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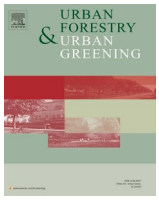

Interactions between management context and tree water use influence stormwater management potential of urban forests

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ABSTRACT

Urban trees can reduce stormwater runoff and mitigate flood risk by increasing infiltration, and storing water in the soil, while reducing nutrient loading, and improving water quality in developed areas. Tree water use can constitute a major component of evapotranspiration, but knowledge gaps about how the local environment affects transpiration limits our ability to predict how management will affect hydrology. In this study, we investigated the influence of management context on the transpiration of deciduous tree species and the relationship between environmental factors (soil moisture and vapor pressure deficit) and tree transpiration. We monitored sap flux rates of three common urban tree species, red maple, tulip poplar, and sweetgum (n=41 trees), during the 2018 and 2019 growing seasons in urban forest patches in Baltimore, MD, in addition to a cluster of trees over turfgrass and single trees over turfgrass in Montgomery County, MD. Management context influenced sap flux and, on a per-tree basis, single red maple trees had greater transpiration than red maple trees in a closed canopy setting in both years. The mean daily sum of sap flux density (*Js*) was 227, 163, and 87.5 g $cm^{-2}d^{-1}$ at the single, cluster, and closed canopy sites, respectively, for red maple trees, with some interannual variability primarily driven by weather conditions. Although *Js* was fairly similar across species in closed canopy conditions throughout the two growing seasons, species differences in sap flux density were observed at the diel (24-h) time scale with tulip poplar being the most sensitive to drought. We also developed whole-tree water use estimates based on DBH, species, and management context. Whole-tree water use varied directly with diameter. Plot-level water use through transpiration was 9.1, 71.2, and 52.4% of precipitation during April-October 2019 in the single, cluster, and closed canopy sites, respectively. These results provide an initial framework for estimating how urban forest management affects the hydrological balance, with useful implications for stormwater managers and modelers.

1. Introduction

Trees in urban environments can reduce stormwater runoff, mitigate the risk of flooding, increase infiltration and water storage capacity in the soil, reduce nutrient loading, and improve water quality (Kuehler et al., 2017). Rainfall partitioning by urban trees depends upon rates of canopy interception, soil infiltration, soil surface evaporation, and transpiration (Berland et al., 2017). Based on an urban water cycle model, evapotranspiration was the largest output (81% of 510 mm rainfall per year) of an urban water balance (Cleugh et al., 2005). Trees further reduce stormwater runoff by increasing infiltration through their roots' influence on water storage and soil structure. For example, urban forest patches in Baltimore, MD could infiltrate 68% of rainfall events (Phillips et al., 2019). In the context of stormwater management, through the process of transpiration, water stored in the soil moves through the tree to the atmosphere and increases soil pore space availability for future storm events. Indeed, tree planting can reduce runoff (Zabret and Šraj, 2019), while street tree removal will increase stormwater runoff (Selbig et al., 2022). However, transpiration rates and whole tree water use and their impacts on stormwater runoff can vary widely, depending on various tree characteristics, including tree species, stem size and leaf area, as well as management context and climate

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factors (Ponte et al., 2021; USDA Forest Service, 2020).

Tree water use can be influenced by various tree characteristics, such as species or hardwood anatomy regarding vessel arrangement (e.g., diffuse-porous and ring-porous). For example, among common tree species in the eastern U.S., tulip poplars (*Liriodendron tulipifera* L.) were shown to have higher transpiration rates than chestnut oaks and northern red oaks (Ford et al., 2011). Species differences in urban settings result in a range of magnitudes of hydrologic impacts, with interception rates varying 2-fold across parks in Ljubljana, Slovenia (Zabret and Šraj, 2019). In an urban park setting in the southeastern US, species impacts on hydrology were due to phenological differences between species (Howard et al., 2022). Diffuse-porous trees (e.g., red maple and tulip poplar) normally have higher transpiration rates than ring-porous species (e.g., oak) (Ford et al., 2011; USDA Forest Service, 2020). For instance, red maple had the highest sap flow rates when compared to oak trees in a deciduous forest (Wullschleger et al., 2001). On the other hand, sapwood area has been shown to be a more significant driver of tree transpiration than species-specific differences (Wullschleger et al., 2001).

The effects of trees in the urban hydrological cycle also depend on interactions between local climate and forest composition and structure. Physical and biological factors influencing tree transpiration interact with climatic variables (e.g., air temperature, humidity, soil moisture). Vapor pressure deficit (VPD), which is estimated based on air temperature and relative humidity, is a major environmental driver of tree transpiration as it regulates stomatal conductance (Chen et al., 2011; Oogathoo et al., 2020; Rodríguez-Gamir et al., 2016; Rogiers et al., 2011; Tirpak et al., 2018). Leaf-level transpiration and stomatal conductance for tulip poplar and white pine trees have been shown to be more responsive to VPD variation than oak and hickory trees due to differences in xylem anatomy (Ford et al., 2011). Tree root distribution can vary widely among species and trees with deeper roots are able to access deeper and more stable water sources of water and be less responsive to seasonal drought (Ford et al., 2008). At a watershed level, these species differences may affect drought sensitivity of a forest stand and, consequently, impact streamflow (Ford et al., 2011).

Urban environments are highly complex and heterogeneous. Management context, referring to urban landscape characteristics and tree configuration, may affect hydrological processes in cities (Law and Hanson, 2016; Pataki et al. 2011; Ponte et al. 2021). For instance, sycamore street trees in Los Angeles, CA had higher rates of sap flux than sycamore trees in irrigated and unmanaged forest sites due to differences in response to VPD and in nutrient availability in the soil (McCarthy and Pataki, 2010). Additionally, isolated red maple street trees experienced a greater daily sum of sap flux density (*Js*) than individuals within a closed canopy (Ponte et al., 2021). The complex and heterogeneous urban landscape therefore can have important influences on the hydrological functions of urban trees.

Although much is known about tree hydrologic processes, especially in natural and plantation forests, knowledge gaps remain with respect to how urban trees contribute to the water cycle via rainfall interception, absorbing stormwater, and through transpiration. This information is needed to efficiently promote their use as a stormwater management tool (Kuehler et al., 2017). The interactions among microclimate, management context, and species-specific characteristics drive variability which has implications for evaluating and quantifying the influence of urban forests on the hydrological cycle. Here, we define management context as different urban tree configurations (e.g., stem density and canopy structure) within the surrounding landscape (Ponte et al., 2021). The main objectives of this study were to quantify water use among several tree species commonly found in eastern US cities, accounting for factors relating to management context and climate, and to upscale total offsets in precipitation by tree transpiration within several urban settings. To accomplish these objectives, we asked the following research questions: (1) How do transpiration rates and whole-tree water use vary among species and management context, specifically closed canopy urban forest stands, small clusters of trees, and isolated individual trees? (2) How do transpiration rates respond to soil moisture and vapor pressure deficit across tree species? (3) What proportion of precipitation is transpired from urban forest plots with different management contexts? These results provide quantitative information on the contribution of tree transpiration in different management contexts to the urban hydrologic budget to assist management decision making.

2. Materials and methods

2.1. Study sites

We monitored sap flux density for a total of 41 trees: five red maple (*Acer rubrum* L.), sixteen tulip poplar *(Liriodendron tulipifera* L.), and ten sweetgum (*Liquidambar styraciflua* L.) trees over two growing seasons. Red maple, sweetgum, and tulip poplar were chosen as the focal species for this study because they are commonly found tree species in urban areas throughout the eastern US. Field sites were located at Asbury Methodist Village, a retirement community in Gaithersburg, MD (39°08'59.5"N, 77°11'44.8"W) and at the Maryland School for the Blind in Baltimore, MD (39°21'59.7"N, 76°32'06.7"W) (Fig. 1). At Asbury Methodist Village, sap flux was measured from trees in a cluster of red maple (n=5) and sweetgum (n=5) trees over turfgrass, and single red maple trees over turfgrass along the sidewalk (n=5). At the Maryland School for the Blind, sap flux was measured from red maple (n=10), sweetgum (n=5), and tulip poplar (n=11) trees in a closed canopy (Table 1, Fig. 1). The field sites were selected based upon site accessibility and safety and the ability to provide security for the monitoring equipment. Permission to access and instrument the study trees was obtained from property owners.

2.2. Atmospheric and soil moisture measurements

This study was conducted from June 2018 to October 2019. Data is presented from June 6th to October 26th, 2018 (DOY 157–299), and through the entire growing season of 2019, April 11th to October 26th (DOY 101–299). Instruments were deployed in June 2018, so early Spring (April and May) data is not available for 2018. At each field location, a weather station (HOBO U30 Station; Onset Computer Corporation, Bourne, MA, USA) was installed outside the forest canopy to characterize potential climate drivers of sap flux, including precipitation, relative humidity, and air temperature. Air temperature and relative humidity measurements were used to calculate the vapor pressure deficit (VPD) (Campbell and Norman, 2012). Additionally, soil moisture probes (Campbell Scientific CS616) were installed vertically in the soil profile to a depth of 30 cm at the dripline of each tree to characterize soil moisture dynamics and identify conditions of potential plant water stress. The data were recorded at 30-min intervals. Mean annual temperature and total annual precipitation data were obtained from the NOAA Online Weather Data (NOAA, n.d.).

2.3. Sap flux measurements

Thermal dissipation Granier sensors (Granier 1987) were inserted radially 2 cm into the sapwood of the monitored trees (n=41) at a breast height of 1.4 m. Each sensor consisted of two thermocouple cylindrical probes of 2 mm diameter placed approximately 15 cm apart. The upper probe was equipped with a constant heating wire supplied with a constant power source to measure the voltage differential (ΔV) between the upper heated probe and the ambient temperature of the below reference probe. ΔV was calculated every 30 seconds and recorded as half-hour averages. Sensors were attached to double-shielded cable wires and connected to a CR 1000 data logger (Campbell Scientific Inc., Logan, UT) with AM 16/32B and AM 416 multiplexers (Campbell Scientific Inc., Logan, UT). Sensors were covered with aluminum shielding to

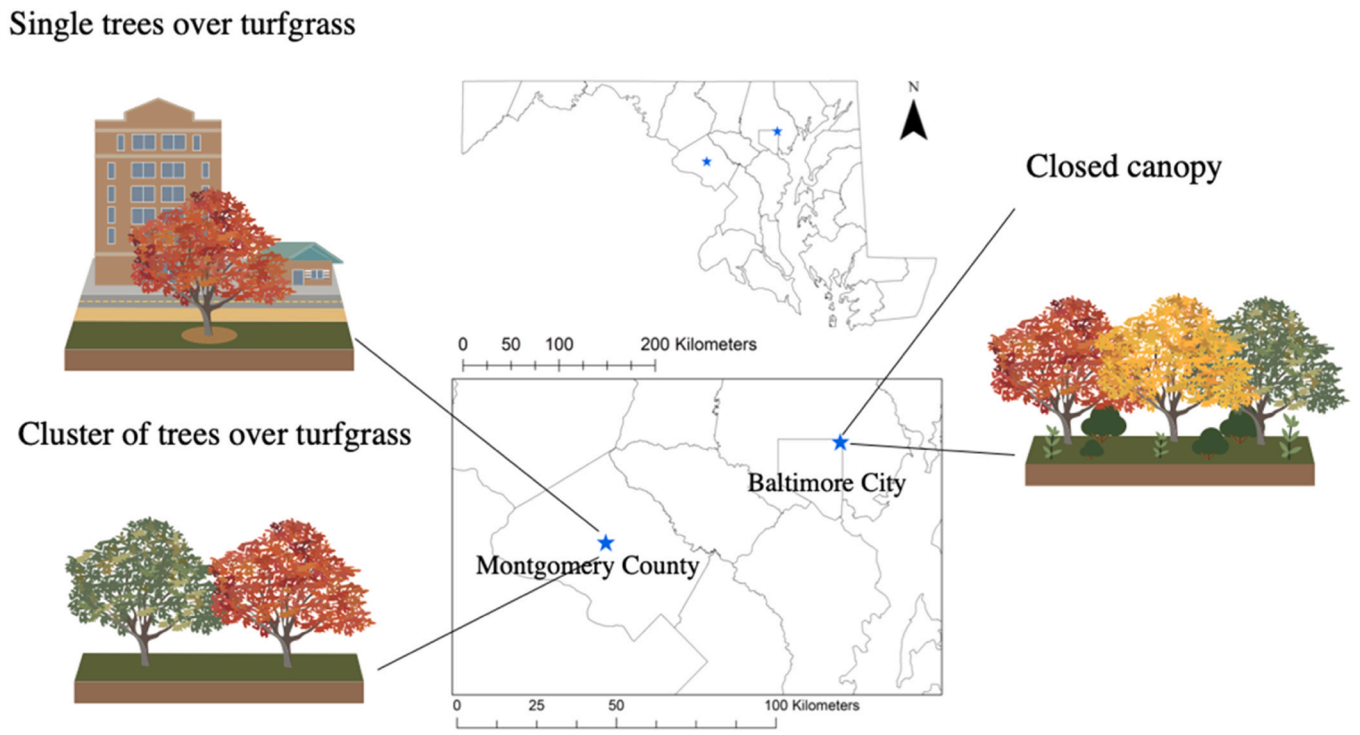

Fig. 1. Study site locations in the State of Maryland, USA. Different leaf colors indicate different tree species (*A. rubrum* L. = red, *L. styraciflua* L. = green, and *L. tulipifera* L. = yellow).

Table 1
Characteristics of surveyed trees, including tree species, diameter at breast height (DBH), tree height, canopy width north-south (N-S) and east-west (E-W), sap flux density (*Js*) and whole-tree water use in 2018 (June 6th to October 26th, 2018) and 2019 (April 11th to October 26th, 2019). Values are mean ± SE.

Management	Species	n	DBH (cm)	Height (m)	Width N-S (m)	Width E-W (m)	*Js* (g cm^{-2}d^{-1}) in 2018	Tree Water Use (L day^{-1}) in 2018	*Js* (g cm^{-2}d^{-1}) in 2019	Tree Water Use (L day^{-1}) in 2019
Closed Canopy	*Acer rubrum* L.	10	35 ± 4.0	20.9 ± 1.7	9.7 ± 0.9	9.0 ± 0.9	91.2 ± 20.9	36.7 ± 10.3	100.5 ± 27.0	40.2 ± 11.4
Closed Canopy	*Liquidambar styraciflua* L.	5	35.7 ± 6.8	29.1 ± 4.8	7.9 ± 1.2	8.7 ± 0.9	100.4 ± 29.6	44.1 ± 16.5	104.6 ± 26.9	45.9 ± 16.5
Closed Canopy	*Liriodendron tulipifera* L.	11	54.1 ± 5.6	33.9 ± 1.4	9.5 ± 0.9	10.3 ± 1.2	115.7 ± 19.3	73.8 ± 17.2	80.1 ± 21.1	49.7 ± 14.6
Cluster	*Acer rubrum* L.	5	24.1 ± 0.7	12.8 ± 0.4	9.7 ± 0.5	9.4 ± 0.4	148.1 ± 38	39.9 ± 10.6	169.9 ± 47.3	45.8 ± 13.0
Cluster	*Liquidambar styraciflua* L.	5	30.2 ± 1.4	14.7 ± 0.8	9.2 ± 0.5	9.4 ± 0.8	161.2 ± 39.8	50.9 ± 13.2	187.1 ± 52.9	61.5 ± 21.4
Single	*Acer rubrum* L.	5	22.4 ± 2.4	8.2 ± 0.3	8.2 ± 0.8	8.7 ± 0.7	204 ± 43.8	49.0 ± 13.3	254.3 ± 49.6	61.5 ± 15.9

prevent interference from thermal heating or rainwater. Sap flux density in the outer 2 cm of xylem (J_S, in grams per second square meter) was calculated according to the empirical formula from Lu (1997), modified from Granier (1987, 1985) (Eq. 1):

$$J_S = 119\left(\frac{\Delta V\max - \Delta V}{\Delta V}\right)^{1.231} \quad (1)$$

We used the software Baseliner 4.0 (Oishi et al., 2016) to convert the data stored in the data logger to the K value and subsequently to J_S (Eq. 2).

$$K = \frac{\Delta V\max - \Delta V}{\Delta V} \quad (2)$$

where ΔVmax is the maximum voltage differential between probes when flux is zero, and K is a dimensionless "flow index".

2.4. Extrapolating sap flux measurements to whole-plot transpiration

To quantify runoff reduction by tree transpiration at the plot level across management contexts, we combined field surveys, our whole-tree water use data, and our precipitation data. In each management context, we performed surveys of living trees within 900 m^2 plots. One plot was surveyed in the single tree site and two plots each in the cluster and closed canopy sites (Table 2). Three of the four plots were 30 m x 30 m, and, to accommodate for monitored trees, one of the plots in the closed canopy site was 20 m x 45 m. We used a Vertex 5 hypsometer (Haglof Inc., Sweden) to measure plot distances. In each plot, we counted all stems (diameter > 2.54 cm), measured each tree's diameter at breast height (DBH), and identified trees to species. To estimate plot-level transpiration in each plot, mean monthly sap flux density for each species and management context was multiplied by the effective sapwood area for each individual tree. The effective sapwood area for an individual tree accounts for observed radial patterns in sap flow, which are

Table 2
Stem count, species, and total sapwood area from surveyed plots in each management context in the 900 m^2 plots.

	Single		Cluster				Closed Canopy			
	Plot 1		Plot 1		Plot 2		Plot 1		Plot 2	
Species	n	Sapwood area (m^2)	n	Sapwood area (m^2)	n	Sapwood area (m^2)	n	Sapwood area (m^2)	n	Sapwood area (m^2)
A. rubrum	4	0.07	8	0.31	5	0.18	23	0.6	8	0.43
L. tulipifera							8	0.38	6	0.56
L. styraciflua			9	0.38	6	0.21	11	0.39		
Other	1	0.02	8	0.27	13	0.68	20	0.16	32	0.61
Total	5	0.09	25	0.96	24	1.07	62	1.53	46	1.6

generally higher in the outer 20 mm where sap flow was measured, than deeper into the xylem (Oishi et al., 2008). Effective sapwood area was estimated based on the approach by Berdanier et al., (2016) who identified a gamma-type model to account for radial trends in sap flow rate for diffuse-porous hardwood species, including the three species measured in our study. Precipitation data from April to May 2019 was used to estimate the percentage of rainfall that left the ecosystem to the atmosphere via tree transpiration.

2.5. Data analysis

Repeated measures analysis of variance (ANOVA) using linear mixed-effects models (Bates and Pinheiro, 1998) was performed to compare *Js* and whole-tree water use across tree species and management contexts and the effect of day of the year. Due to imbalanced study design, species and management context were combined as one factor. Each tree was treated as a random intercept in the models and repeated measurements on the same tree over time were accounted for using autocorrelation-moving average correlation structure. Assumptions of normality and homoscedasticity were checked using QQ and residuals diagnostics plots.

Models were fit in the statistical R software version 4.1.2 (R Core Team, 2021) using the lme function in the *nlme* package (Pinheiro et al., 2021). The final model was chosen based on the smallest value of Akaike information criterion (AIC) from alternative model specifications. The varIdent function was incorporated into the model to accommodate heteroscedasticity. The final model was chosen based on the smallest value of Akaike information criterion (AIC) from alternative model specifications. Additionally, an autoregressive lag 1 covariance structure was incorporated to account for temporal autocorrelation of *Js*. Tukey's HSD post hoc analysis with $\alpha = 0.05$ using the lsmeans function from the package *emmeans* (Lenth, 2019) was conducted to identify significantly different pairs.

We illustrated diel (24-h) time scale differences in transpiration among closed-canopy species by focusing on two representative days from the 2019 growing season. Sap flux response to soil moisture dynamics across different species and management contexts was evaluated by aggregating the soil moisture data into non-limiting conditions (soil moisture $\geq$ 20%) and limiting conditions (soil moisture $<$ 20%). This threshold was selected because hardwood forests have experienced sensitivity to drought and have demonstrated conservative transpiration at a soil water storage below 20% (Novick et al. 2004; Oishi et al. 2010; Stoy et al. 2006; Pataki and Oren, 2003).

We also tested for variability in the sensitivity of daily *Js* to VPD under limiting soil moisture conditions by creating VPD ranges with 0.25 kPa increments. Welch's two sample t-test was performed using the t-test function to identify statistically significant differences between mean *Js* under limiting and non-limiting soil moisture conditions for each VPD range.

3. Results

3.1. Microclimate data

Microclimatic conditions were similar across study sites, but the patterns of precipitation and soil moisture varied among years. The mean annual temperature was 13.7 °C in 2018 and 14.4 °C in 2019. During the growing season, the mean temperature was 20.5 °C and 21.7 °C in 2018 and 2019, respectively. During June-October, 2018, the mean monthly calculated VPD ranged from 0.39 to 0.97 kPa in the single and cluster sites, and 0.38–0.97 kPa in the closed canopy site (Fig. 2c,d). During April-October, 2019, the mean monthly calculated VPD ranged from 0.5 to 1.03 kPa in the single and cluster sites, and 0.54–1.11 kPa in the closed canopy site (Fig. 2c,d). The total annual precipitation for Baltimore, MD was nearly twice the amount in 2018 (1824.2 mm) than in 2019 (968.5 mm). During the growing season (April to October), the total precipitation was 1234.2 mm in 2018 and 572.3 mm in 2019. Soil moisture varied within the growing season in response to precipitation events and water use. The drier year in 2019 led to drier soil at all sites: the lowest mean monthly soil moisture in 2018 was 25.5%, 25.7%, and 27.3% in the single, cluster, and closed canopy sites, respectively, compared with 19.2%, 18.2%, and 11.2% in 2019 (Fig. 2g,h).

3.2. Sap flux and whole-tree water use

Red maple trees, the species that was measured in all management contexts, showed consistently higher daily total *Js* when growing as individual trees compared to when growing in a closed canopy forest in 2018 ($p<0.0001$) and 2019 ($p=0.0002$) (Fig. 3a,b, repeated measures ANOVA used to indicate significant differences). The mean *Js* was 204, 148.1, 91.2 g $cm^{-2}d^{-1}$ in 2018 and 254.3, 169.9, and 100.5 g $cm^{-2}d^{-1}$ at the single site, cluster, and closed canopy sites, respectively (Table 1).

In 2018, we found that single red maple trees had higher daily *Js* than closed canopy tulip poplar and ($p=0.0007$) and closed canopy sweetgum trees ($p=0.0006$) (Fig. 3a, repeated measures ANOVA). Closed canopy red maple trees had lower daily *Js* than cluster sweetgum ($p=0.0087$) and cluster red maple trees ($p=0.0424$) (Fig. 3a). In 2019, there was a similar trend in pairwise differences in *Js* between single red maple and closed-canopy tulip poplar ($p<0.0001$) and sweetgum trees ($p=0.0018$) (Fig. 3b, repeated measures ANOVA). However, in 2019, closed canopy tulip poplar had lower daily *Js* than cluster red maple trees ($p=0.0466$) and cluster sweetgum trees ($p=0.0103$) (Fig. 3b). Despite these differences in *Js*, for whole-tree water use (L day^{-1} $tree^{-1}$), the only pairwise difference was between closed canopy red maple and closed canopy tulip poplar trees (Fig. 3c, $p=0.0393$) in 2018. No significant differences were observed for whole-tree transpiration across tree species and management contexts in 2019 (Fig. 3d).

Single red maple trees had higher *Js* than red maples in cluster or closed canopy conditions in 2018 and 2019 (Fig. 4a, b). Sweetgum trees at the cluster site had higher *Js* than those in closed canopy conditions in 2018 and 2019 (Fig. 4c, d). The mean *Js* was highest for single red maple trees and lowest for closed-canopy tulip poplar trees in 2019 (Table 1). The average whole-tree water use ranged from 36.7 to 73.8 (L day^{-1} $tree^{-1}$) in 2018 and 2019 across the species and management contexts

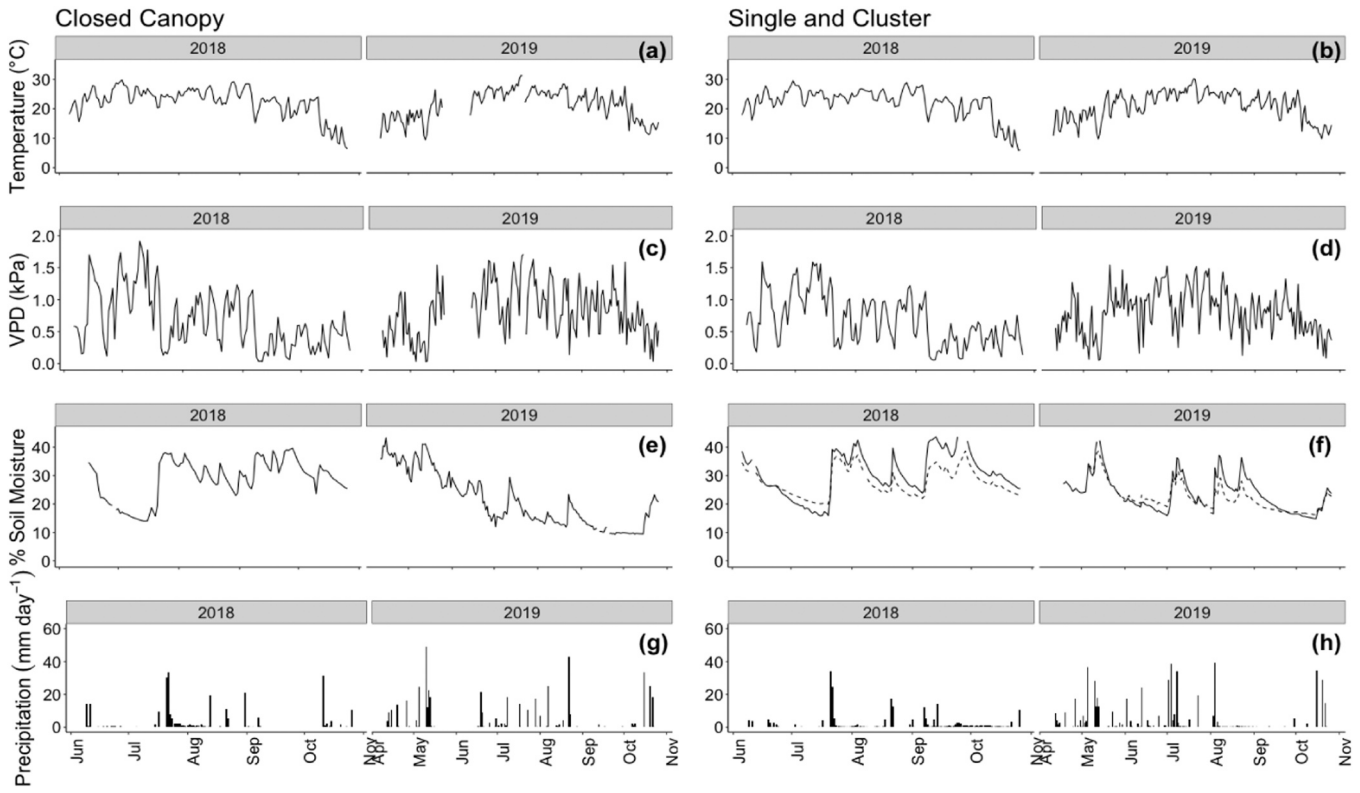

Fig. 2. Microclimate in Baltimore, MD and Gaithersburg, MD in 2018 and 2019. Mean daily air temperature for closed canopy site **(a)** and single and cluster sites **(b);** mean daily vapor pressure deficit (VPD) for closed canopy site (**c**) and single and cluster sites (**d**); mean daily soil moisture in the closed canopy (**e**), single (solid line) and cluster (dashed line) sites (**f**); daily total precipitation for closed canopy site (**g**) and single and cluster sites (**h**). Temperature, VPD and precipitation were not recorded in the Closed Canopy site between DOY 146 (May 26th, 2019) and DOY 164 (June 13th, 2019) due to the weather station's battery failure.

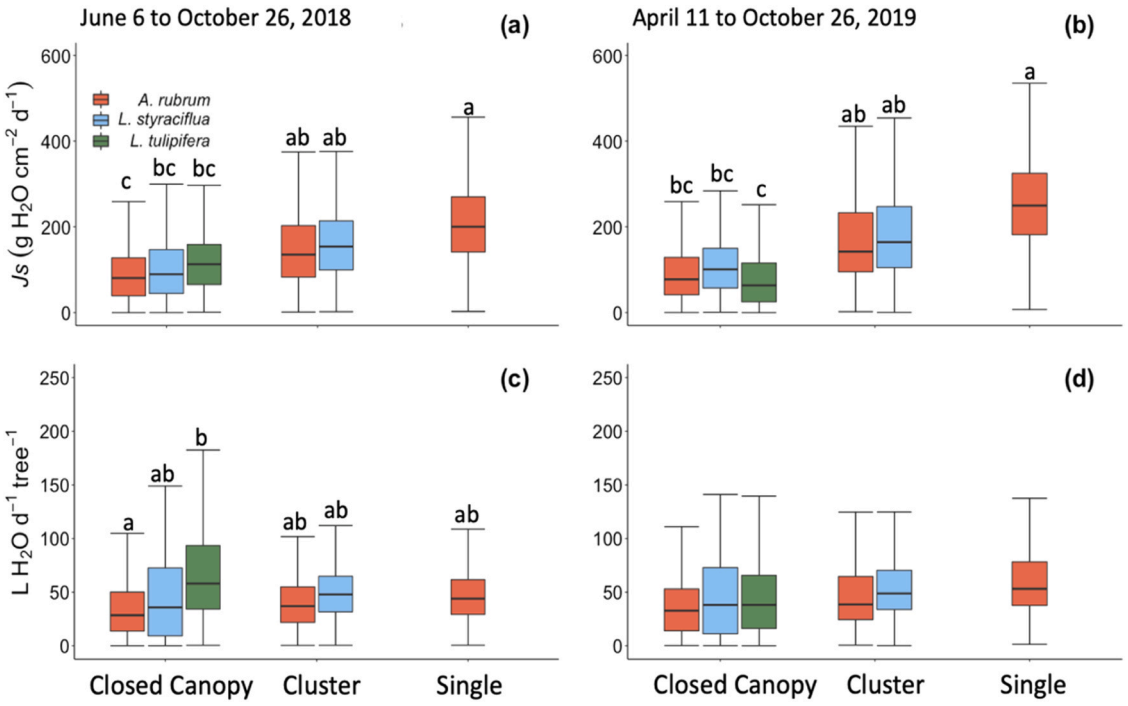

Fig. 3. Observed sap flux density (*Js*) **(a, b)** and modeled whole-tree water use **(c, d)**. Letters indicating significance are derived from a repeated measures ANOVA with Tukey's HSD post hoc analysis with $\alpha = 0.05$. Data was collected from June 6 to October 26, 2018, and April 11 to October 26, 2019.

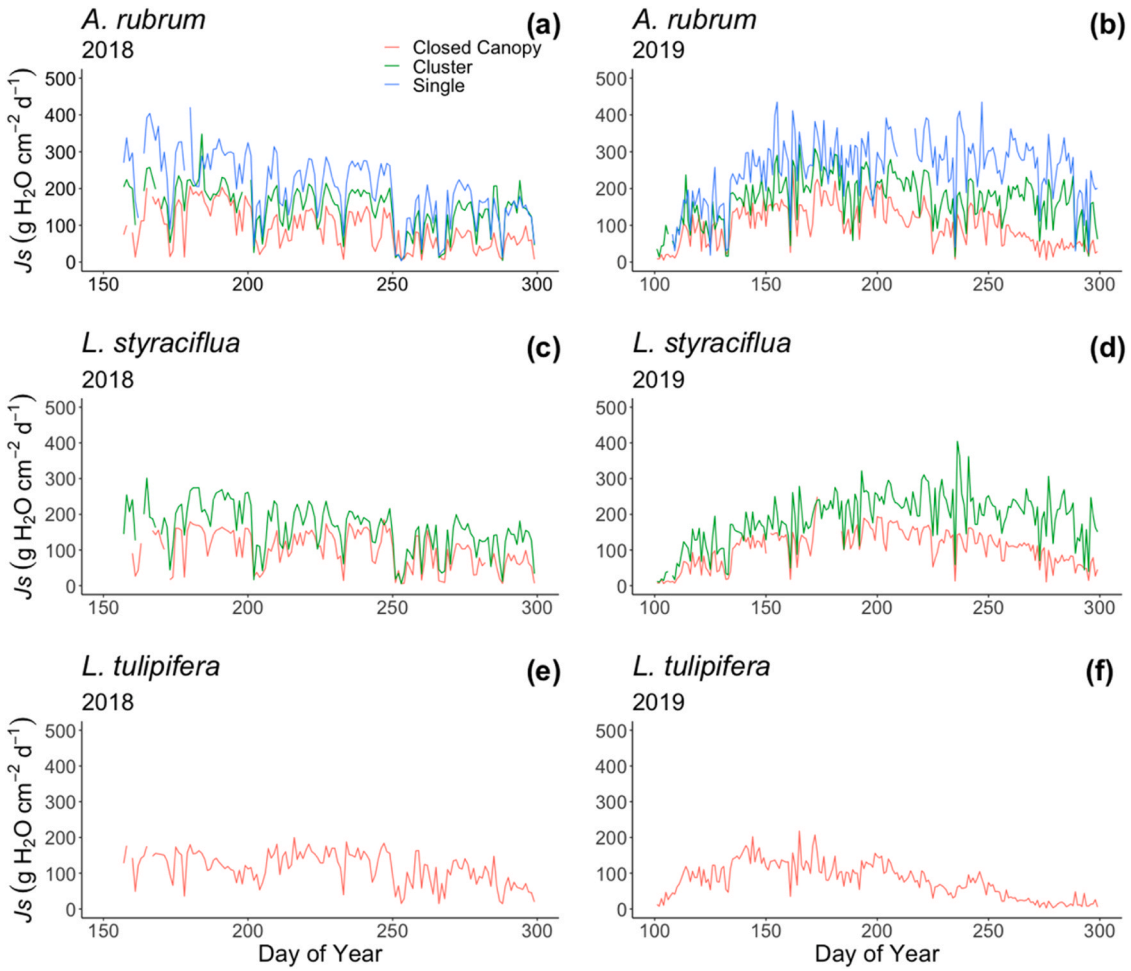

Fig. 4. Time-series of the mean daily sum of sap flux density (*Js*) in the outer 2 cm measured in 2018 and 2019 for the three management contexts for red maple **(a, b)**, sweetgum **(c, d)**, and tulip poplar **(e, f)** species. Gaps in data indicate time periods when sap flux sensors failed.

(Table 1).

3.3. Relationships between sap flux, VPD, and soil moisture

Although no significant differences were observed in mean sap flux density (*Js)* among closed canopy species during the growing seasons of 2018 and 2019 (Fig. 3a, b), differences were observed at the diel (24-h) time scale (Fig. 5a,b,c). We investigated transpiration sensitivity to soil water limitations by focusing on two representative days from the 2019 growing season: a mid-growing season day with high potential ET (i.e., high VPD) and high soil moisture (July 19, 2019), and a proceeding day in the late growing season with similar VPD, but potentially limiting soil moisture conditions (Aug 30, 2019). On July 19, mean vapor pressure deficit (VPD) was 1.53 kPa at the site and mean soil moisture was 0.21, 0.25, and 0.19 for red maple, sweetgum, and tulip poplar trees, respectively. On Aug 30, mean VPD was 1.41 kPa and mean soil moisture was 0.16, 0.17, and 0.15 for red maple, sweetgum, and tulip poplar trees, respectively. When comparing July 19 with Aug 30, tulip poplar was the most sensitive to dry soils in the closed canopy (Fig. 5c). Tulip poplar, red maple and sweetgum trees had a decrease in daily sum of sap flux density of 63.85%, 32.72%, and 16.16%, respectively, from July 19, 2019 to Aug 30, 2019. In addition to lowering peak sap flux rate, under the driest conditions, both red maple and tulip poplar showed delays in their daily start of transpiration, compared to sweetgum.

We expanded our analysis of the response of *Js* to VPD under non-limiting and limiting soil moisture conditions from these two diurnal examples to the entire study period. For tree species in the closed canopy site, data were sorted into VPD ranges with 0.25 kPa increments and soil moisture < 0.20 m3 m-3 or ≥ 0.20 m3 m-3 (Fig. 5d,e,f, Table S1). *Js* for tulip poplar trees followed the diel trend, decreasing with increasing VPD under limiting soil moisture conditions (Fig. 5f). *Js* for red maple trees was significantly different between soil moisture conditions for VPD ranges at 0–0.25 kPa, 0.51–0.75 kPa, and 0.76–1 kPa (Fig. 5d). For sweetgum trees, *Js* was significantly different between soil moisture conditions for VPD ranges at 0.26–0.5 kPa, 0.51–0.75 kPa, and 1–1.25 kPa (Fig. 5e).

3.4. Whole-tree water use estimates based on DBH, species, and management context

Whole tree water use (L H_2O day^{-1} $tree^{-1}$) was estimated by scaling our sap flux density measurements based on effective cross-sectional sapwood area at breast height, accounting for tree size, xylem anatomy, and radial trends in xylem conductivity (Berdanier et al., (2016)). Using the mean sap flux density data collected during July 2018, we estimated whole-tree water use and determined how these would vary from 10 cm to 60 cm DBH by species and management context. Single red maple trees had the highest whole-tree water use when compared to cluster and closed canopy trees (Fig. 6). Whole-tree water use was similar across all closed canopy species.

3.5. Plot-level water use across management contexts

Species, stem count and total sapwood estimated from surveyed plots

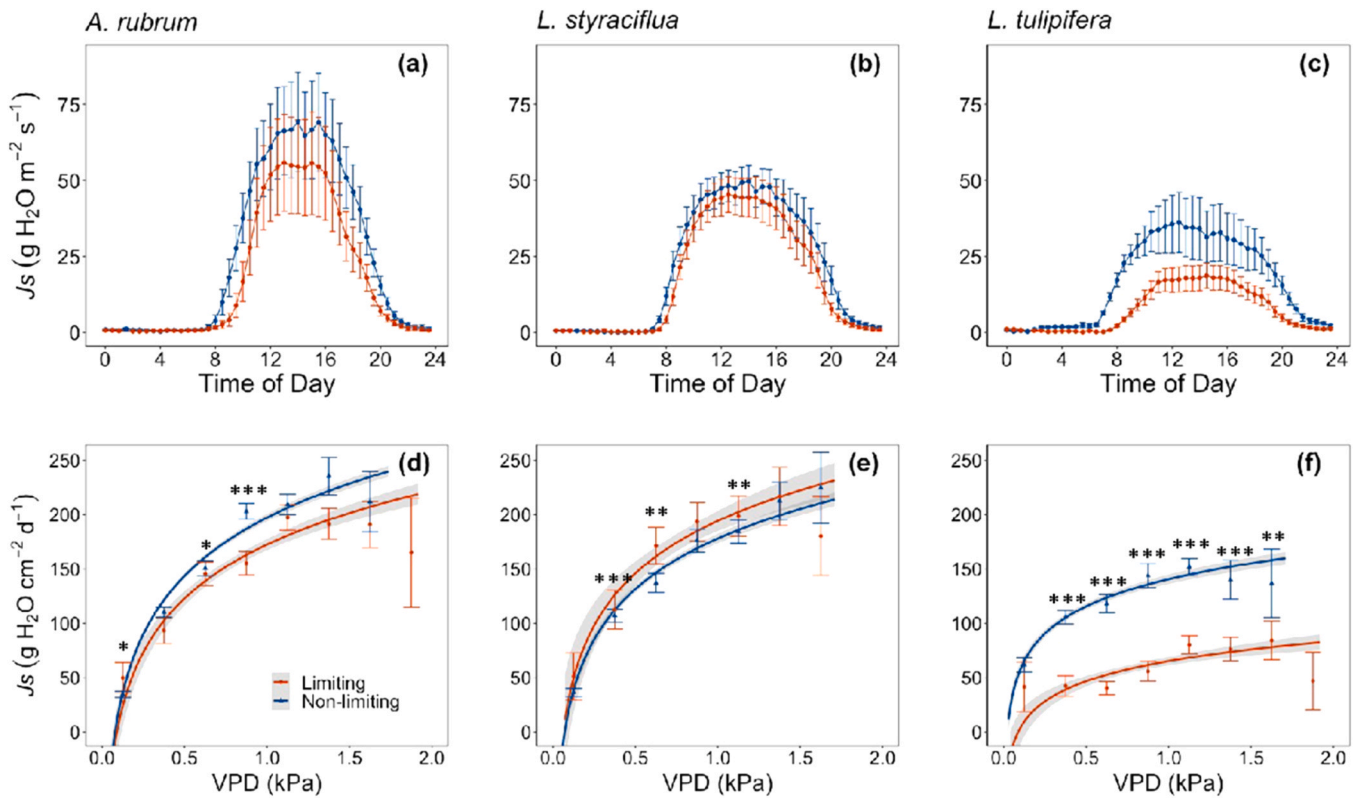

Fig. 5. Time-series from two example days in the closed canopy site representing a mid-growing season day (July 19, 2019) with high soil moisture (blue), and a late-growing season day (Aug 30, 2019) under dry conditions (red) **(a, b, c)**. Half-hourly sap flux density (*Js*) for red maple **(a)**, sweetgum **(b)**, and tulip poplar **(c)** species in the closed canopy site. Values are mean ± SE. Mean *Js* as a function of log VPD under limiting ($\theta < 0.20$) and non-limiting ($\theta \geq 0.20$) soil moisture conditions for red maple **(d)**, sweetgum **(e)**, and tulip poplar **(f)** species in the closed canopy site. Mean *Js* under limiting soil moisture conditions was evaluated by creating VPD 'bins' with 0.25 kPa increments. Values are mean ± 95% confidence interval and asterisks indicate a significant difference (* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$) between limiting and non-limiting soil moisture conditions for Welch's two sample t-test.

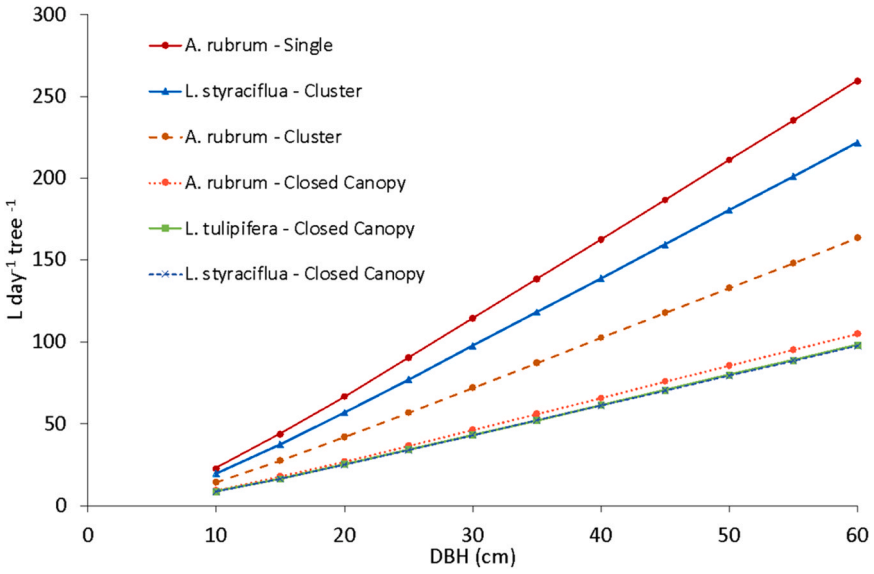

Fig. 6. Whole-tree water use (L day^{-1} $tree^{-1}$) estimates based on diameter at breast height (DBH), species, and management context. Values were estimated based on the mean sap flux density monitored during the month of July 2018. In the closed canopy, values for tulip poplar and sweetgum species are overlapping.

are described in Table 2. The average total sapwood area was 0.09 m^2, 1.02 m^2, and 1.57 m^2 in the single, cluster, and closed canopy 900 m^2 survey plots, respectively. In the cluster site, other species (those not monitored in this study) included *Prunus cerasifera*, *Nyssa sylvatica*, *Amelanchier arborea*, *Zelkova serrata*, *Cercis canadensis*, *Betula nigra,* and *Malus sylvestris*. In the closed canopy site, other species included *Prunus serotina*, *Nyssa sylvatica*, *Carya tomentosa*, *Viburnum prunifolium*, *Fagus grandifolia*, *Ilex opaca*, *Carpinus caroliniana*, *Fraxinus excelsior, Diospyros virginiana*, *Acer platanoides*, *Acer saccharum*, and *Prunus avium*.

The total precipitation (April-October) in 2019 was 577 mm at the

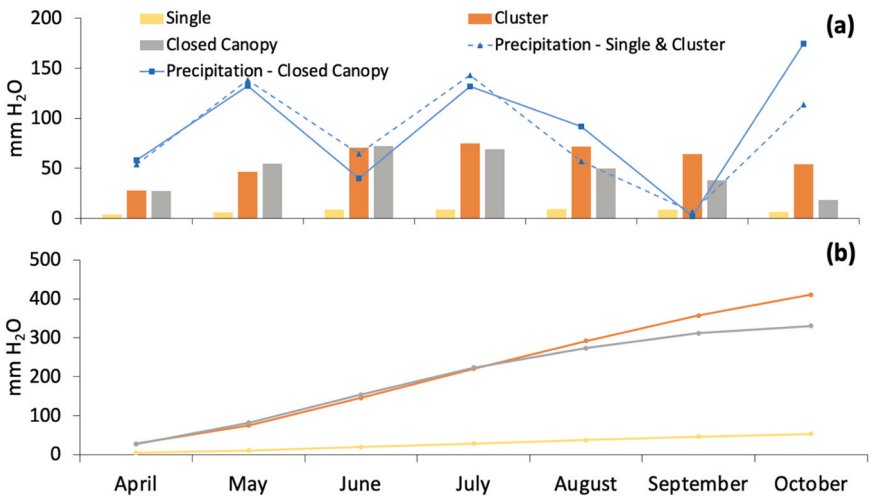

Fig. 7. Monthly plot-level whole-tree water use (mm) through transpiration and total precipitation (mm) **(a)**, and cumulative plot-level transpiration (mm) **(b)** for the study sites in 2019.

single and cluster site and 631 mm at the closed canopy site (Fig. 7a). The estimated cumulative whole-tree water use through transpiration in the 900 m^2 survey plots was 53 mm (9.1% of precipitation), 411 mm (71.2% of precipitation), and 330 mm (52.4% of precipitation) in the single, cluster, and closed canopy sites, respectively (Fig. 7b). September was a particularly dry month with a monthly precipitation of 6.4 mm at the single and cluster sites and 2.2 mm at the closed canopy site; monthly transpiration was 8.8 mm, 64.6 mm, and 38.4 mm in the single, cluster, and closed canopy plots, respectively (Fig. 7a). Monthly transpiration in the cluster and closed canopy sites were similar until the initiation of the dry period in mid-August. The closed canopy site had a higher proportion of drought-sensitive tulip poplar (Fig. 5, Table 2), resulting in a decrease in transpiration, relative to the cluster site.

4. Discussion

In this study we (1) investigated sap flux density and whole-tree water use of deciduous tree species (red maple, tulip poplar, and sweetgum) in different management contexts, (2) determined the relationship between sap flux and environmental drivers (soil moisture and VPD) across species in two growing seasons, and (3) estimated plot-water level water use through transpiration across management contexts. Results showed that isolated red maple trees had consistently higher sap flux density than closed canopy trees. No significant differences were observed for sap flux between closed canopy and cluster species in the two growing seasons. Our estimates of sap flux density and daily water use are similar to those reported in other studies (Thom et al., 2020; Čermák et al., 2000; Wang et al. 2012).

However, species differences in sap flux density were observed at the diel (24-h) time scale with tulip poplar being the most sensitive to drought. Additionally, plot-level water use through transpiration from trees was estimated to be a substantial portion of precipitation inputs in the cluster and closed canopy sites. The range of transpiration as a proportion of precipitation inputs in our study is greater than those found in other settings (Thom et al., 2020). This difference may be due to the later study being conducted on trees *in* stormwater control measures and hence having a stronger runoff component than our setting that focused on urban trees and forest patches that are not designed to convey stormwater.

4.1. Sap flux and whole-tree water use

Management contexts significantly influenced sap flux, and, on a per-tree basis, single isolated red maple trees had greater transpiration rates than red maple trees in a closed canopy setting in both years (Fig. 3a,b). During the two growing seasons, single trees had over twice the mean sap flux density of closed canopy trees (Table 1). Similarly, previous literature has shown that the rate of tree transpiration decreases with increasing stand density due to shielding of microclimate factors outside the stand (e.g., solar radiation and wind) and high humidity in the stand (Asawa et al., 2017; Larcher, 2003). The scope of this research did not determine a precise threshold for tree density at which transpiration of single trees becomes equal to a cluster. Nor were we able to account for all covarying soil characteristics among sites that might help to explain the mechanisms affecting plant water uptake. Nevertheless, the higher rate of transpiration observed by single red maple trees partially offset the larger amount of sapwood area in clustered trees.

Interspecific differences in sap flux rates were not observed among any species in either closed canopy or cluster settings (Fig. 3a,b). This similarity was likely due to the same xylem anatomy (diffuse-porous) of the monitored species. During the 2018 study period, whole-tree water use by tulip poplar was twice as high as red maple (Fig. 3c, Table 1), due primarily to larger sized tulip poplar trees in these stands. However, this same pattern was not observed in 2019, with tulip poplar using roughly the same amount of water as red maple (Fig. 3d). We attribute this change to the fact that tulip poplar showed much stronger sensitivity to soil water limitations than the other species.

4.2. Relationships between sap flux, VPD, and soil moisture

Not surprisingly, whole-tree water use varied directly with diameter (Fig. 6). This range of whole-tree water use overlaps those reported in other studies (Thom et al., 2020; Čermák et al., 2000; Wang et al. 2012), and our range of variability likely reflects the range in tree sizes in our study. The relationship between tree diameter and effective sapwood area, which accounts for radial declines in the hydraulic conductivity of xylem from the cambium to heartwood, was based on a synthesis of data from non-urban trees (Berdanier et al., 2016). Therefore, it may be useful for future studies to confirm whether radial patterns in sap flux density for forest trees are applicable to trees grown in urban contexts. Nevertheless, the linear increase in whole-tree water use with diameter (Fig. 6) provides a useful tool for a quick assessment of water use within an urban environment.

After accounting for VPD, tulip poplar trees showed a large decline in transpiration under the dry conditions of 2019 (Fig. 5). Tulip poplar trees have shown the strongest sap flux sensitivity to drought when compared to other species in deciduous forests (Ford, Hubbard, and Vose, 2011; Oishi et al. 2010; Pataki and Oren, 2003). Tulip poplar often

responds to water stress by increasing the sapwood area to leaf area ratio through premature leaf senescence to increase specific leaf conductance (i.e., drought deciduousness), allowing maintenance of stomatal conductance and photosynthesis (Ford et al., 2011; Kozlowski et al., 1991). Although soil moisture conditions alone have explained little of the variability of *Js* in our previous research (Ponte et al., 2021), using a threshold for drought conditions ($\theta < 0.20$) helped us identify relationship differences between *Js* and VPD across tree species and allowed us to investigate differences in tree response to drought stress. Sweetgum trees showed the lowest decrease in *Js* under low soil moisture conditions across our monitored closed canopy species, but this species has also shown to tolerate drought stress and prevent cell dehydration by reducing transpiration and stomatal conductance, allowing recovery after seasonal drought (Baraldi et al., 2019). We acknowledge that our measurements of soil moisture only cover the upper 30 cm of soil and that trees may alleviate water limitations in shallow soil if they are able to access deeper soil water. Thus, if drought conditions are more severe than experienced during our study period, or if tree access to deeper soil water is restricted either due to soil conditions and/or local hydrologic factors limiting infiltration and recharge, declines in transpiration may be more widespread.

When managing urban forests, it is important to consider not only the maximum transpiration rate of a tree species, but also its sensitivity to environmental conditions. The scope of this study was limited to three common, diffuse-porous, deciduous species. Ring-porous, deciduous species, including many oak species, have a lower ratio of sapwood area to basal area and can exhibit lower transpiration than diffuse-porous species (Oishi et al., 2008). In southeastern deciduous forests, red maple trees were found to be more sensitive to drought than white oak (*Quercus alba*) (Oren and Pataki, 2001). In some cases, it may be desirable to incorporate species into designs and conservation plans that have high water use when conditions are wet but can also decrease water use during drought.

Because of the high tree species richness in the closed canopy plots, we were only able to focus sap flow measurements on three key species. Our sample trees were representative of the size range of canopy trees. We did not measure sap flow on smaller trees, but because the total sapwood area of these is a small proportion of total sapwood area, errors caused by treating small trees like larger ones would be minimal. Thus, the plot-level transpiration estimates provide only a first-order approximation which we use to compare to precipitation inputs. Thermal dissipation probes have been shown to provide reliable relative flow rates, but lower accuracy than some other methods (Flo et al., 2019) and subsequently may underestimate total transpiration (Oishi et al., 2008). However, the low cost of homemade thermal dissipation probes compared to commercial products enables instrumentation of a larger number of trees and better representation of the stand composition. Thus, as future studies expand on sap flow estimates from other urban trees and assess inter- and intra-specific differences, a more comprehensive tool for estimating plot-level transpiration will emerge.

Despite the observation that single trees had the highest transpiration rates across the management contexts, plot-level transpiration from trees was substantially higher at the cluster and closed canopy sites (Fig. 7). Individually planted trees over turfgrass along streets have a greater transpiration rate, but as a land use, contiguous canopy and forest patches have a greater total water use. Turf grass and other herbaceous vegetation are other sources of transpiration that are likely to have increasing significance in the hydrologic budget with decreasing canopy cover. However, these sources of transpiration, as well as sources of evaporation, were outside the scope of this study. Among our study sites, the cluster had the highest estimated plot-level total transpiration of 411 mm from April 11th to October 26th, 2019 (Fig. 7b); approximately 2.07 mm/day. Similarly in Los Angeles, CA, modeled plot-level canopy transpiration was 2.4 mm/day at their highest tree density scenario (Pataki et al. 2011). Even though plot-level transpiration was the lowest for single isolated trees, other hydrological processes (e.g., soil infiltration and canopy interception) as well as integrating street trees as a component of the green infrastructure network can provide opportunities to restore the natural hydrological cycle, promote stormwater runoff reduction, and improve water quality in urban watersheds. For instance, trees significantly increased evapotranspiration rates in bioretention mesocosms and accounted for 8.2–37.5% of average daily water losses (Tirpak et al., 2019). With effective planning and design regarding the drainage area and application of complementary green infrastructure practices (e.g., rainwater tanks and permeable pavement), tree pits could promote up to 90% of annual runoff reduction (Grey et al., 2018). Hydrological processes performed by an isolated tree or a tree in a forest patch are all important green infrastructure components for different contexts and spatial scales.

4.3. Implications for management

The findings of this study provide insight into how different management contexts and microclimate factors influence ecohydrological fluxes of different tree species and in different urban settings. Our study reduces gaps in knowledge of how the local environment affects transpiration, which is a limit to our ability to predict how management will affect hydrology. This study may allow managers and policy makers to have a better understanding of water use by urban trees through transpiration and, consequently, their implication to stormwater management in heterogeneous urban environments. For instance, this project can aid the development and refining of stormwater crediting programs as urban trees can be more accurately incorporated into planning efforts (Center for Watershed Protection, 2017; Hermansen, 2020; Law and Hanson, 2016; Stone Environmental, Inc., 2014). Our whole-tree water use estimates could potentially be used as a tool to inform urban forest managers and practitioners, allowing them to predict whole-tree water use based on DBH, species, and management context and inform urban tree planting efforts. This study also enhances the understanding of how planting density of certain deciduous trees affects tree water use through transpiration.

Further research could build from the knowledge gained here to develop a more comprehensive database of water use by other common urban tree species in different management contexts. Additionally, the scope of this study was limited to tree transpiration and did not account for variability in evaporation of precipitation from canopy interception, soil surface evaporation, or transpiration by grasses and herbaceous vegetation—all of which contribute to total ET. Modeling studies using ecohydrological data are essential to inform landscape design and urban forest management. With rising VPD due to climate change, there is an increasing need to understand plant physiological responses to climate drivers to improve predictions from land-surface models and plan for resilience under the current and future climate stress (Grossiord et al. 2020; Novick et al. 2016).

5. Conclusions

This study used continuous sensor measurements to explore how urban management context impacts the transpiration of deciduous tree species, and to determine the relationships between environmental factors and tree transpiration. We demonstrated the complexity of urban tree transpiration responses to environmental drivers, where management context and species had varying responses at daily and annual scales. Individual tree transpiration rates were greatest in the single-tree context, but plot-level tree water-use was greatest with cluster and closed canopy contexts. Species-level sensitivity to drought and water-stress countered any expected increases in water-use due to differences in tree size. We provide a framework for quantifying the contribution of whole-tree water use to upscale total offsets in precipitation by transpiration within several urban settings. This framework can inform decision-making to conceptualize and include urban trees as components of green infrastructure. Further research using continuous field

monitoring must be performed to simultaneously integrate fluxes of urban trees (transpiration, interception, infiltration, etc.) to assess their impact on urban hydrology and stormwater management. Our findings highlight the potential for urban trees to contribute to this endeavor and point out the complexities of linking them to urban hydrology.

CRediT authorship contribution statement

A. Christopher Oishi: Conceptualization, Data curation, Formal analysis, Visualization, Writing – review & editing. **Nancy Sonti:** Conceptualization, Funding acquisition, Writing – review & editing. **Sarah Ponte:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Tuana Phillips:** Investigation. **Mitchell Pavao-Zuckerman:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Dexter Locke:** Writing – review & editing.

Declaration of Competing Interest

The authors have no competing interests to declare.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2024.128321.

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