Galaxy', *Malus* 'Scarlett' and *Prunus* 'Fugenzo' do not have species epithets, as this is not always included in hybrid taxa (Cubey et al., 2023; Cultivated Plant Code, 2016), each taxon will henceforth be referred to by the genus.

Fifty-four trees (six replicates of each of the nine chosen taxa), were obtained from FP Matthews' nursery (Tenbury Wells, United Kingdom) in January 2021 and subsequently transplanted into 130 L containers with Sylvamix bark-based growing medium with 10% loam added in (Melcourt, United Kingdom). All trees were 4–5 years old at the time of transplanting. During the study period, an organic fertiliser (Ecor 5 Organic Fertiliser 8-5-6, Fargro, United Kingdom) was added as a top fertiliser every sixth month.

2.2 Experimental design

The trees were grown outdoors in the period February 2021 – January 2023 on geotextile-covered ground (Mypex, Don and Low, United Kingdom) in a randomised block design (3 × 3, 3 m apart) at the RHS's Field Research Facility (51°19'21" N, 0°28.23" W). The site has a northern temperate climate, with a mean annual maximum temperature of 15.4°C, a monthly average temperature ranging from 5.3°C (January) to 17.9°C (July) and mean annual precipitation of 667.9 mm (Met Office, 2025b). Trees were irrigated by means of naturally occurring rainfall, an automated drip irrigation system (4 drippers per container), and supplementary manual watering when required, to avoid any water stress. To aid with the maintenance of optimal root-zone moisture levels, starting at planting time, continuous measurements of substrate moisture were obtained with substrate moisture probes (SM150T, Delta-T Devices, United Kingdom) in two containers per taxon. Additionally, weekly point measurements were taken 5 cm from the bottom of the container the second year (by inserting probes through two custom made holes in the containers which fit the probe's sensors), to determine whether additional irrigation was necessary (Supplementary Figure A1). Substrate moisture content was maintained above 0.2 m³ m⁻³ to avoid water stress, while drippers were removed when the moisture concentrations exceeded 0.6 m³ m⁻³, to avoid waterlogging.

As the focus of this experiment was to quantify the trees' response to high ambient temperature and the subsequent cooling potential, we selected July, the warmest month of both 2021 and 2022, as the period of transpiration and cooling assessment for this study.

2.3 Meteorological data

A weather station (WS-GP2 Advanced Automatic Weather Station System, Delta-T Devices, United Kingdom) was installed adjacent to the experimental plot (<20 m). Hourly totals of rainfall (mm) near ground-level, and hourly values of air temperature (°C), relative humidity (%), wind speed (m s⁻¹), radiation (W m⁻²), soil temperature (in the surrounding ground, not the substrate of the

pots, °C) and atmospheric pressure (kPa) at 2 m height were recorded throughout the duration of the experiment. Hourly values were collated into daily and monthly values and were used to calculate vapour pressure deficit (VPD, kPa) (Allen et al., 1998).

2.4 Sap flux (transpiration) measurements

Heat pulse velocities (cm h⁻¹) were measured continuously using the SFM1 sensors (SFM1, ICT, Australia). One SFM1 sensor was installed on the northern side of the trunk of three trees per taxa, at 20–30 cm height above substrate surface (below the first branch) to allow uniform comparison between the trees, with some taxa (i.e., *Cupressus*) having branches growing closer to the ground than others. A plastic spacer of around 0.8–1.0 cm, depending on the thickness of the bark of the tree, was fitted over the probe so that the measuring point of the probe was positioned at 0.2 cm and 2 cm into the wood. However, on inspection, the data collected from the outer part of the wood was less noisy and more consistent. This could have been due to the size of the trees, with some of the smaller trees (i.e., *Ilex aquifolium* 'J.C. van Tol'), not being larger than 2 cm in radius. Consequently, the data used for this study was taken from the outer 0.2 cm part of the sapwood. All probes were covered with reflective foil to minimise the effect of solar radiation on the measurements.

2.4.1 Calculating sap flow and sap flux densities

Heat pulse velocities were corrected for a zero baseline, using periods of time when sap flow values were most likely to approach zero. Heat pulse velocities were selected between 00:00 and 05:00, on days when VPD (calculated from the weather station) was 0. The median of the actual heat pulse velocities observed at these times was used to determine the offset required to be applied to the dataset (Larsen et al., 2020). The corrected heat pulse velocities (V_c , cm h⁻¹) were calculated following Equation 1, applying the offset to the original heat pulse velocity data (V_h):

$$V_c = V_h \pm \text{offset value} \quad (1)$$

A wound-correction was then applied to each sensor, following Equation 2 (Burgess et al., 2001):

$$V_w = bV_h + cV_c^2 + V_c^3 \quad (2)$$

where b , c , and d are unitless coefficients derived from Burgess et al. (2001), according to the size of the wound made by the drill when installing the sensors into the trunk.

Determination of sap flux densities (V_s), i.e., volume of sap flow per area of wood per hour (cm³ cm² h⁻¹), were calculated following Equation 3, adapted from Marshall (1958) by Burgess et al. (2001):

$$V_s = \frac{V_w \rho_b (c_w + m_c c_s)}{\rho_s c_s} \quad (3)$$

where ρ_b is density of wood (kg m⁻³), c_w is specific heat capacity of wood (J kg⁻¹ °C⁻¹), and c_s is specific heat capacity of sap (water, J kg⁻¹ °C⁻¹), m_c denotes the water content of sapwood (m³ m⁻³), and ρ_s is the density of water (kg m⁻³). Sapwood water content was calculated following the method proposed by Marshall (1958). Four wood segments per taxa were sampled in June 2023, after the

experiment was completed. Each segment was cut down to a small cylinder for fresh volume measurements (length and diameter) and fresh weight (W_f). The wooden cores were then oven dried at 70°C for 6 days, and dry weight (W_d) was recorded. Water content was calculated as in Equation 4.

$$\left(\frac{W_f - W_d}{W_d} \right) \quad (4)$$

The calculation was done for each wood core, and an average was taken for each taxon and used in the sap flux calculation. Wood densities for each taxon were taken from a *Global wood density database* (Zanne et al., 2009). Where a specific taxon could not be found, another species within the same genus was used.

Total transpiration per tree was derived by multiplying sap flux with area of sapwood as seen in Equation 5.

$$\text{Transpiration} = V_s A_s \quad (5)$$

where A_s denotes the area of sapwood (cm²) per tree. Sapwood area was calculated from individual trees' stem diameter and sapwood depth at the height of the sensor, discounting for bark and cambium thickness. The trees were assumed to have negligible non-conducting heartwood area due their size and age. Radial differences, although often prominent in sapwood, were not differentiated for, due to the size and age of the trees.

2.5 Calculation of transpirational cooling

Total transpiration per tree was converted into grams per second and multiplied by the latent heat of vaporization factor (2.45 kJ g⁻¹ at 292K and atmospheric pressure) (Wagner and Pruß, 2002; Moss et al., 2019; Rahman et al., 2019) to estimate energy absorption, Q (kJ) associated with tree transpiration (e) (Equation 6):

$$Q = \text{sap flow (gs}^{-1}) \lambda t \quad (6)$$

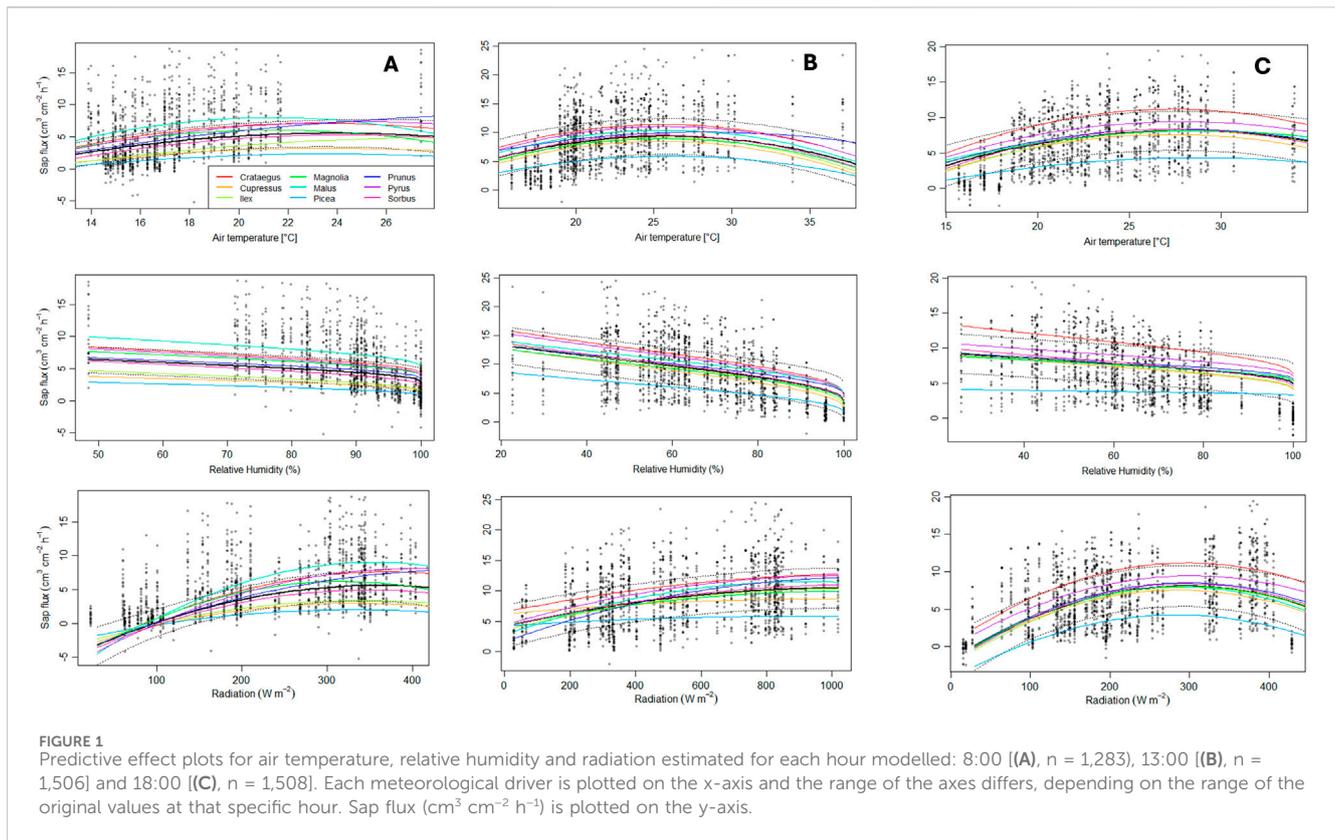
Where λ is the latent heat of vaporization per unit time (s). Transpirational cooling effect (Tr_c , °C) was further obtained following Equation 7, from Nakazato and Inagaki (2012) and Huang et al. (2022):

$$Tr_c = \frac{Q}{\rho * c_p * c_{vol}} \quad (7)$$

Where ρ is the density of air (kg m⁻³), c_p is the specific heat capacity of air (kJ kg⁻¹ °C⁻¹), and C_{vol} (m³) is the crown volume calculated, using a paraboloid volume equation, using measurements of canopy length, depth and height. Volume of the main stem was calculated using the equation of a cone, using the radius at ground level and total height as input measurements. The same was done with each primary branch: girth and length was measured for each individual branch. Branches smaller than 10 cm length and 5 mm diameter were excluded.

2.6 Statistical analysis

All statistical analyses were performed using R studio (R Core Team, 2021). To assess the differences between biomass growth and crown volume, a Two Sample t-test was used ($p < 0.05$). A *post hoc* Tukey test was performed to detect differences between taxa.



To investigate the relationship between transpiration and meteorological drivers, a linear mixed model was fitted to the sap flux measurement of all nine taxa using the “brms” package to account for autocorrelation (Bürkner, 2017). The “brms” uses a Bayesian method and gives a posterior distribution and a 95% confidence interval for the estimated outputs (Korner-Nievergelt et al., 2015). Taxa and their interactions with each driver were used as predictors. Because of the high temporal autocorrelation in the data, i.e., data points close together in time displayed the same results, we decided to select 3 h, and 5 h apart, to best understand the daily influence of the environmental drivers on transpiration. Three different models were fitted, each representing one specific hour of measurements: 08:00, 13:00 and 18:00 BST, in July during both years. Using both years allowed sufficient replicates (Supplementary Tables A1, 3, 4). The 08:00 data was used to assess sap flux at a period when rates were increasing rapidly, the 13:00 data to assess transpiration at peak air temperatures, and the 18:00 data to assess transpiration in the evening when rates were declining.

Each of the three models used taxa and block as random effects. Fixed effects were air temperature (AT), squared expression of air temp (AT^2), relative humidity (RH), soil temperature (ST), year (YR - 2 levels, 2021 and 2022), wind speed (WS), radiation (RAD) and a squared expression of radiation (RAD^2). The squared expressions were included because of the non-linear relationship between AT and RAD and sap flux and including a squared relationship of these parameters improved the model fit.

All predictors were standardised before the model fit, thus all variables had a mean of zero and a standard deviation of one. Standardisation was applied to make effect sizes comparable among variables with different units. After inspection of the residual

distributions of each parameter, RH was transformed by calculating the arcsine of the mean. This transformation avoids that a single observation has too much influence on the result (Stahel, 2002). However, we show the effect plots with the raw data for an easier interpretation of the results (Figure 1).

For the predictive model check, Shinystan (Stan Development Team, 2017) was used and thereby, standard deviation and the mean, min and max of the data were compared with those statistics in replicated data from the model. Using the posterior distribution from the “brms” package, predictive plots were generated to show how the average sap flux changed with a specific meteorological driver (relative humidity, solar radiation and temperature), while all other variables in the model were held constant (Figure 1).

3 Results

3.1 Meteorological variables

Overall, the growing season (May–October) was warmer and drier in 2022 than in 2021 (Supplementary Table A5). July had an average daily maximum air temperature of 22.8°C in 2021, compared to 25.5°C in 2022. Total rainfall at the experimental site in July 2021 was 92.4 mm, and only 7.6 mm in 2022. At 08:00, the VPD did not surpass 1.9 kPa during July for either year, while at 13:00 it reached 4.9 kPa and at 18:00, 3.9 kPa (both during the second year). The highest air temperatures were generally recorded after midday and reached a maximum of 37.1°C on one occasion at 13:00 in July 2022, while corresponding radiation was $1,019.0 \text{ W m}^{-2}$. The morning (08:00) and evening (18:00)

TABLE 2 Standardised model coefficients and confidence intervals (CI) for the environmental drivers at three different time periods: 08:00, 13:00 and 18:00 (average of July 2021 and July 2022 data for all tested taxa).

Time	08:00 (CI)	13:00 (CI)	18:00 (CI)
Air temp	1.0 (0.7–1.2)	1.0 (0.6–1.2)	1.2 (0.8–1.6)
Air temp ²	–0.2 (–0.3––1.0)	–0.6 (–0.7––0.4)	–0.5 (–0.7––0.4)
RH	–4.3 (–5.2––3.3)	–8.7 (–10.4––7.2)	–4.1 (–5.7––2.5)
Soil temp	–0.3 (–0.5––0.1)	0.1 (–0.2–0.4)	–0.2 (–0.5–0.0)
Wind speed	0.0 (–0.1–0.1)	0.2 (0.1–0.3)	0.3 (0.2–0.4)
Radiation	2.2 (1.6–2.9)	1.5 (0.8–2.2)	1.9 (1.5–2.3)
Radiation ²	–0.9 (–1.5––0.4)	–0.4 (–0.6––0.2)	–1.3 (–1.8––0.9)

Standardised coefficients represent transformed values, to better fit the model. Values in bold represent environmental factors having a significant effect on the sap flux value at each time-interval investigated.

TABLE 3 Taxa-specific deviation from the average sap flux across all studied taxa, at 08:00, 13:00 and 18:00 with confidence intervals in brackets.

Taxa	Intercept (CI)		
	08:00	13:00	18:00
<i>Crataegus</i>	2.5 (0.2–5.1)	3.3 (0.3–6.9)	5.4 (2.5–8.7)
<i>Cupressus</i>	–3.8 (–6.1––1.6)	–0.2 (–2.9–2.7)	0.2 (–2.3–2.8)
<i>Ilex</i>	–2.0 (–4.3–0.4)	0.8 (–2.1–3.9)	0.7 (–2.0–3.5)
<i>Magnolia</i>	1.5 (–0.8–4.0)	–0.8 (–3.6–2.0)	–0.8 (–3.5–1.8)
<i>Malus</i>	4.7 (2.5–7.2)	0.5 (–2.6–3.3)	–0.6 (–3.2–2.1)
<i>Picea</i>	–4.9 (–7.2––2.6)	–5.8 (–9.4––2.8)	–6.8 (–9.8––4.0)
<i>Prunus</i>	0.1 (–2.3–2.4)	–0.5 (–3.7–2.3)	–0.2 (–2.7–2.3)
<i>Pyrus</i>	2.4 (0.2–4.6)	2.6 (–0.01–5.6)	1.6 (–0.9–4.1)
<i>Sorbus</i>	0.2 (–2.2–2.6)	0.6 (–2.2–3)	1.2 (–1.4–3.9)

Statistically significant values and the direction of the significance are in bold.

radiation averaged 404 W m^{–2} and 429 W m^{–2} respectively. Wind speed was routinely highest in the afternoons. Mornings had the highest minimum RH (78.7% in 2021, 48.5% in 2022) compared to a minimum of 22.7% at 13:00% and 26.0% at 18:00. Correspondingly, mean sap flux across taxa reached 18.6, 24.4 and 19.4 cm³ cm^{–2} h^{–1} at 8:00, 13:00 and 18:00, respectively; highest transpiration across taxa was found at 13:00, when air temperature, RH and radiation were highest (Supplementary Figure A1; Supplementary Table A5).

3.2 Sap flux and environmental drivers

Low relative humidity was the strongest driver for sap flux across taxa and time of day, and the effect was double as high at 13:00 compared to morning and evening (Table 2). Air temperature and radiation had an increasing effect on sap flux up to a threshold, beyond which sap flux plateaued, although this threshold depended on the time of day and taxa (Figure 1; Tables 2, 3).

Across both years, at 08:00, *Malus*, *Crataegus* and *Pyrus*, respectively, had significantly higher sap flux rates than the remaining taxa, while *Cupressus* and *Picea* had significantly lower sap flux rate than the

remaining taxa (Table 3; Figures 1, 2). An increase in radiation had a smaller effect on the sap flux of *Cupressus*, *Ilex* and *Picea*, respectively, and a greater effect on the sap flux of *Malus* and *Pyrus* (Supplementary Table A2). At 13:00 and 18:00, only *Crataegus* and *Picea* significantly deviated from the mean sap flux in opposite directions; *Crataegus* transpiring more than the average, and *Picea* transpiring less (Supplementary Figure A2; Supplementary Tables A3, 4).

At 08:00, all other drivers being equal, the rise in air temperature had a smaller effect on *Cupressus* and *Picea* compared to remaining taxa (Supplementary Figure A1; Supplementary Table A2). In the morning, sap flux of *Malus* and *Magnolia* started to plateau at air temperatures above 25°C, while the rest of the taxa kept increasing their sap flux in response to increases in air temperature at this hour (Figure 1; Table 4). An increase in RH decreased sap flux across taxa, although it had a smaller effect on *Cupressus* and *Picea*, and a greater effect on *Malus* at 8:00 and *Crataegus* at 18:00 (Supplementary Tables A2, 3).

At 13:00, peak sap flux occurred for eight of the nine taxa when air temperatures were between 28°C–30°C (Figure 1; Table 4). Only *Prunus* had peak sap flux at a higher temperature (around 35°C, but with no upper limit detected, Table 4). At 13:00, radiation had a slightly stronger increasing effect on *Prunus* and a slightly smaller effect on *Cupressus* (Supplementary Figure A1; Supplementary Table A3).

Air temperature that corresponded to maximum sap flux was higher in the evening than at midday, averaging 33°C at 18:00, with no upper limit detected across taxa, and with no significant differences detected between taxa (Figure 1; Table 4). An increase in RH however, had a stronger negative effect on the sap flux of *Crataegus*, which had the highest transpiration at this hour, and a less negative effect on *Picea*, with lowest transpiration at this hour (Supplementary Figures A1, 2; Supplementary Table A4). The effect of the wind speed or “year” was not assessed for individual taxa, as no general difference was traced for these variables.

3.3 Total transpiration and cooling potential

Scaling up sap flux density to whole-tree transpiration (L tree^{–1}), the taxon with the highest water-use alternated throughout the month both years (Figures 3, 4). In 2021, *Prunus* had the highest daily water-use average (1.6 L), *Crataegus* 2nd (1.5 L) and *Pyrus* 3rd (1.2 L). In 2022, *Pyrus* had the highest water-use with a daily average of 3.7 L, *Prunus* 2nd (3.5 L) and *Malus* 3rd (3.1 L). In 2021, *Magnolia*

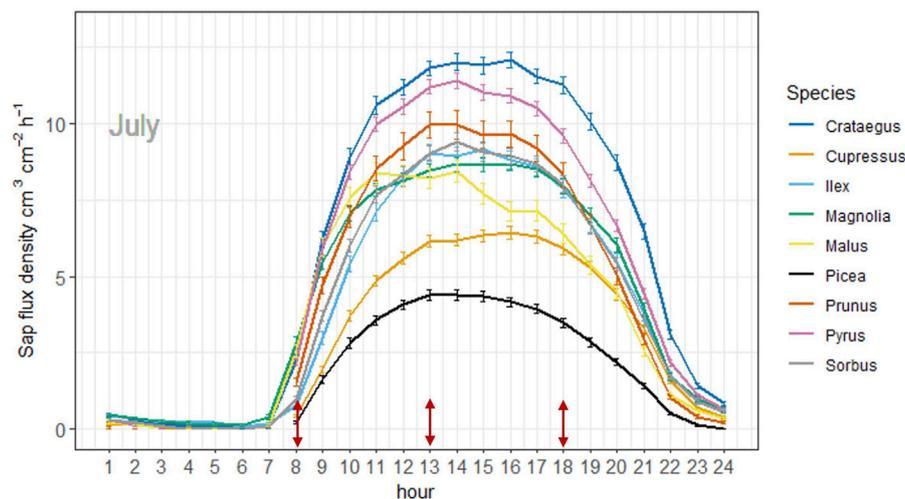


FIGURE 2
Hourly sap flux ($\text{cm}^3 \text{cm}^{-2} \text{h}^{-1}$) for July 2021 and 2022. Each line represents the average of 2–4 replicates of each taxon. Red arrows indicate the hours that were selected for the model outputs.

TABLE 4 Modelled values (and confidence intervals) of air temperature and relative humidity corresponding to maximum sap flux levels for each taxon at 8:00, 13:00 and 18:00.

	Temp ($^{\circ}\text{C}$)	RH (%)	Temp ($^{\circ}\text{C}$)	RH (%)	Temp ($^{\circ}\text{C}$)	RH (%)
	8:00		13:00		18:00	
<i>Crataegus</i>	29.6 (25.4-x)	66 (42–85)	28.9 (26.2–32.6)	10 (0–38)	31.9 (28.6-x)	44 (2–92)
<i>Cupressus</i>	31.6 (25.3-x)	95 (84–100)	28.4 (26.0–30.8)	13 (0–40)	31.6 (28.5-x)	81 (48–100)
<i>Ilex</i>	—	83 (63–96)	28.5 (26.1–31.2)	10 (0–36)	33.3 (29.8-x)	75 (34–100)
<i>Magnolia</i>	25.5 (23.4–28.2)	73 (52–90)	28.9 (26.0–31.7)	26 (2–64)	34.9 (29.9-x)	95 (76–100)
<i>Malus</i>	25.5 (23.5–27.9)	54 (32–74)	28.8 (24.0–31.8)	29 (2–69)	34.9 (29.0-x)	94 (72–100)
<i>Picea</i>	—	96 (87–100)	29.6 (28.3–34.1)	63 (17–98)	33.5 (25.9-x)	78 (36–100)
<i>Prunus</i>	—	82 (65–95)	34.8 (26.8-x)	37 (6–77)	32.3 (28.8-x)	94 (74–100)
<i>Pyrus</i>	—	64 (44–81)	29.3 (26.8–32.3)	9 (0–34)	33.0 (29.4-x)	85 (57–100)
<i>Sorbus</i>	—	70 (50–87)	28.6 (26.0–31.4)	15 (0–49)	31.8 (28.8-x)	73 (34–100)

Data were taken from both July 2021 and 2022. Where a maximum value estimated by the model was outside of the range of values observed, the value has been replaced with an x. Because no “maximum” value of radiation was found within the observed values at 13:00, radiation was excluded from the table.

had the lowest water-use (0.4 L), while the second year both *Ilex* and *Picea* had the lowest of 1.1 L (Table 5). *Cupressus* however, had by far the highest water-use per crown area (5.4 L m^{-2}) second by *Pyrus* (2.4 L m^{-2}), and consequently *Cupressus* had the highest transpirational cooling effect (Figure 7). Due to its compact shape, *Ilex* was the next most effective at cooling, while *Pyrus* also had a large cooling effect, due to a combination of a high water-use and a compact canopy shape (Figures 6, 7).

3.4 Woody biomass and crown volume

3.4.1 Woody biomass

In terms of woody biomass (stem and primary branches), most of the trees more than doubled in size from June 2021 to

November 2022, while *Magnolia* nearly quadrupled in size and *Sorbus* tripled (Figure 5). *Crataegus* and *Malus* put on the least woody growth relative to size, with a 76% and 66% increase, respectively. Before the first growing season, *Crataegus*, *Malus*, *Prunus* and *Pyrus* were the largest trees in terms of woody biomass, with *Sorbus* and *Cupressus* in the middle, while *Ilex* and *Magnolia* were smallest (Figure 5). The growth rate mostly mirrored the size of the trees in November 2022, with the largest difference from the first measurement being that both *Crataegus* and *Malus* had dropped from the largest category to the medium, being outgrown by *Prunus*, *Pyrus* and *Sorbus* (Figure 6). In 2021, *Prunus* and *Pyrus* had the largest sapwood area (15.9 and 16.0 cm^2 , respectively), with *Ilex* and *Magnolia* having the smallest (5.1 and 5.3 cm^2 , respectively). In 2022, *Prunus* was slightly bigger than *Pyrus* (23.3 and 22.2 cm^2 , respectively) and

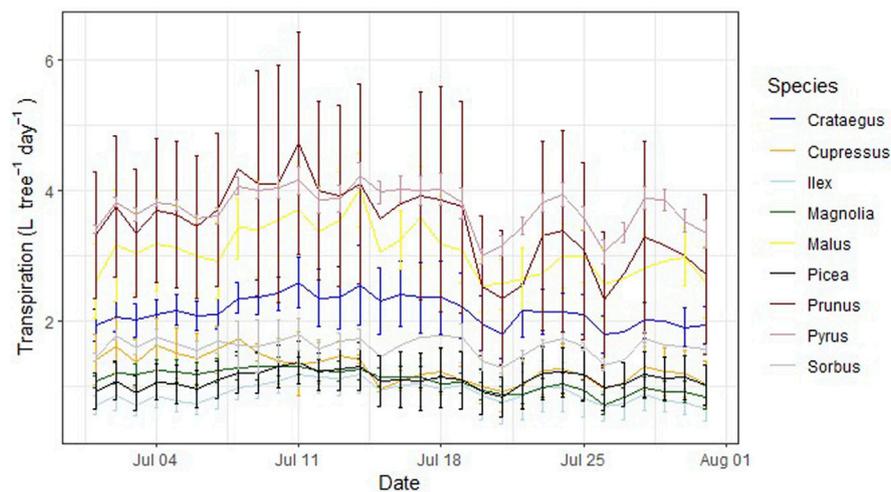


FIGURE 3
Daily transpiration volumes for each taxon, during July 2021. Each line represents the average of hourly values of the three trees per taxon.

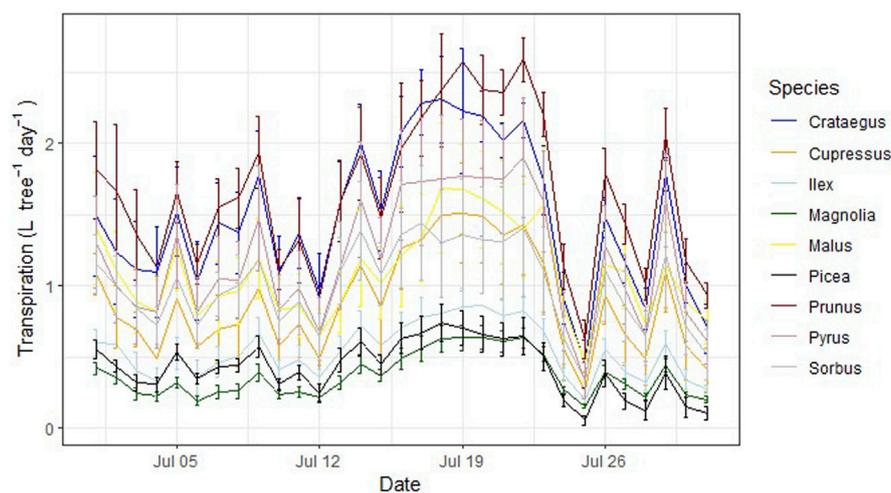


FIGURE 4
Daily transpiration volumes for each taxon, during July 2022. Each line represents the average of hourly values of three trees per taxon, with associated standard errors.

Magnolia had surpassed *Ilex* (9.9 and 7.3 cm² respectively, [Supplementary Table A6](#)).

3.4.2 Crown size

Mean crown volume across taxa doubled from June 2021 to June 2022 ([Figure 5](#)). In 2021, *Prunus* had the largest crown volume, followed by *Malus* and *Crataegus*, with *Cupressus*, *Ilex* and *Picea* having the smallest canopies ([Figure 5](#)). From 2021 to 2022, *Sorbus* had the largest relative growth (236% increase), while *Crataegus* had the smallest growth increase of 60%, displaying a similar trend from the woody biomass volume ([Figures 5, 6](#)). However, *Malus*, together with *Magnolia*, had the second largest growth relative to size (134% increase), while canopies of *Prunus*, *Malus* and *Crataegus* were in 2022 of similar size. Projected crown area reflected a similar order to crown volume ([Table 5](#)).

4 Discussion

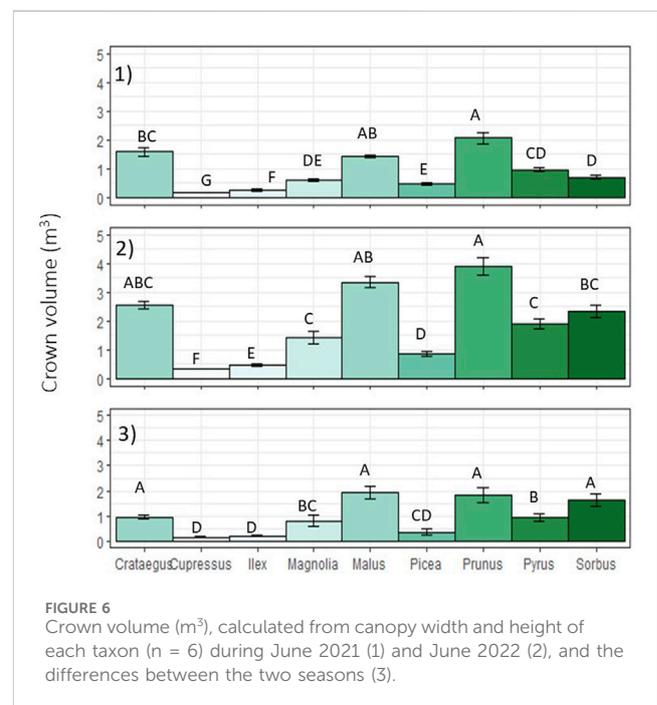
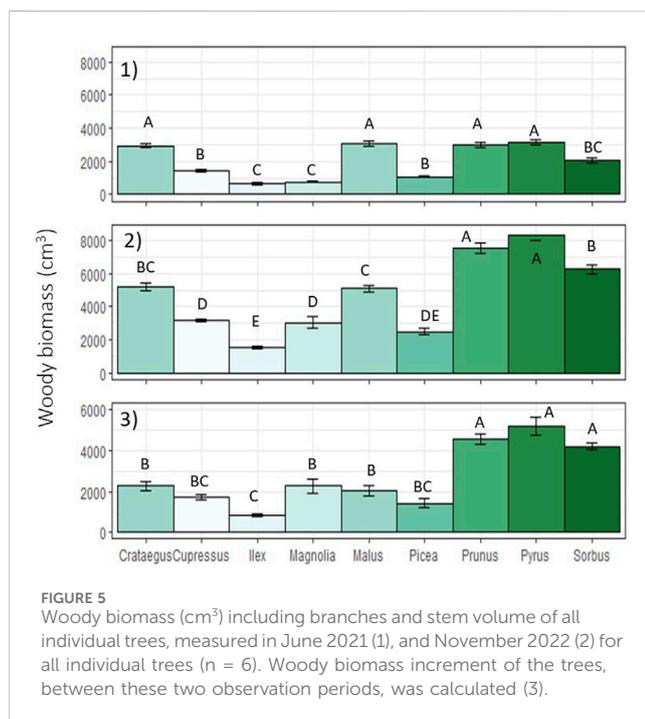
4.1 Meteorological drivers of sap flux

In general, sap flux densities were higher in July 2022 compared to July 2021, due to 2022 being both warmer and drier, and consequently exhibiting higher VPDs. Sap flux response to environmental drivers differed significantly between taxa and time of day, resulting in differences in water-use and transpirational cooling effect ([Table 5](#); [Figure 7](#)). Overall, the differences in sap flux response between taxa were greatest in the morning; when *Malus*, *Crataegus* and *Pyrus*, had a higher sap flux rate than the average, and *Cupressus* and *Picea* lower ([Table 3](#)). Although *Malus* had the highest sap flux density at 8:00, it also had the steepest decrease in response to peak-air temperatures and

TABLE 5 Daily average of total volume of transpiration in July 2021 and 2022.

	Volume (L)		Crown area (m ²)		Volume/Crown area (L m ⁻²)	
	2021	2022	2021	2022	2021	2022
<i>Crataegus</i>	1.5	2.2	1.9	2.8	0.8	0.8
<i>Cupressus</i>	0.9	1.3	0.1	0.2	6.7	5.4
<i>Ilex</i>	0.5	1.0	0.7	1.0	0.8	0.9
<i>Magnolia</i>	0.4	1.1	0.6	1.1	0.6	1.0
<i>Malus</i>	1.1	3.1	1.7	3.3	0.6	0.9
<i>Picea</i>	0.4	1.1	0.7	1.1	0.6	1.0
<i>Prunus</i>	1.6	3.5	2.3	3.8	0.7	0.9
<i>Pyrus</i>	1.2	3.7	1.0	1.6	1.2	2.4
<i>Sorbus</i>	1.0	1.6	1.1	2.6	0.9	0.6

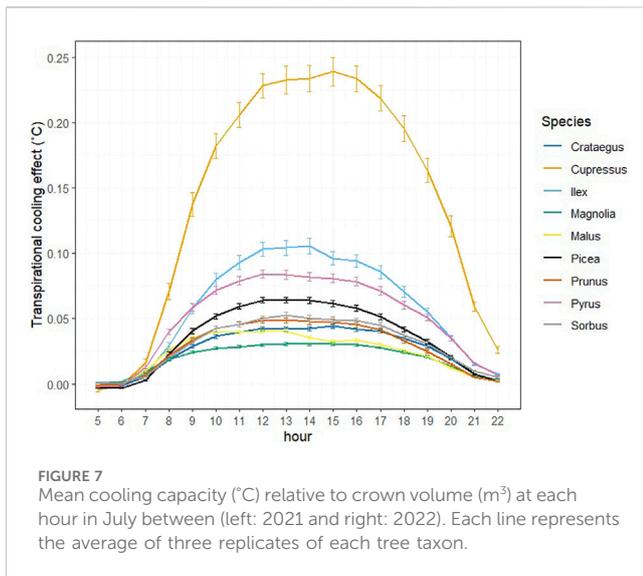
Volumes are based on hourly sap flux values between 05:00 and 22:00 (n = 2–4). Values of projected crown area is an average of all six replicates on the plot (m²).



increasing RH at this hour. This may be associated with its darker scarlet leaf colour (Supplementary Figure A2), leading to overheating of the leaf surface and a closing of stomata to prevent excessive water loss. Leaf colour or leaf lightness is linked to the leaves' reflectance, with a darker leaf colour decreasing short-wave reflectance, and therefore increasing temperature, while the opposite is true for a lighter colour (Ferguson et al., 1973; Vaz Monteiro et al., 2016). *Malus* also had the steepest increase in sap flux in response to solar radiation in the morning, a trait that could be important for soil moisture reduction, with this taxon effectively utilising spells of sunshine between rainfall, common in the temperate climate of the UK. This taxon can arguably grow well in most conditions in the UK; effectively

using radiation when available, while reducing water-use during peak-temperatures. However, a cultivar with similar habit, but greener/more lightly coloured leaves would be better suited for warm urban areas avoiding inhibition of photosynthetic efficiency (and consequent reduction in growth) due to overheating.

In addition to *Malus*, *Crataegus* had the strongest response in sap flux to a change in RH and air temperature. This strong response translated into high water-use during favourable conditions, effective removal of soil moisture and higher transpirational cooling, while reducing water-loss during peak-temperatures. Neither *Crataegus* nor *Malus* had the largest woody biomass accumulation, but were superseded in these characteristics by *Prunus*, *Pyrus* and *Sorbus* (Figure 5). Due to the higher woody



growth rates, and consequently larger sapwood areas, both *Pyrus* and *Prunus* had higher total transpiration volumes than *Crataegus* and *Malus*, with *Pyrus* having a higher transpirational cooling potential (Figures 3, 4, 7). However, the large crown volume of *Malus*, show that this taxon put their resources into growing the crown rather than the main stem, with a large crown being key for cooling through shading.

In the afternoon and evening, wind speed was generally higher than in the morning and was positively correlated with sap flux. In the morning, with wind speed averaging $<2.5 \text{ m s}^{-1}$, no effect was detected on sap flux rates, demonstrating that the effect of wind was only relevant at higher speeds (Tables 2). This could be important under future climates, with an expected increase in storms and higher average windspeeds. However, no difference was found in how the sap flux of the taxa fluctuated with the wind but rather needs to be seen together with other environmental drivers, as having an additional increasing effect on sap flux when values reach $3\text{--}4 \text{ m s}^{-1}$ (Supplementary Tables A2, 5).

4.2 Transpirational cooling

In temperate regions, cooling through transpiration has been estimated to have a significant impact on human thermal comfort (Leuzinger et al., 2010; Zou and Zhang, 2021). *Cupressus* had the highest transpirational cooling effect relative to size (Figure 7). This was due to *Cupressus* having a very narrow canopy shape (Figure 5), however sap flux density of *Cupressus* was lower than the deciduous taxa (Figure 2). In addition, there was a smaller change in sap flux for *Cupressus* and *Picea* in response to increases in air temperature, decreases in RH and increases in radiation, compared to the rest of the taxa. This could be due to the characteristics of scale- and needle-leaves: sunken stomata and a tough leaf surface, which gives a stronger protection from the surrounding environment and, to some extent, reduced water loss (Hirons and Thomas, 2018). This could put these taxa at a disadvantage when attempting to respond to low and changeable levels of solar radiation (Davies et al., 2009; Goddard et al., 2010). Together with *Ilex*, *Pyrus* also showed a high

transpirational cooling potential, from the combination of high sap flux and a compact crown shape (Figures 2, 7). *Pyrus* would be a more efficient choice due to having a larger canopy, which could also provide more direct shading than *Cupressus* and *Ilex* (Figure 5). *Pyrus calleryana* ‘Chanticleer’, grows to be a relatively larger garden tree (12 m high and 4–8 m wide) (RHS, *Pyrus*, 2025a), compared for instance to *Ilex* ‘J.C. van Tol’, which is estimated to grow to 4–8 m height (2.5–4 m wide) (RHS, *Ilex*, 2025b), and *Cupressus*, also estimated to grow 12 m high, but as with the *Ilex*, only 2.5–4 m wide (RHS, *Cupressus*, 2025c). This is important in a garden setting, as *Ilex* would fit into smaller places, and would be an efficient cooler relative to size (Figure 7). *Ilex* had the smallest stature and lowest growth rate of all the taxa, so a high sap flux rate was somewhat unexpected. However, it is well adapted to a temperate climate and due to its evergreen nature would be a fitting plant choice for smaller gardens, where a less vigorous, but high water-using species is sought.

The second year of the study included a period of unusually high temperatures (4 days of maximum air temperatures above 30°C), providing insight into the water use of each species under heat events expected to become more frequent in the future (IPCC, 2023). At 13:00, *Crataegus*, *Cupressus*, *Ilex*, *Magnolia*, *Malus* and *Sorbus*, all had their peak transpiration rate when ambient temperature was around 29°C . For *Picea* and *Pyrus* it was around 30°C , and for *Prunus* 35°C . While in the evening, peak sap flux of all taxa except *Prunus*, corresponded to a higher air temperature than in the daytime. This is likely due to less evaporative demand together with lower light intensity in the evening, allowing for less stomatal control of water loss than during the day (Moore et al., 2021). This is relevant in an urban context, due to the urban heat island (UHI) effect, which is particularly prevalent in the evening and into the night, when built-up structures store more heat from the sun than green infrastructure. Trees, in this context, can make an important contribution to ambient cooling.

Rahman et al. (2014) compared transpirational cooling potential of five commonly planted tree species and found it driven by both species’ growth rates and stress tolerance. Similarly, Leuzinger et al. (2010), found species-specific cooling differences, with trees with cooler canopies having a higher cooling effect. Due to increased shortwave and longwave radiation from the urban fabric, trees in urban environments are particularly exposed to heat stress (Leuzinger et al., 2010; Stanley et al., 2019). It is therefore important to monitor trees’ responses to high temperatures to understand how they might affect trees’ capacity to cool and to what extent careful planting choices might help. In addition, due to the UHI effect, evaporative demand is likely to increase, leading to greater water requirements and this may be a problem in an urban context where soil water deficit is a common problem, and it will in return constrain transpiration and growth of urban trees (Bialecki et al., 2018). Previous studies have shown how the cooling effect of *P. calleryana* was severely reduced by urban stressors such as soil compaction (Rahman et al., 2014; Rahman et al., 2015). In our study, *P. calleryana* ‘Chanticleer’ had an increasing sap flux rate under high air temperatures in the morning and evening, while at 13:00, it peaked around 30°C , demonstrating a capacity to reduce water-loss under high temperatures and high evaporative demand. This would lead to a reduction of cooling capacity, but also a better strategy to avoid dehydration and to grow in areas prone to soil drought.

Richter et al. (2022) found that the most water-conservative species in their study, *Quercus robur* and *Acer pseudoplatanus*, had the largest reduction in sap flux during a decline in soil moisture compared to the non-conservative *Fraxinus excelsior*. In our study, *Prunus* 'Fugenzo' is an example of a non-conservative taxon which, when soil moisture is abundant, did not reduce sap flux values under high evaporative demand. Rahman et al. (2020) found that the *Tilia cordata*, with high water use, was more efficient at cooling asphalt-covered ground, where evapotranspiration from grass was absent, compared to the more conservative but water-use-efficient *R. pseudoacacia*. Over grass surfaces however, the *R. pseudoacacia* had a better cooling potential, possibly due to the grass absorbing more of the latent heat. Thus, the optimum species for cooling potential also depends on the surface under/around it and the type of soil/substrate which they are planted in. The capacity of a tree to regulate air temperature through transpiration is often restricted during water-limited periods, which frequently correspond with when cooling is most needed, i.e., during summer months. Trees which are most likely to be able to provide any cooling service are trees which will grow well under hot conditions and exhibit a less conservative regulation of the stomata (Buckley, 2005; Pataki and Oren, 2003). An example of such taxon in our study is the *Prunus* 'Fugenzo'. However, this is only true if the water stress is not too severe, i.e., causing irreversible damage to the plant. Instead, we would recommend trees with high water-use rate under favourable conditions (such as *Crataegus* 'Prunifolia Splendens' in our study), which can regulate water-use during peak temperatures in the day.

4.3 Wider context of garden trees' planting

Our work considers the context of 1. Climate changing and (peri)urban areas (where most people now live, globally) being warmer and suffering with other associated environmental concerns; 2. Green areas, and particularly trees within them being able to alleviate some of those issues; 3. Decreasing green areas due to pressure from development (certainly the case for domestic gardens in the UK). Hence this quest for trees that fit into those smaller green areas, while being more "efficient" in the delivery of services, and being well-matched to the local environmental conditions. From the synergy of having plants which excel in service delivery in the weather conditions they most often experience, a greater level of overall benefit is gained by all occupants of that space.

Design of green spaces and domestic gardens will always, in large part, be driven by non-horticultural factors such people's preferences for certain species/cultivars, shapes, smells and colours (Patino et al., 2023). Increasingly, however, the consideration of a chosen plant's environmental impact (such as the capacity to cool or increase air quality), along with the environmental conditions a plant can grow in, is also part of the decision-making process (Tomatis et al., 2023).

The focus of this paper was on understanding the cooling potential of small garden trees, by monitoring sap flux and canopy characteristics, and on their capacity for carbon drawdown and storage by monitoring growth over time. While outside of the scope of this paper, we acknowledge the contribution

of other services these trees are providing (e.g., the ability to capture pollution, provide habitat and food sources for wildlife; Steinparzer et al., 2023).

4.4 Experimental limitations and other considerations

Sap flow measurements are prone to some uncertainties when it comes to scaling up to absolute tree transpiration volume (Larsen et al., 2020); radial differences of sap flow rates within the sapwood and seasonal differences of wood-water content were not accounted for when scaling up. Instead, these parameters were measured once for minimum intrusiveness (i.e., to minimise drilling of wood cores and limiting installation of probes into the sapwood). However, due to the age and uniformness of the individual trees within a taxon, we are confident that the relationship between meteorological drivers and sap flux densities, and consequently trees' transpirational cooling potential, are well represented in our study although uncertainties remain with the total volumes of water demand. Although the trees were kept under optimal conditions, further studies in a wider context (i.e., other soil conditions, trees planted in the ground, etc.) would help to understand if these water-use trends would be the same under different conditions.

5 Conclusion

Overall, *Malus* 'Scarlett' had the highest sap flux density in the mornings, while *Crataegus* 'Prunifolia Splendens' averaged the highest sap flux density during daytimes and evenings. In addition, *Malus* displayed large crown volume growth which would provide shading. Both taxa would be suitable garden trees to provide soil moisture reduction in smaller gardens during the growing season, but particularly *Crataegus* 'Prunifolia Splendens', having the highest sap flux for a longer period during the day (Figures 1, 2). For woody growth, and associated carbon sequestration however, they were not the most efficient taxon in the study.

Pyrus calleryana 'Chanticleer' had the largest growth of woody biomass and consequently carbon sequestration. It also had the largest total transpiration and was the third most efficient cooler. However, because it is a relatively large tree in a garden context, it might not be suitable in smaller spaces and has been used more in street planting.

Prunus 'Fugenzo' continued to increase its transpiration rate in response to the highest ambient temperature at 13:00, with no indication of a plateauing of sap flux during peak-temperature. Therefore, it could lead to excessive water loss where soil water is limited and would not be recommended in areas prone to soil moisture deficit. If soil moisture was not limiting it would however be providing transpirational cooling under rising temperatures.

Taxa with smaller canopies in combination with high water demand provided the most transpirational cooling relative to size, such as *Cupressus*, *Ilex* and *Pyrus* in this study. This demonstrates how 'the bigger the better' is not necessarily the case for

transpirational cooling. Rather, the ratio between sapwood and crown volume in combination with water demand, might be a better indicator of transpirational cooling efficiency.

Our work highlights multiple options of trees suitable to provide ecosystem services for small garden spaces, as well as which traits, exemplified by specific taxa, might not be suitable in certain environments. It highlights the importance of considering the prevalent diurnal weather and climatic context of the garden, not just to enable tree survival and growth, but also to maximise what we can gain from trees environmentally.

Data availability statement

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

Author contributions

EL: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review and editing. TB: Conceptualization, Resources, Supervision, Writing – original draft, Writing – review and editing. RT: Investigation, Writing – review and editing. JB: Investigation, Writing – review and editing. ND: Conceptualization, Funding acquisition, Investigation, Writing – review and editing. MG: Conceptualization, Funding acquisition, Investigation, Resources, Writing – original draft, Writing – review and editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. We would like to thank Frank P. Matthews and the RHS for funding this project, and Alistair Griffiths for seeking out the funding.

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Acknowledgments

We would like thank Paul Mealey for expert irrigation help, Rebekah Mealey for her expertise on growing nursery trees and Andy Hiron for valuable advisory input and a loan of sap flow sensors. We would like to extend thanks to RHS colleagues who have contributed valuable feedback over various stages of this project.

We thank Jordan Bilsborrow for taxa namechecking. We are grateful to Fränzi Korner at Oikostat for assistance with statistical analyses.

Conflict of interest

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

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2025.1515809/full#supplementary-material>

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