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Tree traits and meteorological factors influencing the initiation and rate of stemflow from isolated deciduous trees

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Abstract:

Tree canopy processes affect the volume and biogeochemistry of inputs to the hydrological cycle in cities. From June 2012 to November 2013, we studied stemflow production from 37 isolated deciduous park trees in a semi-arid climate dominated by small precipitation events. To clarify the effects of canopy traits on stemflow metrics, we analysed branch angles, bark relief (one component of roughness), tree size, canopy and wood cover fraction, median leaf size, and branch and leader counts. High branch angles contributed to stemflow production in both single-leader and multi-leader trees. While bark relief was negatively correlated with stemflow rates in multi-leader trees, it was positively correlated with rates for single-leader trees, possibly reflecting the conducive role of linear furrows once bark of single-leader trees is saturated. The association between numerous leaders, low stemflow initiation thresholds, and high rates deserves further study. Among meteorological variables, rain depth was strongly correlated with stemflow yields; rainfall inclination angle and wind speed were positively correlated with yields, while total intra-storm break duration and vapour pressure deficit were inversely related. For rain depths <3 mm, greater stemflow was generally associated with leafless canopies. In support of integrated stormwater management, our results can inform climate-sensitive selection and siting of urban trees with traits that tend to either promote or minimize stemflow, depending on infiltration potential.

KEY WORDS stemflow; canopy water balance; urban hydrology; urban forestry; stormwater management

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INTRODUCTION

Given the hydrological implications of vegetation-related planning and management decisions in forested, agricultural, and urban settings, it is critical to refine our understanding of the processes at this interface of the atmospheric and terrestrial portions of the hydrologic cycle. Tree canopy water balances have been most actively studied and modelled since the 1970s (Rutter *et al.*, 1971; Gash, 1979) from single-tree (David *et al.*, 2006; Guevara-Escobar *et al.*, 2007) to stand scales (Carlyle-Moses and Price, 1999, 2007); in semi-arid (Návar, 2011), arid (Llorens and Domingo, 2007), temperate (Levia *et al.*, 2014; Van Stan *et al.*, 2014), and tropical ecosystems (Herwitz, 1985; Germer *et al.*, 2010) and from the varied perspectives of canopy architecture (Park and Cameron, 2008), meteorology (Van Stan *et al.*, 2011), biogeochemistry (Neary and Gizyn, 1994; Michopoulos, 2011), and groundwater recharge (Taniguchi *et al.*, 1996).

Precipitation incident on vegetation canopies is partitioned into interception loss, I_c, the portion directly evaporated from leaf and wood surfaces; throughfall, *TF*, which reaches the ground directly through gaps or drips from the canopy; and stemflow, *SF*, which is funnelled to the base of the plant via the branch infrastructure and bole (Helvey and Patric, 1965; Valente *et al.*, 1997). In broadleaf deciduous forests, understory precipitation in the form of *TF* and *SF* can represent from 70 to 80% and 3 to 10% of rain incident on the canopy respectively (Llorens and Domingo, 2007; Van Stan *et al.*, 2011). However, compared with the dispersed nature of *TF* inputs to the forest floor, the concentration of *SF* in a much smaller area means that this input may have a disproportionate impact on terrestrial hydrological processes (Levia and Frost, 2003; Staelens *et al.*, 2007; Germer *et al.*, 2010; Levia *et al.*, 2010). As in natural and managed forests, areas at the base of urban tree trunks can constitute hot spots (and hot moments) of hydrological and biogeochemical enrichment (e.g. McClain *et al.*, 2003; Staelens *et al.*, 2007). Implications of this concentrated flux are intensified in urban landscapes characterized by impervious surfaces, compacted and constrained soils, and high pollutant levels (Xiao and McPherson, 2011). Extremes of drought and

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flood are common outcomes of meteorological variability in cities, making trees appealing as potential rainfall interceptors (Xiao *et al*., 2007; Inkiläinen *et al*., 2013; Livesley *et al*., 2014). Trees of certain forms in some climates (e.g. Germer *et al*., 2010) may funnel sufficient *SF* to create water quantity and quality issues in urban conditions. In conducive planting sites, however, high *SF* producers have the potential to self-irrigate and self-nourish (Levia and Frost, 2003), to direct pollutants from canopies to soils for biofiltration (Xiao *et al*., 2007), and even to recharge groundwater via preferential pathways along roots (Tanaka, 2011).

There is evidence that *SF* processes in urban trees, particularly those isolated from their neighbours, differ from those observed in natural forest stands (Xiao *et al*., 2000; Guevara-Escobar *et al*., 2007), meaning that findings from forested environments cannot necessarily be applied in single-tree situations (Livesley *et al*., 2014). The empirically based model developed by Xiao *et al*. (2000) confirms the relevance of three broad influences on *SF* : (i) magnitude and duration of rain, (ii) meteorological conditions, and (iii) canopy characteristics. Research on these factors in non-urban forests around the world is now readily available (e.g. Staelens *et al*., 2008; Levia *et al*., 2011), but fewer studies have been performed in urban settings and for isolated trees (Xiao *et al*., 2000; Guevara-Escobar *et al*., 2007; Livesley *et al*., 2014). We do not yet know how similar or different the meteorological and trait-related controls are on *SF* processes in isolated trees compared with those in closed, rural forests.

Rain depth is commonly the dominant meteorological predictor of *SF* volume (Germer *et al*., 2010; Návar, 2011), but other factors can play a role, including storm duration (Levia, 2004), rainfall intensity (Calder, 2001; Price and Carlyle-Moses, 2003; Carlyle-Moses, 2004), wind speed (André *et al*., 2008b) and direction (Van Stan *et al*., 2011), rainfall inclination angle (Van Stan *et al*., 2011), and vapour pressure deficit (*VPD*) (Van Stan *et al*., 2014).

In general, studies focusing on canopy traits point to the collective importance of a tree's *SF*-conducting infrastructure (Pypker *et al*., 2011; Levia *et al*., 2014). Diameter at breast height (*DBH*) is usually a strong predictor of *SF* production (Deguchi *et al*., 2006; André *et al*., 2008b; Šraj *et al*., 2008; Germer *et al*., 2010; Van Stan and Levia, 2010), but studies showing high yields for small trees (Germer *et al*., 2010; Levia *et al*., 2014) are stimulating further research. Wood cover fraction and wood volume have implications for *SF*, particularly during seasonal defoliation when increased *SF* in leaf-off condition has often been observed (André *et al*., 2008b; Dunkerley, 2013). In a study of 10 European beech saplings, Levia *et al*. (2014) concluded that greater *SF* yields were associated with higher woody surface area per unit projected canopy area (*PCA*), higher ratios of woody to foliar biomass, greater branch counts per *PCA*, and higher mean branch inclination angles. Effective canopy area (greater for columnar trees) can influence *SF*, particularly where inclined rainfall is common (Xiao *et al*., 2000; Guevara-Escobar *et al*., 2007), in sparse forests, and for isolated trees (Herwitz and Slye, 1995). Canopy cover fraction, canopy volume, and leaf area index, have been explored (e.g. Marin *et al*., 2000; Park and Hattori, 2002; Xiao and McPherson, 2011), but their influence cannot be generalized across species, ecosystems, or rainfall regimes (Pypker *et al*., 2011). Bark relief is one trait that clearly limits *SF* through at least two mechanisms: increased storage capacity per unit area (Herwitz, 1985; Levia and Herwitz, 2005) and greater surface areas associated with deeply furrowed bark (Van Stan and Levia, 2010). Leaf size has been studied less than composite canopy measures, although hydrophobicity and inclination angles have been explored (Holder, 2012). Modelling exercises by Xiao *et al*. (2000) found high sensitivity of *SF* to increases in leaf zenith angles.

Research to date suggests that for trees of comparable size, *SF* production tends to be greater if a tree has a moderately dense canopy, high woody to foliar biomass ratio, highly inclined branching angles, and smooth bark, acknowledging that different meteorological regimes can modify these characteristics' importance. Such generalizations are based on studies of diverse species from different climates, making definite conclusions on the role of individual traits and meteorological factors problematic. A systematic approach, focusing on diverse and detailed canopy traits in isolated trees subject to similar meteorological forces is used for this study. Specific objectives of the study were to (i) derive, for each tree on a study basis, the threshold rain depth for *SF* initiation, P'' (mm), the flow rate once P'' has been satisfied, Q_{SF} ($\mathrm{l\,mm^{-1}}$) and rate per unit *PCA*, $Q_{SF}\ PCA^{-1}$ ($\mathrm{l\,mm^{-1}\,m^{-2}}$); (ii) characterize the relationships between canopy traits and the aforementioned *SF* metrics; and (iii) identify meteorological and seasonal variables that influence *SF* yield. Our null hypothesis is that *SF* initiation thresholds and rates in this sample of isolated urban park trees will be similar in magnitude and will be controlled by the same meteorological and trait variables observed in forested environments.

STUDY AREA AND METHODS

Study area

McArthur Island Park (MIP) in the City of Kamloops, British Columbia, Canada (50°41′43″N, 120°22′38″W, elevation 344 m a.m.s.l.), is a 51-ha multi-use sport and leisure facility on the north shore of the Thompson River

(Figure 1). Many trees within the perimeter access road at MIP are isolated, which, for the purpose of this study, refers to trees unobstructed within a field of view 35° from vertical, centred where the lowest branch met the bole. Most trees at MIP are deciduous, including cultivated species of maple (*Acer* spp.), ash (*Fraxinus* spp.), and oak (*Quercus* spp.).

Environment Canada's 'Kamloops A*' climate station (refer to climograph, Figure 2), located 4.4 km west-north-west of MIP (elevation 345 m a.m.s.l,), has an associated mean annual (1981–2010) temperature of 9.3 °C and mean monthly temperatures ranging from −2.8 °C (January) to 21.5 °C (July). Of mean annual precipitation (277.6 mm), rain accounted for 81% (224.3 mm) and snow for the remainder. The area averages 101 rain-days per year with approximately 82% having associated rain depths between 0.2 and <5 mm. Only 4 rain-days per year have depths between 10.0 and <25.0 mm, while rain-days with depths ≥25.0 mm occur, on average, once every 5 years. MIP is extensively irrigated to meet tournament-standard turf conditions and sustain cultivated, non-native tree species. As a result, the park's climate is more aligned with a moist continental Cwb Köppen climate type than its native mid-latitude, semi-arid steppe climate (BSk Köppen climate type; Ross, 2013).

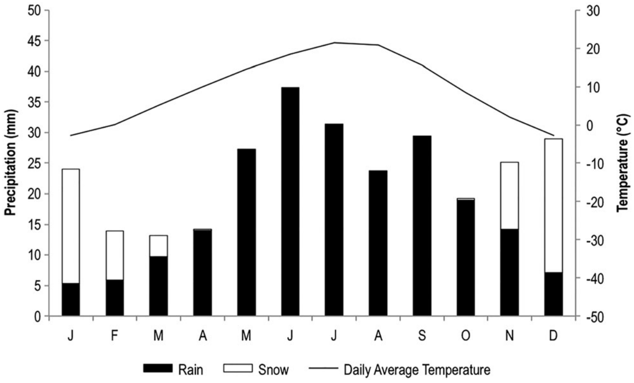

Figure 2. Climograph for the Meteorological Service of Canada's Kamloops A* climate station (50°42′08″N, 120°26′31″W) (1981–2010 normals; Environment Canada, 2014)

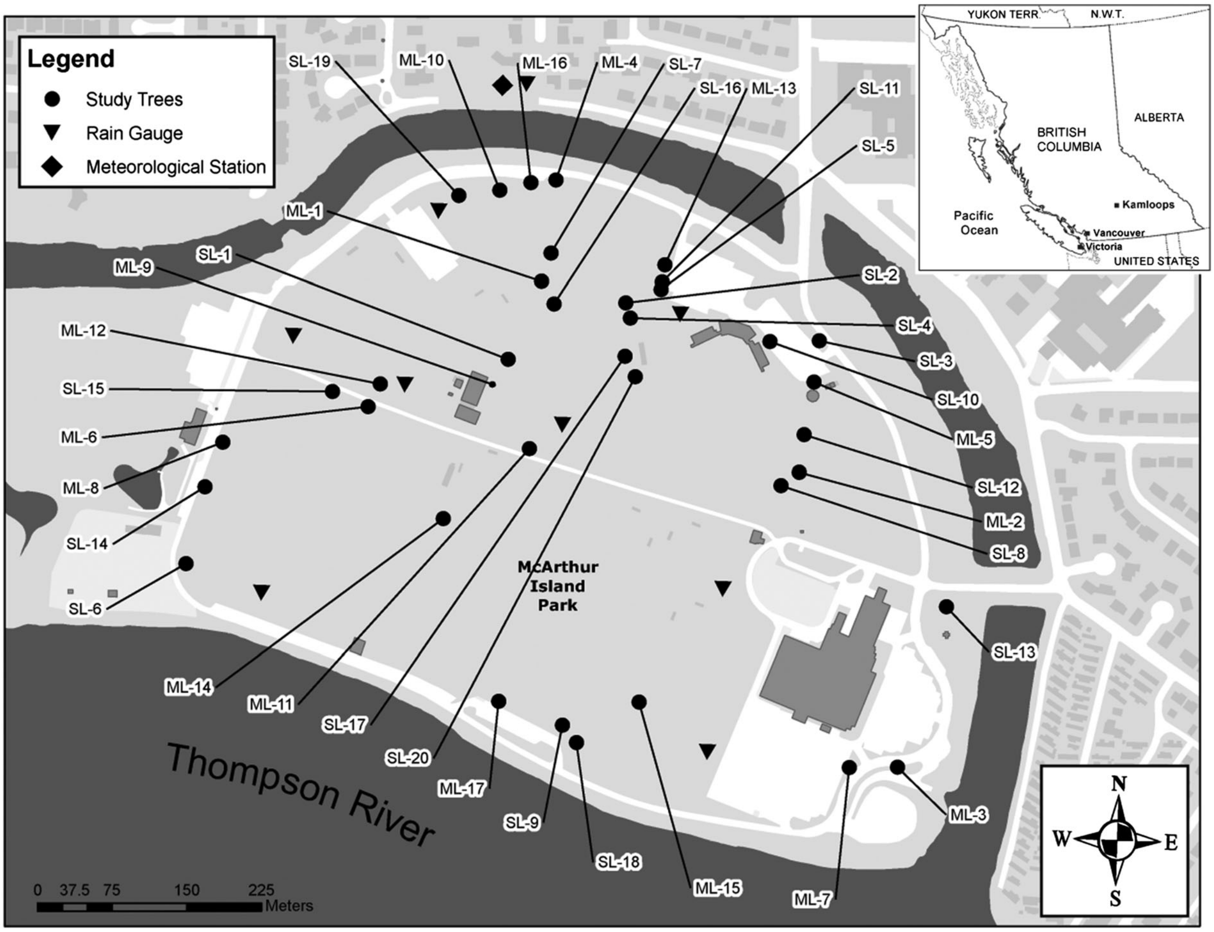

Figure 1. Location of study trees, meteorological station, and manual rain gauges within McArthur Island Park

Tree selection and the measurement and derivation of tree traits

Using the City of Kamloops' ArcGIS inventory and on-site evaluation, we selected study trees that were: (i) deciduous trees in good condition, (ii) trees representing diverse canopy characteristics, and (iii) 'isolated' trees as defined in the preceding texts. For each study tree, we measured *DBH* (cm); tree height, *H* (m); and average canopy width, *CW* (m), then calculated *PCA* (m^2), projected wood area (m^2), canopy height to width ratio (dimensionless), canopy volume, Vol_C (m^3), and wood volume, Vol_W (m^3). Following Korhonen and Heikkinen (2009), leaf-on canopy cover fraction, *CC* (%), and leaf-off wood cover fraction, *WC* (%), values were determined using separate sets of beneath-canopy skyward photographs taken using a Nikon 7100D (lens set to 70-mm focal length) tripod-mounted at 0.3-m height. Photoshop® CC was used to select either cover or open areas within the canopy for 24 photographs per tree (six for each cardinal-direction transect), then cover percent averages at each distance from the bole were weighted to yield full-canopy average *CC* and *WC*. The number of leaders for multi-leader trees, L_n, consisted of the primary leader (largest and most vertical) plus secondary leaders (at least two thirds the size of the primary leader and converging at the base of the canopy). Counts of 'feeder' branches greater than 20-mm diameter intersecting primary and secondary leaders (primary leader only for SL trees) were used to generate a total branch count, B_n, for the tree. Branch angles were calculated for only those feeder branches intersecting the primary leader. Four angles were used in the final analyses (mean and degrees from horizontal): the angle of branch-leader intersection in the upper third of the canopy, *AIU*, and in the full canopy, *AIF*, and average overall angle from intersection to furthest extent of the branch in the upper, *AAU*, and full canopy, *AAF*. For each tree, overall frequency of discontinuity, was calculated by assigning a branch a 'discontinuous' rating if the inner or mid-third of the branch drained away from the bole. Angle and discontinuity metrics were chosen to address knowledge gaps regarding the complexity and importance of horizontal and vertical variation in branch architecture for *SF* processes (Levia and Frost, 2003; Pypker *et al*., 2011). A quantitative bark relief index, *BRI*, was calculated using the ratio of the furrowed circumference of the tree bole to the surface (unfurrowed) circumference at breast height. For example, if a tree bole's unfurrowed (or outer) circumference was 0.5 m and the length of a ribbon closely following all bark contours was 0.6 m, the *BRI* would be 1.20 (ratio of furrowed to unfurrowed circumference). A tree with perfectly smooth bark has a *BRI* of 1.00. This measure reflects principles and methods pioneered by Yarranton (1967) and Van Stan *et al*. (2010) to measure bark microrelief. A sample of leaves or leaflets (13 to 49 per tree) was sorted by size. The median leaf's area was calculated using Photoshop® CC to yield median leaf size, *MLS* (cm^2).

Precipitation and stemflow measurement

Measurement of precipitation and *SF* was made on an event basis from 12 June 2012 to 3 November 2013. An Onset® (Onset Computer Corporation, Bourne, MA, USA) RG3-M tipping bucket rain gauge (TBRG) connected to an Onset® Hobo® U-30 USB data logger recorded rainfall depth and intensity. Accompanying the TBRG was a manually read polyethylene gauge. The TBRG and adjacent manually read rain gauge were between 80 and 770 m from the study trees. Eight additional manually read gauges were distributed throughout MIP, such that no study tree was more than 215 m from a gauge; precipitation from all manual gauges was collected less than four hours (but no more than 10 h) after the end of an event.

Stemflow collection collars fabricated using corrugated polyethylene hose were wrapped twice around each tree at angles to promote drainage to reservoirs. One edge was stapled to the trunk and sealed with 100% silicone. Each collar drained to a 17-l polyethylene pail inside a 114-l lidded polyethylene reservoir to accommodate overflow; each reservoir was weighted and its lid secured with elastic cord.

Measurement and derivation of meteorological variables

In addition to rain depth and intensity, an Onset® U-30 NRC weather station connected to the U-30 USB data logger measured the following meteorological variables (1-s measurements averaged and logged on a 1-min basis): wind speed and maximum 3-s gust speed ($m\,s^{-1}$), wind direction (degrees clockwise from north = 0°), solar radiation ($W\,m^{-2}$), barometric pressure (mbar), temperature (°C), and relative humidity (%). Event and 5-min averages were calculated for each of these, and the latter two were used to derive event and 5-min averages for *VPD* (kPa). Because net radiant energy has been shown to be a minor contributor to evaporation of wetted canopies (refer to Carlyle-Moses and Gash, 2011), an evaporation coefficient, *E*, based on the aerodynamic approach to estimating evaporation from wetted surfaces (Dalton, 1802; refer to Ward and Robinson, 2000), was calculated based on *VPD* and wind speed:

$$E = W \cdot VPD \tag{1}$$

where *W* is the wind speed ($m\,s^{-1}$).

Tipping bucket records were used to identify the start and end of each rain event (separated by rain-free breaks of at least 12 h) as well as duration of breaks (≥0.5 h without a tip), yielding the total duration of intra-storm breaks, D_B (h) and total rain duration, D_R (h). Two measures of intensity were calculated: (i) 5-min maximum intensity, I_{max5}, (mm h^{-1}), and (ii) 5-min weighted intensity, I_{wt5} (mm h^{-1}). To derive the 5-min weighted averages, 5-min (unweighted) averages were multiplied by rain depth in those 5 min; values were totalled then divided by event rainfall depth to give averages reflecting conditions during rain. Event and 5-min average rainfall inclination angles were also calculated using rainfall intensity, wind speed, and relationships with drop size and terminal fall velocity (Herwitz and Slye, 1995). The Laws and Parsons' (1943) best-fit equation is the basis for droplet size:

$$D = 2.23\ (0.03937\ PI)^{\ 0.102} \tag{2}$$

where D is the median raindrop diameter (mm) and PI is the rainfall intensity (mm h^{-1}). The following empirical best-fit equation (Gunn and Kinzer, 1949) yields terminal fall velocity:

$$U_v = (3.378(\ln(D))) + 4.213 \tag{3}$$

where U_v is terminal velocity (m s^{-1}) of any droplet of diameter D. Substituting this value and wind speed allows for calculation of inclination angle:

$$\tan P_{inc} = \frac{W_{wt5}}{U_v} \tag{4}$$

where P_{inc} is the rainfall inclination angle (degrees from vertical), W_{wt5} is the 5-min weighted average wind speed (m s^{-1}), and U_v is terminal fall velocity (m s^{-1}). Table I lists all meteorological variables used in the analyses along with abbreviations and units.

Data analysis

Using exploratory cluster analysis (K-means method; IBM® SPSS® Statistics Version 22, hereafter SPSS®) of 34 independent trait variables (not including L_n), the 37 study trees were assigned to clusters that corresponded to two general canopy morphologies: single-leader (main stem with intersecting feeder branches) and multi-leader (two or more leaders converging at the base of the canopy, each of these intersected by feeder branches). Herwitz (1987), Dunkerley (2013), and others have documented that *SF* drains to and along the undersides of upright branches, suggesting that *SF* production processes might differ in trees with single trunks compared with their multiple-leader counterparts.

Using double mass analysis (Searcy and Hardison, 1960), it was determined that the slope and intercept of TBRG *versus* manual gauge rainfall depths were significantly ($\alpha = 0.05$) different from unity and zero respectively, for the period after 1 April 2013, and as such, a correction factor was applied to the TBRG data after this date (refer to Schooling, 2014). Data for valid events with rain depths equal to or greater than the first event that yielded $SF \geq 0.01$ l, even if some larger events produced no *SF*, were plotted (*SF* in L *vs P* in mm). The mean threshold rainfall depth required for *SF* initiation, P'', and the mean *SF* flow rate once P'' that has been satisfied, Q_{SF}, were derived empirically using the slope, α, and intercept, β, from these linear regression equations for each individual tree:

$$P'' = \left|\frac{\beta}{\alpha}\right| \tag{5}$$

and

$$Q_{SF} = \alpha \tag{6}$$

There is precedent for using multiple regression to analyse the influences of both trait and meteorological variables on *SF* (e.g. Staelens *et al.*, 2008; Van Stan *et al.*, 2014). We used stepwise-up multiple regression to identify the major variables influencing the dependent variables (Armstrong and Hilton, 2010). Multicollinearity was quantified using the variance inflation factor statistic (Hair *et al.*, 1998; Allison 1999) and although a threshold variance inflation factor of 4 to 10 is often applied (refer to O'Brien, 2007), we use a stricter criterion of ≤2.5 to ensure collinearity is minimal (refer to Næs and Mevik, 2001). All multiple linear

Table I. List of selected meteorological variables

Category	Meteorological variable	Abbreviation	Units
Depth	Rain depth	P	mm
Duration	Duration of rain	D_R	h
	Duration of breaks ≥ 30 min	D_B	h
Intensity	5-min weighted rainfall intensity	I_{wt5}	mm h^{-1}
	5-min maximum rainfall intensity	I_{max5}	mm h^{-1}
Angle	Rainfall inclination angle	P_{inc}	degree from vertical
Wind	5-min weighted average wind speed	W_{wt5}	m s^{-1}
Vapour pressure deficit	Vapour pressure deficit	VPD	kPa

For meteorological variable regressions during transitional leaf states, actual canopy cover, *ACC* (%), was included as a ninth potential predictor of stemflow volume.

regressions were run in Smith's Statistical Package following transformations of dependent and independent variables (if necessary) as described by Schooling (2014). To facilitate comparison of Q_{SF} for trees of widely varying sizes, leaf-on multiple regression analyses at the group level were run for $Q_{SF}\ PCA^{-1}$ as well as for P'' and Q_{SF}. Using 18 trait variables, we identified those which significantly ($p \leq 0.05$ or $p \leq 0.10$ when specified) explained variation in P'', Q_{SF}, and $Q_{SF}\ PCA^{-1}$ for each tree group. Analyses for single-leader trees used 17 variables as L_n was constant.

On an individual tree basis, we explored the role of actual canopy cover, ACC, during spring and fall using multiple regression of SF volume on P and ACC, calculated as

$$ACC = WC + LF(CC - WC) \tag{7}$$

where LF is the observed leaf fraction at event date.

The influence of storm meteorology on SF volume was also analysed at the tree level with multiple regression yielding an equation of significant ($p \leq 0.10$) meteorological variables (out of eight potential variables for leaf-on and leaf-off condition or nine variables, including ACC, for transitional leaf condition; refer to Table I). Occurrence or non-occurrence of a significant ($p \leq 0.10$) meteorological variable in each tree's equation formed the basis of a full-sample analysis (both groups combined) using a one-way ANOVA with Tukey honest significance difference post-hoc (Tukey, 1953) in SPSS® to detect associations between meteorological variables and canopy characteristics.

RESULTS

Precipitation profile

Between 12 June 2012 and 2 November 2013, 101 events with precipitation depths ≥0.2 mm were recorded; frequency values of depth by precipitation type are presented in Figure 3. A total of 394.4 mm fell: 327.9 mm as rain (86 events), 9.3 mm as mixed (4 events), and 57.2 mm as snow (11 events). We collected 89.8% of this total depth and estimated the remainder (primarily snow) using Environment Canada (2014) data for the nearby Kamloops A* station. Frequency of rain by depth class approximated 1981–2010 normals for Kamloops.

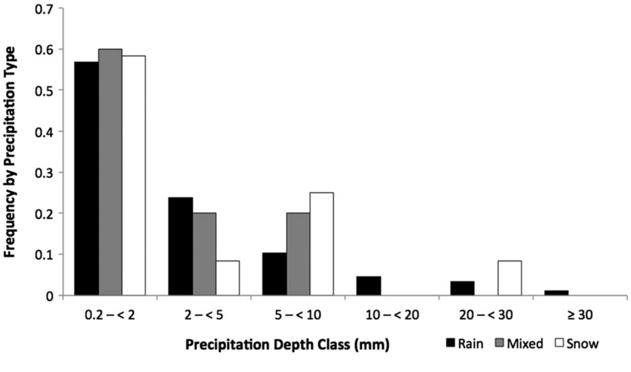

Figure 3. Frequency of precipitation events by type and depth class

Influence of canopy characteristics

Thirty-seven isolated trees of 21 cultivated species were chosen (10.2–68.7 cm DBH; Table II). Table III summarizes means and ranges for these trait metrics for each group (Group SL, single-leader; Group ML, multi-leader). Results of multiple regressions of P'', Q_{SF}, and $Q_{SF}\ PCA^{-1}$ for Group SL and ML trees on canopy trait variables are presented in Table IV. For rain events <3 mm, while trees were either in full leaf or completely leafless, SF volume was plotted against rain depth. Figure 4 depicts, for four variously sized trees (two each from Groups SL and ML), the patterns that were evident for many trees. Stemflow from leafless trees generally started at lower threshold rain depths than when leaves were present, and when it was produced, volumes were often higher for leafless trees, especially for rain events < 2 mm. For example, none of the four trees produced SF in leaf-on condition for 1.1-mm rain events, but when leafless, SL-7 produced 1.5 l, SL-15 produced 0.57 l, ML-5 produced 0.68 l and 0.06 l, and ML-9 produced 3.55 l and 2.39 l for 1.1 mm events. At a 1.4-mm rain depth, there was still a differential between leaf-on and leaf-off SF for these trees: 0.17 l *versus* 0.46 l (SL-7), no SF *versus* 0.13 l (SL-15), 0.07 l *vs* 1.31 L (ML-5), and 1.12 l *versus* 2.73 l (ML-9). At rain depths ≥2.1 mm, leafless trees occasionally out-produced leafed trees, but no longer consistently.

Influence of meteorological and seasonal factors

For leafed and leafless trees with data for ≥9 rain events, SF volume was regressed on eight core meteorological variables; in addition, ACC was used for trees in leaf transition with ≥10 events. Regression equations for individual trees' leaf-on, transitional, and leaf-off periods are provided in Appendix Tables I, II, and III respectively. When trees were grouped by whether or not each meteorological variable was significant ($p \leq 0.10$) in the individual tree's SF volume regression equation, significant differences between group means ($p \leq 0.10$) were found for some canopy traits. Appendix Table IV summarizes these relationships between meteorological and trait variables for our study trees.

DISCUSSION

Controls on SF processes in this study's isolated trees in an urban park situation are discussed in the context of the

Table II. Single-leader (Group SL) and multi-leader (Group ML) study trees listed in ascending order of diameter at breast height, *DBH*, with associated overall height, *H*, average canopy width, *CW*, and projected canopy area, *PCA*

Tree ID	Latin name	Common name	*DBH* (cm)	*H* (m)	*CW* (m)	*PCA* (m^2)
SL-1	*Cercidiphyllum japonicum*	Katsuratree	10.2	5.7	3.7	11.1
SL-2	*Cercis canadensis*	Eastern Redbud	10.5	4.9	4.0	13.5
SL-3	*Quercus rubra*	Red Oak	11.4	6.3	5.1	17.6
SL-4	*Prunus virginiana* 'Shubert'	Shubert Chokecherry	12.7	7.2	4.5	19.5
SL-5	*Robinia pseudoacacia* 'Purple Rain'	Purple Rain Bl. Locust	14.6	7.9	6.9	34.1
SL-6	*Gleditsia triacanthos*	Honeylocust	15.1	9.9	6.4	46.1
SL-7	*Acer saccharinum*	Silver Maple	15.9	9.6	5.1	20.2
SL-8	*Tilia cordata*	Littleleaf Linden	17.2	8.1	4.6	17.5
SL-9	*Fraxinus pennsylvanica*	Green Ash	19.0	10.5	6.0	27.3
SL-10	*Acer rubrum columnar*	Columnar Red Maple	19.0	11.3	5.2	22.4
SL-11	*Fraxinus pennsylvanica*	Green Ash	19.7	10.6	5.6	25.5
SL-12	*Quercus rubra*	Red Oak	20.3	10.1	7.3	44.0
SL-13	*Quercus macrocarpa*	Bur Oak	21.5	9.8	7.5	37.2
SL-14	*Quercus robur columnar*	English Columnar Oak	23.5	14.6	2.8	6.3
SL-15	*Acer x freemanii* 'Armstrong'	Armstrong Freeman Maple	24.1	13.1	3.5	11.1
SL-16	*Aesculus hippocastanum*	Horsechestnut	31.0	10.8	5.8	27.7
SL-17	*Prunus padus* var. *commutata*	Mayday Cherry	34.3	9.6	8.5	50.3
SL-18	*Quercus palustris*	Pin Oak	43.0	14.1	13.6	149.1
SL-19	*Quercus palustris*	Pin Oak	52.7	13.8	13.7	150.6
SL-20	*Quercus palustris*	Pin Oak	60.7	24.7	14.2	164.8
ML-1	*Salix babylonica*	Weeping Willow	15.2	8.1	5.9	28.9
ML-2	*Sorbus quercifolia*	Oak-leaf Mountain Ash	18.3	6.3	4.4	15.9
ML-3	*Prunus virginiana* Shubert	Shubert Chokecherry	18.8	8.5	6.6	35.2
ML-4	*Gleditsia triacanthos* 'Sunburst'	Sunburst Honeylocust	21.0	8.7	7.8	52.5
ML-5	*Acer platanoides*	Norway Maple	24.6	8.7	8.1	54.2
ML-6	*Acer platanoides* 'Crimson King'	Crimson King Maple	26.0	8.9	5.3	23.4
ML-7	*Fraxinus pennsylvanica*	Green Ash	28.9	12.6	7.5	43.5
ML-8	*Acer platanoides*	Norway Maple	36.9	10.3	10.1	84.7
ML-9	*Fagus sylvatica 'Riversii'*	Riversii European Beech	38.8	11.0	9.3	65.8
ML-10	*Aesculus hippocastanum*	Horsechestnut	41.3	8.3	7.5	46.5
ML-11	*Acer platanoides* Crimson King	Crimson King Maple	43.0	12.0	10.7	99.7
ML-12	*Tilia cordata*	Littleleaf Linden	46.0	11.2	7.6	43.5
ML-13	*Fraxinus pennsylvanica*	Green Ash	51.8	13.0	14.2	163.8
ML-14	*Robinia pseudoacacia*	Black Locust	54.3	10.5	11.2	103.0
ML-15	*Catalpa speciosa*	Northern Catalpa	58.0	14.2	9.5	79.5
ML-16	*Eleagnus angustifolia*	Russian Olive	66.8	16.8	15.1	206.6
ML-17	*Acer saccharinum*	Silver Maple	68.7	18.6	16.7	214.5

few other urban SF studies as well as the broader SF literature, revealing both common and contrasting factors.

Stemflow initiation threshold

Examination of the multiple regression equations in Table IV reveals some common factors within and between groups for different dependent variables. Firstly, threshold rainfall depth for *SF* initiation, P'' was directly related to *DBH* but only for single-leader trees; on the other hand *BRI* was positively related to P'' for both single-leader and multi-leader trees. The influence of *BRI* is apparent when comparing P'' for some Group SL and ML trees of similar size, whereby smoother bark (in concert with other traits) was associated with lower P''. For example, trees SL-6 and ML-1 had *DBH* of 15.1 and 15.2 cm respectively but contrasting *BRI* values of 1.01 and 1.22; their P'' values were 2.0 and 3.6 mm respectively. In addition, tree SL-9 (*DBH* = 19.0 cm, *BRI* = 1.09) had P'' of 3.7 mm compared with P'' of 1.3 mm for smooth-barked ML-3 (*DBH* = 18.8 cm, *BRI* = 1.01). The increase in P'' with increasing *DBH* likely reflects the increased surface area and thus water storage capacity offered by larger trees, while trees of similar size (i.e. *DBH*), but with greater *BRI*, exhibit greater P'' because of the increased effective surface area and thus storage potential per unit area of bark (Levia and Frost, 2003; Levia and Herwitz, 2005; Levia *et al.*, 2010).

For Group SL, additional trait variables were significant at the $p \leq 0.10$ level: canopy cover (*CC*) (positive) and angle of branch intersection in the *AIU* (negative, such that higher P'' was associated with lower branch angles). Neither of these variables was significant ($p \leq 0.10$) for multi-leader P'' while tree height, *H*, was a factor only for Group ML trees. Finally,

Table III. List of selected tree and canopy metrics indicating mean (range) values within Group SL ($n = 20$) and Group ML($n = 17$)

Tree trait		Group SL (single-leader)		Group ML (multi-leader)	
		Mean	Range	Mean	Range
Basic tree	*DBH* (cm)	23.8	(10.2–60.7)	38.7	(15.2–68.7)
Size metrics	Tree Height, *H* (m)	10.6	(4.9–24.7)	11.1	(6.3–18.6)
Canopy	Canopy width, *CW* (m)	6.7	(2.8–14.2)	9.3	(4.4–16.7)
Dimension	Canopy height-to-width ratio, *HWR*	1.49	(0.79–4.13)	1.12	(0.71–1.47)
Metrics	Projected canopy area, *PCA* (m^2)	44.8	(6.3–164.8)	80.1	(15.9–214.5)
	Projected wood area, *PWA* (m^2)	11.3	(1.4–54.9)	34.1	(2.6–109.4)
	Canopy volume, Vol_C (m^3)	371.2	(28.3–1801.2)	803.6	(56.9–3872.0)
	Wood volume, Vol_W (m^3)	28.4	(1.0–183.5)	120.8	(3.1–551.4)
Cover metrics	Canopy cover, *CC* (%)	89.3	(74.9–99.6)	92.4	(80.7–98.8)
	Wood cover, *WC* (%)	23.1	(10.5–41.0)	37.8	(14.7–68.4)
Branch and bark metrics	Branch count, B_n (no. branches)	28.2	(12–52)	59.3	(27–85)
	Leader count, L_n (no. leaders)	1.0	(1–1)	3.6	(2–6)
	Intersection angle, full tree avg, *AIF* (degree)	43.6	(14.3–68.1)	44.8	(25.0–60.2)
	Intersection angle, upper 1/3 avg, *AIU* (degree)	48.0	(20.4–75.1)	46.0	(22.6–58.8)
	Average angle, full tree avg, *AAF* (degree)	43.3	(18.2–77.0)	41.3	(6.5–66.2)
	Average angle, upper 1/3 avg, *AAU* (degree)	49.5	(13.5–83.0)	43.8	(−3.3–66.2)
	Frequency of discontinuity, full tree, *FD*	0.17	(0.00–0.48)	0.18	(0.00–0.59)
	Bark relief index, *BRI* (ratio)	1.08	(1.00–1.23)	1.18	(1.00–1.43)
Leaf size	Median leaf size, *MLS* (cm^2)	26.8	(1.4–92.2)	23.2	(1.8–71.6)

Table IV. Multiple regression equations for stemflow initiation thresholds, P'' (mm), flow rates post-initiation, Q_{SF} ($l\,mm^{-1}$) and flow rates per unit projected canopy area $Q_{SF}\,PCA^{-1}$ ($l\,mm^{-1}\,m^{-2}$) as functions of tree morphological traits, generated for single-leader (Group SL, $n = 20$), and multi-leader trees (Group ML, $n = 17$)

Equation	R^2	*SEE*	$p \le$
P'' Group SL			
$-18.10\ DBH^{-1} + 1.34 BRI^3 + 2.56$	0.528	0.69	0.05
$-11.85\ DBH^{-1} - 313.76\ CC^{-1} 1.57\ BRI^3 + 32.19\ AIU^{-1}$	0.660	0.62	0.10
P'' Group ML			
$-10.63\ BRI^{-1} + 2.34 \ln H$	0.546	1.31	0.05
$-9.11\ BRI^{-1} + 2.72 \ln H - 0.010\ L_n^3$	0.632	1.22	0.10
Q_{SF} Group SL			
$\left(0.23\sqrt{H} + 2.62\ BRI - 0.015\ B_n + 0.12 \ln Vol_C - 0.47\ MLS^{-1} - 2.64\right)^2$	0.860	0.16	0.05
Q_{SF} Group ML			
$e^{\left(0.51\ L_n + 3.51E-06\ WC^3 - 0.67\ BRI^3 - 36.35\ AIF^{+} - 0.0002\ CW^3\right)}$	0.952	0.22	0.05
$Q_{SF}\ PCA^{-1}$ Group SL			
$e^{\left(0.0006\ AIF^2\ -2.48\ BRI^{-1}\ -1.14\ MLS^{-1}\ -2.17\right)}$	0.853	0.33	0.05
$e^{\left(0.0004\ AIF^2\ +7.76E-06\ WC^3 - 6.09\ BRI^{-1} - 6.31E-06\ B_n{}^3 - 5.23E-06\ DBH^3 - 1.22\ MLS^{-1}\right)}$	0.931	0.25	0.10
$Q_{SF}\ PCA^{1}$ Group ML			
$-0.062 \ln CW + 1.48E - 07 WC^3 - 0.10\ BRI + 1.15E - 07\ AIF^3 + 0.0004\ L_n^3 + 0.25$	0.901	0.013	0.05

The first variable listed explained more variation than any other. Standard error of the estimate, *SEE*, is given in units defined in the preceding texts.

the number of leaders, L_n, was inversely related to P'' for the multi-leader trees. The increase in P'' with increasing *CC* and decreasing *AIU* is probably a consequence of the decrease in the effective rainfall input, and thus, the potential water volume that could be partitioned into *SF*, reaching the branches and the boles of trees, and the decrease in the coupling of branch flow with flow down the bole and increased potential for *TF* to be generated respectively (Herwitz, 1987; Levia and Frost, 2003; Xiao *et al*., 2000; Xiao and McPherson 2011).

In this study, the smallest event to generate $SF \geq 0.01$ l was 0.9 mm for SL-1, ML-3, ML-5, and ML-9. This compares to mean *SF* initiation thresholds of 3.4 ± 0.3 mm for beech and 10.9 ± 1.2 mm for oak in a temperate mixed

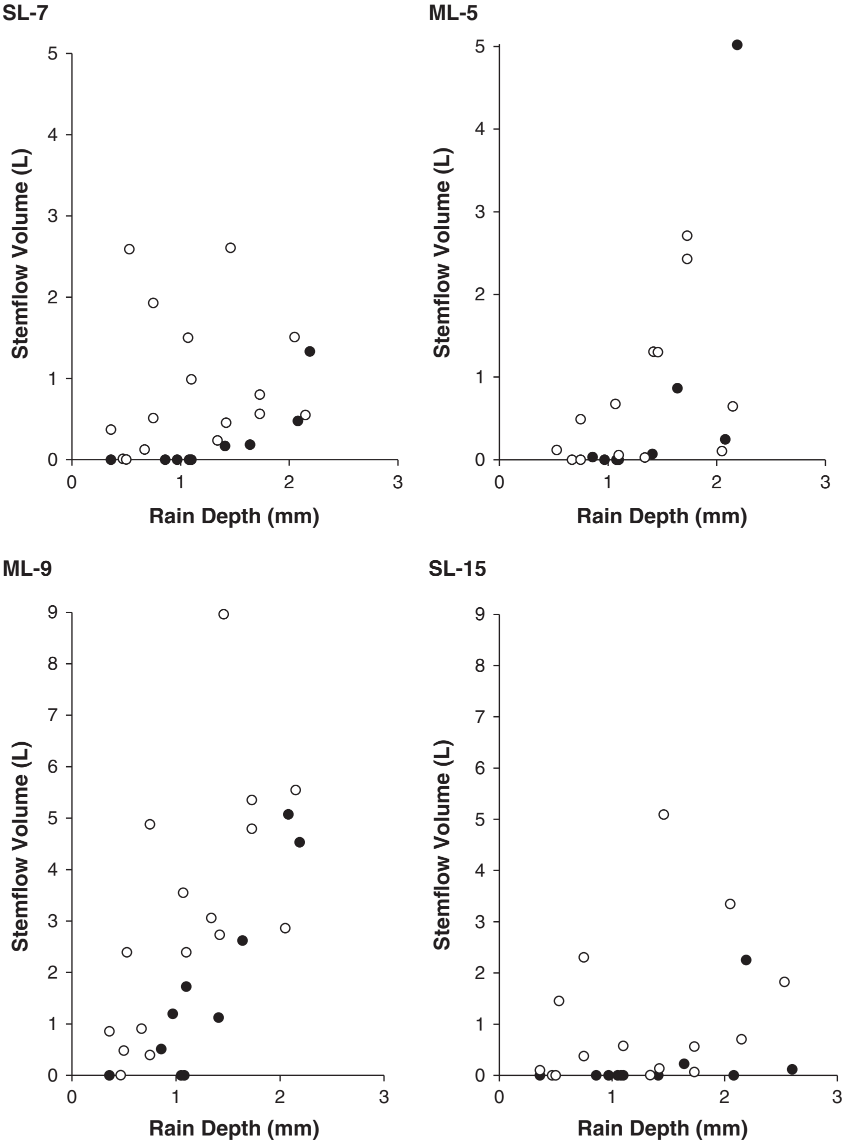

Figure 4. Comparison of stemflow volume (l) produced from rain events less than 3 mm by trees in full leaf (closed circles) *versus* leafless (open circles) conditions

forest (André *et al.*, 2008b), > 1 and >4 mm for urban *Eucalyptus saligna* and *E. nichollii* trees respectively (Livesley *et al.*, 2014), and 1.5 – 4.9 mm for six species in a laurel forest in the Canary Islands (Aboal *et al.*, 1999a). Study trees with the lowest derived thresholds included SL-1 (small *DBH* with smooth bark and numerous, steeply inclined branches), SL-3 (small, smooth bark, high *CC*), ML-3 (small, smooth bark, with numerous branches), and ML-9 (medium-sized but extremely smooth-barked with many leaders). These examples serve to confirm the importance of conducive traits identified by others including smooth bark (Levia and Herwitz, 2005; Van Stan and Levia, 2010) and high branch inclination angles (Herwitz, 1987; Xiao *et al.*, 2000; Levia *et al.*, 2014). As we did for single-leader trees, André *et al.* (2008a) found that lower P'' (reflecting lower apparent storage capacity) was associated with smaller *DBH* trees; for our multi-leader trees, *H* was highly correlated with *DBH* (Spearman $r \leq 0.01$) and may have been acting as a proxy for the latter size-related variable. The fact that L_n was inversely related to P'' for Group ML suggests that the benefits of having multiple major *SF* flowpaths to the base of the canopy outweighed the disadvantages associated with increased wood area to be saturated, particularly for smooth-barked trees.

Stemflow rate

Stemflow rate was significantly ($p \leq 0.05$) correlated with *BRI* in both Group SL and ML trees, positively for single-leader trees, but inversely for multi-leader trees. This implies that for single-leader trees, more deeply furrowed bark may contribute to higher *SF* rates, particularly if furrows are linear rather than diamond-shaped or forked (Levia and Herwitz, 2005). In fact, the five highest Q_{SF} values among Group SL trees (1.97–3.611 mm^{-1}) were for trees with moderate bark relief (*BRI* ranging from 1.15–1.20) and bark with linear furrows. The highest $Q_{SF}\,PCA^{-1}$ value was for SL-14, an English columnar oak with linearly furrowed bark of moderate relief. Others have documented the promotion of *SF* production (and resistance to evaporative forces) by such linear microrelief, despite its association with higher normative bark water storage and delay of *SF* initiation (Levia and Herwitz, 2005). Most smooth-barked and flaky-barked trees had lower rates, although two of the highest $Q_{SF}\,PCA^{-1}$ values were for trees with extremely low *BRI*, suggesting that other traits (such as high branch angles) in association with smooth bark may contribute to high rates on a per-canopy-area basis.

Tree height explained more variability in Q_{SF} (57%) than any other factor for Group SL trees, although it was not significant ($p \leq 0.10$) for Group ML trees and is not identified frequently in the literature (e.g. Germer *et al*., 2010). It is possible that *H* was acting as a proxy for *DBH* (as discussed in the preceding texts) or other closely correlated size-related variables in this study. Branch count, B_n, was inversely related to Q_{SF} in single-leader trees only. Reduced *SF* with more branches was also found by Herwitz (1985), who attributed this effect to increased storage capacities, but Návar (1993), Aboal *et al*. (1999b), and Levia *et al*. (2014) all found higher B_n to promote *SF*. Specifically, Levia *et al*. (2014) concluded that woody biomass, branch count (both per unit *PCA*), and mean inclination angles were the most important factors governing $SF\,PCA^{-1}$ in their study of European beech saplings. For Group SL trees, greater canopy volume, Vol_C, was associated with higher Q_{SF}, as found by Martinez-Meza and Whitford (1996) for certain desert shrubs, Crockford and Richardson (1990) for pine and eucalypts (crown size per *DBH*), and Aboal *et al*. (1999b) for a laurel forest. Aboal *et al*. (1999b) also noted that small leaves contributed to more efficient *SF* production, counter to the positive relationship between median leaf size, *MLS*, and Q_{SF} for our Group SL study trees. For Group ML trees, L_n explained 52% of variation in Q_{SF}, while *WC* was also positively related, given that L_n has not been examined to our knowledge (although both factors are consistent with findings of Levia *et al*. [2014] that woody biomass is associated with high *SF*), we recommend further study to refine understanding of its potential role. The regression equation for Group ML Q_{SF} suggests that L_n may be of particular importance when a tree also has smooth bark and high full-canopy intersection angles, *AIF*, and when *CW* is relatively small (minimizing the distance that *SF* needs to travel to reach the bole). Few specific results are published on *CW*, but many authors corroborate the importance of associated traits such as high branch inclination angles for *SF* in trees and shrubs (Martinez-Meza and Whitford, 1996; Crockford and Richardson, 2000; Barbier *et al*., 2009; Levia *et al*., 2014; Van Stan *et al*., 2014). Herwitz (1987) observed that >80% of impacting rain became branchflow for branch angles >60° in the laboratory, but there is a ‘tipping point’ at which the benefits of high branch angles in conducting *SF* will be offset by a tree’s smaller *PCA* (Pypker *et al*., 2011; Levia *et al*., 2014).

Derived Q_{SF} for single-leader trees ranged from 0.33 (SL-3: small, smooth, and relatively few branches) to 3.611 mm^{-1} (SL-20: tallest study tree, large volume, moderate *BRI*, and disproportionately low branch count). For multi-leader trees, Q_{SF} ranged from 0.48 (ML-4: moderate *BRI*, only one secondary leader, low wood cover, *WC*, and *AIF*, and relatively high *CW* for its size) to 7.451 mm^{-1} (ML-9: very smooth bark, many leaders, moderate *WC*, relatively low *AIF*, and average *CW*). The latter tree’s early and voluminous *SF* production in this study is consistent with findings of others studying beech species (e.g. Levia *et al*., 2014, 2010; Staelens *et al*., 2008; Van Stan *et al*., 2014). Based on observations of *SF* on the study tree’s trunk, it is possible that the bark may not be only smooth but hydrophobic, a condition possibly enhanced by the presence of water-repellent lichen (Shirtcliffe *et al*., 2006), which we observed along preferential flowpaths on the trunk of ML-9. Water repellency in *Acacia* bark has been linked to presence of a waxy substance called suberin (Borgin and Corbett, 1974), which has also been extracted from beech bark (Perra *et al*., 1993).

For comparison, a sample of *SF* rates observed by others includes 0.08 ± 0.041 mm^{-1} for oak and 0.09 ± 0.021 mm^{-1} for beech in a mixed stand (André *et al*., 2008b), and a range of 0.070 ± 0.011 to 0.172 ± 0.0131 mm^{-1} for five tropical tree species (Park and Cameron, 2008). The derived rate for ML-9 in our study is over 43 times greater than the highest rate calculated by Park and Cameron (2008), which even the lowest rates for our study trees exceed. Researchers in urban environments have long been aware that *SF* rates and yields tend to be greater for isolated trees (e.g. Xiao *et al*., 2000; David *et al*., 2006; Guevara-Escobar *et al*., 2007) although the magnitude of this effect depends on climate, rainfall depth, and storm meteorology, as well as tree species and size. In general, gains because of unobstructed precipitation appear to more than offset losses from an open-grown canopy to evaporative forces (Gash *et al*., 1995) and dislodgement of potential *SF* by wind.

For Q_{SF} PCA^{-1}, *BRI* was again positively related for Group SL trees and inversely related for Group ML trees. Angle of intersection (full tree) explained over 73% of variation in Q_{SF} PCA^{-1} for Group SL and was also a positive factor for Group ML; this agrees with the results of studies cited in the preceding texts (e.g. Levia *et al.*, 2014) and confirms that this factor remains highly influential once rate is standardized per unit *PCA*. Remaining factors for Group SL were *MLS* and *WC* (both positive) and B_n and *DBH* (both inverse) of which *WC* was inversely related to Q_{SF} PCA^{-1} for Group ML (*WC* appeared to promote *SF* when there was a primary bole, but suppressed it when multiple leaders conveyed flow to the base of the canopy). The inverse relationship between *DBH* and Q_{SF} PCA^{-1} indicates that single-leader trees with lower basal areas tended to have higher rates per *PCA*, as well as lower P'', meaning that especially for small events, they are likely to out-produce larger-*DBH* trees. Canopy width explained 38% of variability in Q_{SF} PCA^{-1} for Group ML trees; the inverse relationship likely reflects that traits associated with narrower trees (e.g. high branch angles and *CC*) promoted *SF* in multi-leader trees. The final positive factor for Group ML trees, one also significant ($p \leq 0.10$) for P'' and Q_{SF}, was L_n: more leaders meant higher yields because of both lower thresholds and higher rates. Highest derived Q_{SF} PCA^{-1} for Group SL trees was $0.2021\,\mathrm{mm}^{-1}\,\mathrm{m}^{-2}$ for SL-14 (the tightly columnar oak with relatively high *BRI* and *WC* as well as exceptionally high branch angles) and for Group ML was $0.1131\,\mathrm{mm}^{-1}\,\mathrm{m}^{-2}$ for ML-9 (the European beech with very low *BRI* and numerous leaders but moderate values for other conducive traits).

Influence of leaf condition on stemflow from rain

The tendency of leafless trees in both groups to produce *SF* at smaller rain depths and in greater quantities than leafed trees for a given rain depth $<3\,\mathrm{mm}$ is consistent with the significant inverse correlation ($p \leq 0.10$) of *ACC* to *SF* yields in regression equations for over half of the study trees analysed in transitional leaf states. While many researchers have observed this pattern (Helvey and Patric, 1965; Xiao *et al.*, 2000; André *et al.*, 2008a; Staelens *et al.*, 2008), others have found the reverse (Liang *et al.*, 2009) or no significant difference between seasons (Deguchi *et al.*, 2006). The observed pattern of increased *SF* yields from defoliated trees was less distinct as rain depth increased, implying that storm characteristics and other canopy traits may supersede *ACC* in importance. For example, Van Stan *et al.* (2014) found that (i) presence of leaves increased direct associations between *SF* and rainfall intensity for yellow poplar and American beech, (ii) a positive relationship between *SF* and wind speed for leafed canopies switched to an inverse one for leafless canopies, (iii) beech exhibited strengthened differences between leaf states for *SF* – rainfall depth and *SF* – wind speed associations, and (iv) relationships were further modified by *DBH* class.

Meteorological influences on stemflow for various leaf conditions

Rain depth, *P*, had a dominant influence on *SF* volume for individual trees: in only two cases did rain duration (usually closely correlated with depth) supersede *P*. This finding is supported by most studies, including André *et al.* (2008b) for oak and beech and Levia *et al.* (2010) and Van Stan *et al.* (2014) for beech and yellow poplar. Xiao *et al.* (2000) made the distinction that *SF* for saturated canopies was tightly controlled by *P* while *SF* from unsaturated canopies reflected storage capacity and the various morphological and meteorological factors associated with wetting-up. Carlyle-Moses and Price (2006) found that funnelling ratios increased with greater rain depths up to a threshold for a growing-season mixed deciduous forest; once this level of saturation was reached, the authors speculated that flowpaths were overloaded and more intercepted rain was diverted to *TF*.

Break duration was inversely related to *SF* (except for ML-7) and was significant ($p \leq 0.10$) for various trees and leaf conditions. While some studies have explored intra-storm variability of *SF* (e.g. Levia *et al.*, 2010), very few have quantified the influence of storm breaks. For an oak – beech stand, André *et al.* (2008b) did discern that storage capacity and rainfall threshold appeared to increase with the ratio of potential dry-period evaporation to preceding rain volume. In light of our findings, this relationship may also apply to intra-storm breaks.

Neither measure of rainfall intensity was consistently correlated to *SF* yield in our study. According to Levia and Frost (2003) and exemplified by Carlyle-Moses and Price (2006) for red oak, sugar maple, and American beech, *SF* is often found to vary inversely with rainfall intensity; however, Van Stan *et al.* (2014) observed positive correlations between *SF* and rainfall intensity for American beech and yellow poplar but emphasize that tree size, bark roughness, and other meteorological factors interact with intensity in complex ways.

When it was significant ($p \leq 0.10$), rainfall inclination angle, P_{inc}, was always positively correlated with *SF*, occurring frequently for Group SL trees and occasionally for Group ML trees in leaf-on and leaf-off but not transitional states. Herwitz and Slye (1995) found differential *SF* generation from rain inclined >19° from vertical across varying storm depths, durations, and intensities. Using this angle to categorize rainfall as inclined or not, Van Stan *et al.* (2011) found significant correspondences between wind-driven inclined rain and *SF* production in American beech and yellow poplar for almost all storm events. They observed preferential *SF* generation in both species when winds were from particular directions and noted that the vertically deeper canopy of beech trees enhanced efficiency of inclined rainfall capture and funnelling as *SF*. Among our trees, P_{inc} was a significant ($p \leq 0.10$) factor for *SF* volume for highly columnar SL-14 in leaf-on condition, but there was no consistent association with greater height-to-width ratios. In our study, event average P_{inc} was ≥20° for only 3 of 60 rain events (5%), 10° to <20° for 20% of events, 5° to <10° for 30% of events, and <5° for 45% of events. The significance ($p \leq 0.10$) of P_{inc} for many trees in leafed and leafless conditions suggests that *SF* in isolated deciduous trees may be sensitive to rain falling at less inclined angles (from vertical) than observed in forest studies.

With two exceptions, 5-min weighted average wind speed, W_{wt5}, was always positively related to *SF* and occurred more commonly for leaf-on and leaf-off than transitional conditions. This agrees with findings of Xiao *et al.* (2000) for isolated oak and pear trees and André *et al.* (2008b) that higher wind speeds during rain enhanced *SF* production for oak and beech, apparently by reducing *SF* initiation thresholds. This direct association was strongly demonstrated by Van Stan *et al.* (2014) for three size classes of American beech and yellow poplar during the growing season; for leafless canopies (particularly smaller ones), however, *SF* was inversely related to wind speed, possibly reflecting increased evaporation from bark in the absence of shelter from leaves.

After *P*, inverse *VPD* (i.e. transformed to strengthen linearity for regressions) was the second most common factor influencing *SF* volume, certainly for leaf-on trees; because the inverse variable influenced *SF* positively, higher values of *VPD* were associated with lower *SF* volumes. Staelens *et al.* (2008) documented this relationship for a beech forest, while Van Stan *et al.* (2014) confirmed the inverse effect of *VPD* for leafed American beech and yellow poplar, noting that the effect was enhanced for taller trees.

CONCLUSION

This study of isolated deciduous park trees confirms the volumetric importance of *SF* and the influence of various canopy traits on *SF* initiation thresholds and rates as well as meteorological characteristics on *SF* volumes. Smooth bark and steeply inclined branch angles are among traits previously associated with high *SF* yields; we also found that *SF* initiation threshold rain depth decreased and *SF* rate increased with higher numbers of leaders converging at the base of a canopy. These traits were apparent in the sole European beech in our study that exhibited the lowest *SF* initiation threshold and highest *SF* rate among multi-leader trees. Single-leader trees tended to have higher *SF* yields if they had (i) high branch angles; (ii) low *DBH* and canopy cover (associated with lower thresholds); (iii) greater tree height, *BRI* (particularly when furrows were linear), canopy volume, and median leaf size; and (iv) fewer branches (associated with higher *SF* rates). Given that bark relief was correlated with both *SF* initiation threshold and rate for single-leader trees, resultant *SF* yield depended on rainfall depth, duration, and other storm and trait variables.

Despite the diversity of study tree species and sizes, patterns emerged regarding event meteorology including (i) the strong correlation between rainfall depth and *SF* yield, (ii) the influence of inclined rainfall at closer to vertical angles than previously observed, and (iii) the already established relationships between *SF* yield and wind speed (positive) and *VPD* (inverse). The effects of intra-storm break duration and rainfall intensity were less clear and warrant further study. Like others, we found seasonal patterns of enhanced *SF* from leafless canopies, especially at low rain depths; eight of 13 trees in partial leaf exhibited an inverse relationship between *SF* yield and *ACC*.

Among the reasons, our findings may depart from earlier results are differences in climate, tree species, and event profiles, but the primary one is likely our focus on isolated trees in an urban park situation. We expect that our trees' canopies were subject to influences that are undetectable (or at least complicated) in a forest setting. It is clear that *SF*, based on volumes we measured, must be managed in an urban setting, either as a resource in the form of supplemental irrigation where infiltration is possible, or as a hazard if excess *SF* becomes runoff on polluted impervious surfaces. In general, tree species with high branch angles, smooth bark (or linearly furrowed bark for single-leader trees), and many secondary leaders (for multi-leader trees) may be selected if *SF* production is desirable. If existing trees exhibit these traits, we recommend integration of absorbent landscaping (e.g. rain gardens, pervious pavers) at or near their bases. While interception loss by urban trees is substantial, *SF* can no longer be dismissed as insignificant, particularly in isolated trees; in fact, planting trees that divert intercepted rain to *SF* could reduce *TF*, which typically falls on paving. Future work should address *SF* quantity and quality (nutrients and pollutants) for isolated deciduous and coniferous trees of diverse ages and sizes in a range of climates and urban conditions. This body of knowledge will provide valuable guidance as we respond to the need for urban trees and their ecosystem services in ever-densifying cities.

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APPENDIX TABLE I. MULTIPLE REGRESSION EQUATIONS FOR STEMFLOW, *SF*, VOLUME (L) AS A FUNCTION OF METEOROLOGICAL VARIABLES, GENERATED FOR SINGLE-LEADER (GROUP SL, $N=20$), AND MULTI-LEADER TREES (GROUP ML, $N=17$) FOR N RAIN EVENTS DURING LEAF-ON CONDITION

Tree ID	Stemflow volume regression equation	R^2	*SEE*	n	$p\leq$
SL-1	$0.36\ P+0.56\ W_{wt5}-1.07$	0.885	1.12	27	0.05
SL-2	$0.43\ P+0.77\ W_{wt5}+0.19\ VPD^{-1}-2.85$	0.967	0.71	18	0.05
SL-3	$0.33\ P$	0.605	2.18	26	0.05
SL-4	$0.39\ P+0.12\ P_{inc}+0.23\ VPD^{-1}-3.10$	0.967	0.79	21	0.05
SL-5	$1.44\ P+0.30\ P_{inc}+0.75\ VPD^{-1}-9.25$	0.955	2.92	18	0.05
SL-6	$0.51\ P-0.076\ D_B+0.062\ P_{inc}+0.18\ VPD^{-1}-1.76$	0.931	1.07	22	0.10
SL-7	$1.30\ P+0.21\ P_{inc}-5.81$	0.880	4.05	25	0.05
SL-8	$0.51\ P-1.89$	0.876	1.66	20	0.05
SL-9	$1.44\ P+0.23\ P_{inc}+1.25\ VPD^{-1}-13.27$	0.907	4.26	20	0.05
SL-10	$1.32\ P+0.34\ P_{inc}-7.97$	0.867	4.63	21	0.05
SL-11	$1.64\ P+0.43\ P_{inc}+1.01\ VPD^{-1}-15.14$	0.939	4.58	21	0.05
SL-12	$0.42\ P-1.73$	0.721	1.66	21	0.05
SL-13	$1.98\ P+0.61\ P_{inc}+1.06\ VPD^{-1}-17.27$	0.947	5.26	18	0.05
SL-14	$1.34\ P-0.17\ I_{max5}+0.45\ P_{inc}-6.09$	0.916	3.68	20	0.10
SL-15	$1.31\ P+2.60\ W_{wt5}-5.96$	0.925	3.28	23	0.05
SL-16	$0.95\ P-3.64$	0.931	2.18	21	0.05
SL-17	$1.30\ P+0.15\ P_{inc}-5.23$	0.953	2.50	20	0.05
SL-18	$1.86\ P+0.44\ VPD^{-1}-9.37$	0.931	4.60	23	0.10
SL-19	$4.85\ D_R+0.51\ I_{max5}-19.37$	0.794	10.49	19	0.05
SL-20	$3.33\ P+6.62\ W_{wt5}+0.82\ VPD^{-1}-23.21$	0.941	6.80	17	0.05
ML-1	$3.18\ D_R+0.40\ P_{inc}-9.36$	0.836	4.58	21	0.05
ML-2	$0.96\ P+0.44\ P_{inc}+1.01\ VPD^{-1}-11.65$	0.911	3.54	24	0.05
ML-3	$1.42\ P-0.12\ D_B+1.46\ W_{wt5}+0.53\ VPD^{-1}-4.73$	0.978	2.09	26	0.05
ML-4	$0.48\ P-1.52$	0.913	1.08	17	0.05
ML-5	$2.78\ P+3.37\ W_{wt5}-8.33$	0.828	10.11	27	0.05
ML-6	$2.20\ P-9.08$	0.851	8.11	19	0.05
ML-7	$0.69\ P+0.25\ D_B+0.23\ I_{wt5}+0.58\ VPD^{-1}-10.74$	0.942	2.75	15	0.10
ML-8	$3.46\ P+0.59\ P_{inc}+1.66\ VPD^{-1}-26.45$	0.947	6.95	19	0.05
ML-9	$8.22\ P-1.11\ D_B-9.35$	0.958	12.92	28	0.05
ML-10	$2.96\ P-0.97\ VPD^{-1}-5.15$	0.923	6.81	22	0.05
ML-11	$2.52\ P+3.24\ W_{wt5}+0.53\ VPD^{-1}-14.87$	0.968	4.53	20	0.10
ML-12	$2.94\ P-15.51$	0.900	8.98	16	0.05
ML-13	$0.62\ P+0.13\ I_{wt5}+0.061\ I_{max5}-6.62$	0.994	0.50	12	0.05
ML-17	$0.72\ P+3.02\ W_{wt5}+0.71\ VPD^{-1}-9.70$	0.902	2.51	18	0.05

The first variable listed explained more variation than any other. Standard error of the estimate, *SEE*, is given in units defined in the preceding texts.

APPENDIX TABLE II. MULTIPLE REGRESSION EQUATIONS FOR STEMFLOW, *SF*, VOLUME (L) AS A FUNCTION OF METEOROLOGICAL VARIABLES, GENERATED FOR SINGLE-LEADER (GROUP SL, $N = 20$), AND MULTI-LEADER TREES (GROUP ML, $N = 17$) FOR RAIN EVENTS DURING TRANSITIONAL LEAF CONDITION

Tree ID	Stemflow volume regression equation	R^2	*SEE*	*n*	$p \leq$
SL-2	$0.70\ P - 0.12\ D_B - 0.91$	0.997	0.39	12	0.05
SL-4	$0.55\ P - 0.023\ D_B - 0.10\ I_{max5} + 0.44\ W_{wt5} - 0.011\ ACC$	0.992	0.37	17	0.10
SL-5	$1.92\ P - 0.40\ D_B - 0.056\ ACC$	0.997	0.81	19	0.05
SL-6	$0.63\ P - 0.028\ ACC + 0.55$	0.996	0.41	11	0.05
SL-10	$1.14\ P - 0.36\ D_B + 1.49\ W_{wt5} - 0.036\ ACC$	0.995	0.71	13	0.05
SL-12	$0.60\ P - 0.04\ VPD^{-1} - 0.014\ ACC$	.998	0.35	11	0.10
SL-16	$1.32\ P - 2.26$	0.977	1.57	12	0.05
SL-17	$1.95\ P - 0.15\ D_B - 0.43\ I_{max5} - 0.071\ ACC$	0.983	1.87	17	0.10
SL-19	$2.77\ P - 0.89\ D_B - 0.34\ I_{max5} - 0.12\ ACC + 6.31$	0.997	1.41	11	0.10
ML-1	$1.08\ P + 1.30\ I_{max5} - 8.57$	0.951	4.37	14	0.05
ML-3	$1.51\ P - 0.034\ ACC$	0.913	1.21	13	0.10
ML-4	$0.41\ P + 6.05\ W_{wt5} - 3.04$	0.796	3.04	13	0.05

The first variable listed explained more variation than any other. Standard error of the estimate, *SEE*, is given in units defined in the preceding texts.

APPENDIX TABLE III MULTIPLE REGRESSION EQUATIONS FOR STEMFLOW, *SF*, VOLUME (L) AS A FUNCTION OF METEOROLOGICAL VARIABLES, GENERATED FOR SINGLE-LEADER (GROUP SL, $N = 20$) AND MULTI-LEADER TREES (GROUP ML, $N = 17$) FOR RAIN EVENTS DURING LEAF-OFF CONDITION

Tree ID	Stemflow volume regression equation	R^2	*SEE*	*n*	$p \leq$
SL-1	$-0.042\ D_B + 0.40\ P + 0.047\ I_{wt5} - 0.28$	0.984	0.31	22	0.10
SL-2	$0.54\ P - 0.54$	0.909	0.26	16	0.05
SL-3	$0.33\ P + 0.011\ P_{inc} - 0.33$	0.896	0.17	16	0.10
SL-4	$0.064\ W_{wt5} + 0.082$	0.326	0.11	9	0.10
SL-5	$1.33\ P + 0.060\ P_{inc} - 1.24$	0.910	0.75	12	0.05
SL-6	$0.83\ P - 0.029\ D_B - 0.075\ I_{max5} + 0.49\ W_{wt5} - 0.61$	0.993	0.44	21	0.10
SL-7	$0.87\ P + 0.86\ W_{wt5} - 0.92$	0.897	0.50	17	0.05
SL-8	$0.41\ P + 0.27\ W_{wt5} - 0.57$	0.914	0.20	15	0.05
SL-9	$1.59\ P - 0.11\ D_B - 0.27\ I_{max5} + 0.69\ W_{wt5} - 1.27$	0.987	1.03	25	0.05
SL-10	$0.46\ W_{wt5} + 0.33\ P + 0.\ 062\ I_{max5} - 0.57$	0.927	0.19	13	0.05
SL-11	$0.62\ P + 0.028\ P_{inc} - 0.90$	0.858	0.40	15	0.05
SL-14	$0.081\ I_{max5} + 0.38\ P + 0.61\ W_{wt5} - 1.20$	0.879	0.44	10	0.10
SL-15	$-1.72\ W_{wt5} + 1.57\ P + 0.12\ VPD^{-1} - 3.55$	0.802	0.75	15	0.10
SL-16	$0.23\ W_{wt5} + 0.042\ I_{max5} + 0.038\ VPD^{-1} - 0.53$	0.886	0.14	11	0.10
SL-19	$1.30\ P + 0.93\ W_{wt5} + 0.17\ VPD^{-1} - 3.60$	0.955	0.54	12	0.05
ML-1	$0.018\ I_{wt5} - 0.041$	0.886	0.02	12	0.05
ML-2	$0.54\ P + 0.033\ P_{inc} - 0.65$	0.855	0.37	14	0.05
ML-3	$2.13\ P - 0.31\ D_B + 0.12\ I_{wt5} - 1.87$	0.999	0.47	14	0.05
ML-4	$0.38\ P + 0.015\ P_{inc} - 0.58$	0.897	0.20	15	0.05
ML-5	$2.35\ P - 0.076\ D_B - 1.94$	0.917	1.12	14	0.10
ML-6	$0.74\ P + 0.69\ W_{wt5} - 1.22$	0.890	0.45	14	0.05
ML-9	$5.42\ P - 2.33\ W_{wt5} + 0.25\ VPD^{-1} - 7.53$	0.959	1.77	17	0.10
ML-10	$1.23\ W_{wt5} + 0.91\ P - 1.40$	0.784	0.66	12	0.05
ML-11	$1.47\ P + 0.78\ W_{wt5} - 2.66$	0.951	0.60	11	0.05
ML-15	$0.13\ P - 0.14$	0.884	0.08	12	0.05

The first variable listed explained more variation than any other. Standard error of the estimate, *SEE*, is given in units defined in the preceding texts.

APPENDIX TABLE IV. SUMMARY OF MEANS AND STANDARD DEVIATIONS, *SD*, FOR CANOPY TRAITS OF GROUP SL AND ML (COMBINED) TREES GROUPED BY WHETHER OR NOT EACH METEOROLOGICAL VARIABLE WAS SIGNIFICANT ($P \leq 0.10$) IN THE INDIVIDUAL TREE'S STEMFLOW VOLUME REGRESSION EQUATION (BETWEEN-GROUP DIFFERENCES ANALYSED VIA ONE-WAY ANOVA, $P \leq 0.10$)

Meteorological variable (sign indicates positive or negative relationship with stemflow volume)	Trait variable	Non-occurrence group mean ± SD (*n*)	Occurrence group mean ± *SD* (*n*)	*p*-value
LEAF-ON CONDITION				
+ Rainfall intensity (5-min weighted average)	Bark relief index	1.10 ± 0.08 (32)	1.26 ± 0.22 (2)	0.018
	Frequency (discontinuity)	0.15 ± 0.15 (32)	0.36 ± 0.33 (2)	0.081
+ Rainfall inclination angle (5-min weighted average)	*DBH* (cm)	32.9 ± 16.9 (21)	20.4 ± 7.4 (13)	0.018
	Average canopy spread (m)	8.4 ± 4.0 (21)	6.1 ± 1.9 (13)	0.054
	Canopy volume (m^3)	690.4 ± 895.6 (21)	214.8 ± 158.5 (13)	0.068
	Wood volume (m^3)	75.9 ± 103.4 (21)	15.2 ± 18.2 (13)	0.045
	Intersection angle, full tree (degree above horizontal)	41.9 ± 13.0 (21)	49.0 ± 9.9 (13)	0.100
	Branch count	46.9 ± 20.8 (21)	32.2 ± 15.2 (13)	0.035
+ Wind speed (5-min weighted average)	Canopy volume (m^3)	382.6 ± 408.6 (26)	917.7 ± 1322.1 (8)	0.074
	Wood volume (m^3)	35.7 ± 46.0 (26)	107.8 ± 152.4 (8)	0.037
	Median leaf size (cm^2)	21.6 ± 13.4 (26)	35.7 ± 26.4 (8)	0.050
+ Inverse vapour pressure deficit (variable transformed)	Average angle, full tree (degree above horizontal)	47.6 ± 18.2 (18)	37.1 ± 14.2 (15)	0.080
TRANSITIONAL LEAF CONDITION				
– Total break duration (h)	No. branches, full tree	42.7 ± 21.4 (6)	25.3 ± 9.7 (6)	0.100
	No. leaders at canopy base	1.83 ± 1.0 (6)	1.0 ± 0.0 (6)	0.065
LEAF-OFF CONDITION				
+ Rainfall inclination angle (5-min weightedaverage)	Wood cover (%)	27.0 ± 10.3 (20)	14.6 ± 2.7 (5)	0.015
+ Inverse vapour pressure deficit (variable transformed)	*DBH* (cm)	21.7 ± 12.0 (21)	36.7 ± 12.3 (4)	0.032
	Tree height (m)	9.1 ± 2.5 (21)	12.2 ± 1.5 (4)	0.027
	Wood cover (%)	22.8 ± 10.3 (21)	33.4 ± 7.0 (4)	0.062