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1 A novel framework to study the effect of tree architectural traits on stemflow yield and its  
2 consequences for soil-water dynamics

3

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10

11 Abstract

12 A novel experimental approach and numerical framework are proposed to study the effect of tree  
13 architectural traits on stemflow yield and its effects on soil-water dynamics. The framework includes  
14 a data mining workflow employing information from two experimental steps: (i) evaluation of the  
15 effect of tree aboveground architecture on stemflow yield and (ii) quantification of specific  
16 parameters for soil-water dynamics with and without stemflow. We studied double-funnelling  
17 (stemflow and root-induced preferential flow) under three sycamore (*Acer pseudoplatanus* L.) trees  
18 growing on a slope in Scotland during the summer season and measured architectural traits. Stemflow  
19 yield ranged from 1.3 to 3.8 % of the incident rainfall, with funnelling ratios of between  $2.2 \pm 2.1$  and  
20  $5.2 \pm 3.9$ . Double-funnelling to a depth of up to 400 mm beneath the soil surface occurred as matrix  
21 flow and was significantly and positively correlated with the vertical root distribution. Soil-water  
22 dynamics were distinctly different with and without stemflow. Our framework revealed that the  
23 number of tree branches, their insertion angle, leaf number, and stem basal diameter influenced  
24 stemflow yield within rainfall thresholds of 1.1 and 3.5 mm d<sup>-1</sup>. The framework also showed that  
25 stemflow yield had a negative impact on soil matric suction, while air temperature was the most  
26 influential covariate affecting soil-water dynamics, likely due to its strong correlation to  
27 evapotranspiration during the summer season. In spite of the study limitations, such as small sample  
28 size and differences between individuals, we show that the proposed framework and experimental  
29 approach can contribute to our knowledge of how stemflow generated aboveground triggers major  
30 responses in soil-water dynamics belowground.

31

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34 Keywords: temperature, soil moisture, matric suction, preferential flow, sycamore

35

36

37 1. Introduction

38

39 Stemflow is a poorly studied hydrological process that occurs mostly in woodland  
40 ecosystems (Levia and Germer, 2015). Stemflow comprises the funnelling of incident  
41 precipitation around the tree stem, with subsequent flow occurring along roots and into soil  
42 pores (i.e. double-funnelling; Johnson and Lehmann, 2006). Stemflow has been overlooked  
43 due to its point-source nature and its apparently small contribution to the water cycle (Levia  
44 et al., 2011). However, many geoscientists now acknowledge the potential role of stemflow  
45 in the regulation of hydrological and biogeochemical cycles in forests and shrublands (Levia  
46 and Germer, 2015).

47

48 Stemflow generally represents 1 to 20 % of incident precipitation (Levia and Frost, 2003).  
49 But, in reality, a substantial volume of water can concentrate around the tree bole in a single  
50 precipitation event (e.g. Gonzalez-Ollauri and Mickovski, 2017a). Stemflow is formed in the  
51 forest canopy, and recent work has strived to unveil how canopy architecture can regulate the  
52 formation of stemflow before being funnelled belowground (e.g. Levia et al., 2010, 2015;  
53 Bialkowski and Buttle, 2015; Yuan et al., 2017; del Campo et al., 2018). However, tree  
54 architecture is complex (e.g. Barthélémy and Caraglio, 2007; Côté et al. 2011), and varies  
55 with tree age (e.g. Meinzer et al., 2011), and across species and biomes (e.g. Wright et al.,  
56 2005; Kattge et al., 2011). Outcomes from advanced data mining frameworks (e.g. Torgo,  
57 2011) could have important applications in the elucidation of strategies by practitioners  
58 seeking to control relevant phenomena that are regulated through stemflow (e.g. groundwater  
59 recharge and nutrient cycling, Levia et al., 2011; del Campo et al., 2014; 2018).

60

61 Double-funnelling results into various modes of subsurface flow, e.g. preferential flow,  
62 bypass flow and matrix flow (Liang et al., 2011; Spencer and van Meerveld, 2016), or even  
63 surface runoff (Herwitz, 1986; Miyata et al., 2009). Tracking double-funnelling is labour-  
64 intensive (e.g. Liang et al., 2011; Germer, 2013; Spencer and van Meerveld, 2016), and it is  
65 difficult to identify the subsurface flow mode, its potential drivers, and the subsequent effect  
66 in the soil. For trees growing on slopes, stemflow is funnelled towards the downslope part of  
67 the stem and soil (Liang et al., 2011; Spencer and van Meerveld, 2016), where macropores  
68 and gaps between the root and soil channel this subsurface flow (Martinez-Meza and  
69 Whitford, 1996; Schwärzel et al., 2012; Spencer and van Meerveld, 2016). There is little  
70 convincing information, however, indicating whether the subsurface flow mode associated to  
71 double-funnelling is species-specific and season-dependent, or whether it changes with

72 meteorological conditions, e.g. rainfall intensity or inter-rainfall interval (van Stan et al.,  
73 2012; Tanaka et al., 2017). The subsurface flow mode may also depend on soil  
74 characteristics, such as moisture content and texture, as well as plant root density. In spite of  
75 the advances made over the last decade to generate knowledge on how soil hydrology is  
76 impacted by stemflow (for review, see Levia and Germer, 2015), linking double-funnelling  
77 and subsequent changes to soil-water dynamics in response to meteorological events has not  
78 yet been attempted.

79

80 Changes in soil moisture and matric suction related to double-funnelling can help to clarify  
81 what level of stemflow yield leads to noticeable hydrological responses in soil. Measuring  
82 soil hydrological variables also allows an assessment of whether double-funnelling occurs  
83 along the same soil paths repeatedly, and whether it influences mechanical stresses in soil,  
84 that could then affect how vegetation protects against rainfall-induced, shallow landslides  
85 (Gonzalez-Ollauri and Mickovski, 2017a,b). Changes in soil temperature at zones with signs  
86 of double-funnelling may also indicate the arrival of water and nutrients transported from the  
87 canopy to soil (e.g. Germer et al., 2012), that in turn alter soil microbial activity (McClain et  
88 al., 2003; Kuryakov and Blagodatskaya, 2015; Rosier et al., 2016). However, studying soil-  
89 water dynamics influenced by stemflow is experimentally challenging and data are difficult  
90 to analyse. Therefore, robust experimental and numerical frameworks should enable us to  
91 overcome these problems and so elucidate relationships between stemflow and soil-water  
92 dynamics.

93

94 The aim of our study is to propose a novel experimental approach and numerical framework  
95 to estimate how aboveground tree architecture affects stemflow yield and, subsequently, soil-  
96 water dynamics. Our objectives are: (i) evaluation of the effect of aboveground tree  
97 architecture on stemflow yield; (ii) identification of soil-root zones subjected to double-  
98 funnelling; (iii) quantification of soil moisture, matric suction and soil temperature with and  
99 without stemflow and (iv) evaluation of the effect of two external meteorological variables  
100 (i.e. rainfall and air temperature) on soil-water dynamics in contrast with stemflow yield. To  
101 achieve these objectives, we studied double-funnelling and its effect on soil-water dynamics  
102 under sycamore (*Acer pseudoplatanus* L.) trees. Sycamore is a deciduous, broadleaf, fast-  
103 growing tree with a broad, domed crown and smooth bark (Pasta et al., 2016). Mature  
104 sycamores are very resistant to wind loading, coastal exposure, and pollution, and these  
105 features make it a useful species for protecting slopes against landslides, erosion, and rockfall

106 (Norris et al. 2008). Therefore, sycamore is a potentially useful species in protection forests  
107 and on unstable slopes. Understanding how the architectural traits of sycamore affect soil  
108 hydrological characteristics will allow a full assessment of the utility of this species for  
109 ecological engineers.

110  
111

## 112 2. Materials and Methods

113

### 114 2.1. Tree individuals and study site

115

116 The study site was located adjacent to Catterline Bay, Aberdeenshire, UK (WGS84 Long: -  
117 2.21 Lat: 56.90; supplementary material Fig. S1a), within the temperate humid climate zone  
118 (Cgc: subpolar oceanic climate; Köppen, 1884). The mean annual temperature over the  
119 period 2011 – 2018 was 8.9 °C and the mean annual rainfall was 556.8 mm (voor de Poorte,  
120 2018). The precipitation at the site is characterised by frequent, low-intensity rainfall events  
121 (Gonzalez-Ollauri and Mickovski, 2016; 2017a) and the prevailing wind is south-westerly.  
122 Three adjacent sycamore (*Acer pseudoplatanus* L.) individuals (Syc1, Syc2, and Syc3), that  
123 were approximately 40 years old, were chosen for the study (Fig. S1b). The stand was  
124 established on a  $20.3 \pm 11.6^\circ$  southwest facing slope, oriented  $260\text{-}280^\circ$  from due north. Soil is  
125 well-drained (saturated hydraulic conductivity:  $7.1 \times 10^{-5} \text{ m s}^{-1}$ ), with a soil organic matter  
126 content of 12.4 %. Landslide prone silty sands (sand: 66.8 %; silt: 1.4 %; clay: 0.8 %) overlie  
127 conglomerate rock. The topsoil at the site (to a depth of 600 mm beneath the soil surface) had  
128 a mean dry bulk density of  $1.3 \text{ g cm}^{-3}$ , a drained cohesion of 30.5 kPa, a mean angle of  
129 internal friction of  $19.4^\circ$ , and a specific gravity of 2.6.

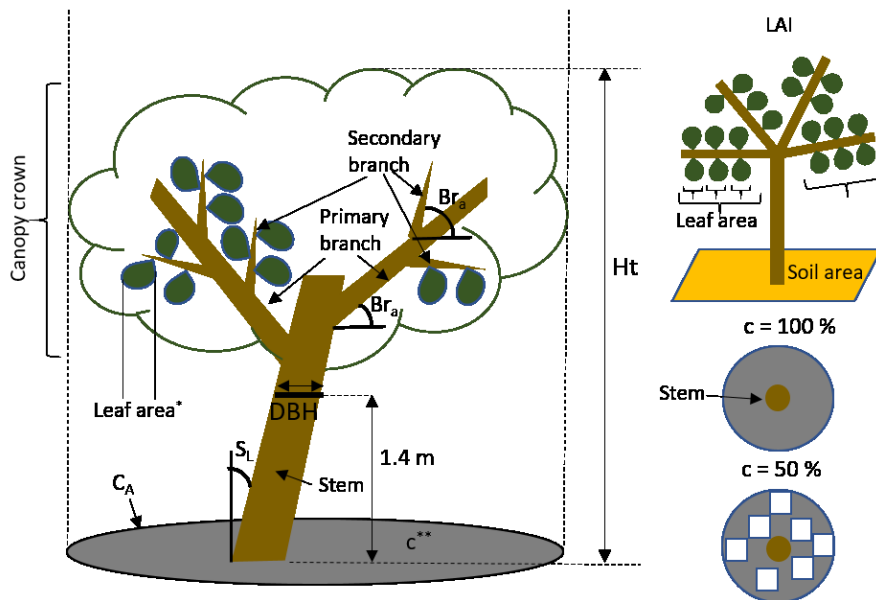
130

### 131 2.2. Aboveground tree architectural traits

132

133 The aboveground architecture of the tree individuals was characterised with 13 readily  
134 measurable traits reported to influence stemflow yield (Levia et al., 2015; Fig. 1). A  
135 surveyors' meter tape was used to measure: (i) the tree's basal area or diameter at breast  
136 height (*DBH*; m) and (ii) the projected canopy-crown area ( $C_A$ ;  $\text{m}^2$ ) according to Spoke's  
137 distance method (Blozan, 2008), assuming a circular crown projection on the ground surface.  
138 A spherical crown densiometer was used to estimate (iii) the canopy cover fraction ( $c$ ; %;  
139 Lemon, 1956). (iv) Tree height (*Ht*; m) was measured from an upslope position with a Leica®

140 laser meter. (v) The leaf area index ( $LAI$ ) was estimated with the Wolf et al. (1972) direct  
 141 method. A hand-held inclinometer was used to measure (vi) the stem lean from the vertical  
 142 ( $S_L$ ; °), (vii) the maximum branch insertion angle from the horizontal ( $_{mx}Br_a$ ; °), and (viii) the  
 143 mean branch insertion angle above the horizontal ( $_{av}Br_a$ ; °). (ix) The number of primary  
 144 ( $PBr$ ; developing directly from the main stem) and (x) secondary branches ( $SBr$ ; borne  
 145 directly on the primary branches) were counted manually to then calculate the branch count  
 146 per unit projected area of tree crown (Levia et al., 2015). Finally, (xi) the total number of  
 147 leaves ( $nL$ ;  $m^{-2}$ ), (xii) leaf biomass ( $L_{BM}$ ;  $g\ m^{-2}$ ), and (xiii) branch biomass ( $Br_{BM}$ ;  $Kg\ m^{-2}$ ) per  
 148 unit projected area of tree crown was estimated through a destructive method that involved  
 149 cutting a primary and two secondary branches from a fourth, unstudied, sycamore individual.  
 150 Leaves were counted and, along with woody parts, were oven-dried at  $60^{\circ}C$  until a constant  
 151 mass was reached.



152  
 153 Figure 1. Illustration showing tree architectural traits measured in this study.  $DBH$ : diameter at breast height;  $C_A$ : projected  
 154 canopy-crown area;  $c$ : canopy cover fraction;  $Ht$ : tree height;  $LAI$ : leaf area index;  $S_L$ : stem lean;  $Br_a$ : branch insertion angle.  
 155 On the right-hand side, the concept of  $LAI$  and two  $c$  examples are illustrated, i.e. dense canopy crown with  $c=100\%$  and  
 156 sparse canopy crown with  $c=50\%$ , where the white squares portray the penetration of sunlight through the canopy.

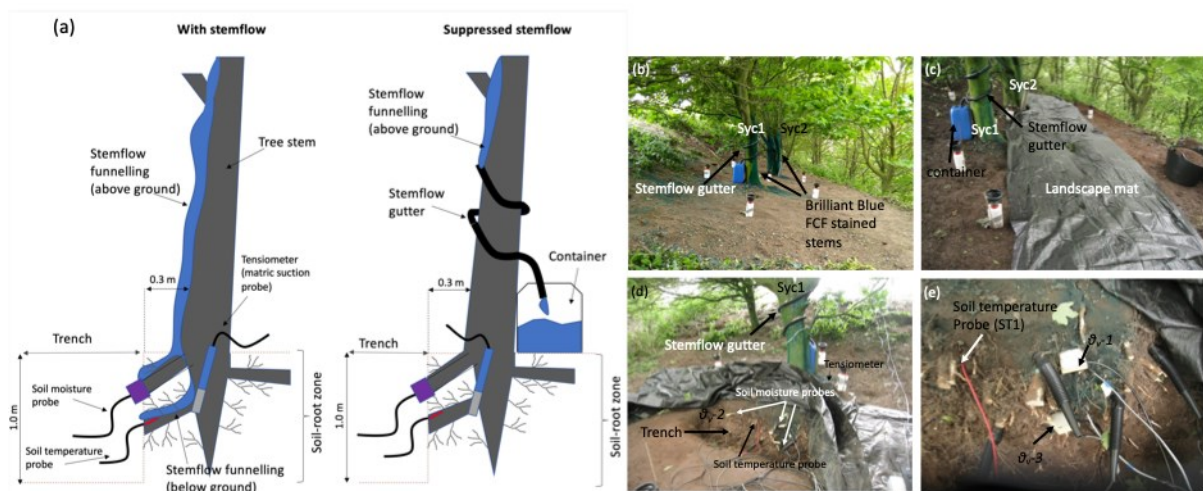
157

### 158 2.3. Double-funnelling and subsurface flow

159

160 To identify the zones where double-funnelling results in an accumulation of subsurface flow,  
 161 on 18/06/2018, we sprayed 20 l of a dye solution (i.e. Brilliant Blue FCF;  $5\ g\ l^{-1}$ ) between  
 162 ground level and a height of 1.7 m on the downslope side of the stem (Laing et al., 2011;  
 163 Nespoulous et al., 2019) on two of the sycamore individuals (Syc1 and Syc2; Fig. 2b). For  
 164 this, we used a 20 l backpack sprayer for 35 minutes per individual, corresponding to a

165 precipitation intensity of  $45.7 \text{ mm h}^{-1}$ . Before we sprayed the dye solution, we used a  
 166 moisture profile probe (Delta-T®) to measure the mean soil volumetric moisture content ( $\theta_v$ ,  
 167 %) within a soil depth range of 0.0 – 0.3 m below ground level (b.g.l) and 0.15 m away from  
 168 the tree bole on the downslope side of the stem. Mean profile  $\theta_v$  was  $5.1 \pm 2.3\%$ . Thirty-six  
 169 hours after spraying the dye solution, we dug a 2.0 x 1.0 m trench downslope from each tree  
 170 0.3 m away from the tree bole (Fig. 2). The wall of each trench was smoothed with a knife  
 171 prior to mapping the dyed areas and the root profiles onto a 1.0 m x 0.5 m gridded acetate  
 172 sheet (Böhm, 1979). The area of dyed soil was quantified at 0.1 m intervals along the soil  
 173 profile by examining the proportion inside each grid square that was stained (Nespoulous et  
 174 al., 2019). The cross-sectional area of all roots ( $A_r$ ;  $\text{mm}^2$ ) was quantified at the same soil  
 175 depth intervals (Gonzalez-Ollauri and Mickovski (2016); Eqs. 1 and 2 (Table 1)), once  
 176 sycamore roots had been identified (Reward et al., 2012).  
 177



178  
 179 Figure 2. (a) Illustration showing the experimental setup deployed onsite to study soil-water dynamics with stemflow (Syc2)  
 180 and without stemflow (Syc1); (b) Brilliant Blue FCF was sprayed on the stem of Syc1 and Syc2 prior to suppressing  
 181 stemflow in Syc1 with a gutter. Most of the dye solution infiltrated the soil next to the tree bole; (c-e) trenches were dug to  
 182 observe the distribution of Brilliant Blue FCF belowground and to install sensors monitoring soil-water dynamics at the root-  
 183 soil interface. The trenches were covered with a landscape mat to avoid interference with dripfall and throughfall,  $\theta_{v-1}$ ,  $\theta_{v-2}$ ,  
 184 and  $\theta_{v-3}$  indicate the soil moisture probes used under Syc1 (see Table 2). More images from the experimental set up are  
 185 shown in supplementary material.

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191

192

Table 1. List of equations used in this study. †variable scaled with the projected canopy-crown area ( $C_A$ ,  $m^2$ ). ‡Equations implemented in the data mining workflow (see Section 2.6).

Definition	Equation	No	Parameters	Units	Source
Cross-sectional area of roots	$Ar = \pi \cdot (\Sigma d/2)^2$	Eq.(1)	$Ar$ : Cross-sectional area of all roots at a given soil depth $d$ : root diameter	$mm^2$ $mm$	Gonzalez-Ollauri and Mickovski (2016)
Vertical root distribution	$Ar(z) = Aro \cdot e^{-z/b}$	Eq.(2)	$Ar(z)$ : cross-sectional area of all roots along the soil profile $Aro$ : cross-sectional area of the stump $b$ : mean rooting depth $z$ : soil depth	$mm^2$ $mm^2$ $mm$ $mm$	Preti et al. (2010) Gonzalez-Ollauri and Mickovski (2016)
Stemflow yield	$Sy = a + b \cdot Pg$	Eq.(3)	$Sy$ : stemflow yield $Pg$ : incident rainfall $a$ : intercept $b$ : slope	L $mm$	Deguchi et al. (2006)
Stemflow funnelling ratio	$SFR = \frac{Sy}{Pg \cdot DBH}$	Eq.(4)	$DBH$ : stem diameter at breast height (i.e. 1.4 m from the ground level)	$m^2$	Herwitz (1986)
‡Stemflow yield and tree architecture	$Sy = f(Pg, Ht, C_A, DBH, c, LAI, S_L, PBr, SBr, mxBra, mnBra, nL, L_{BM}, Br_{BM}, C_{BM})$	Eq.(5)	$Ht$ : tree height $C_A$ : projected canopy-crown area $DBH$ : diameter at breast height (i.e. 1.4 m from the ground level) $c$ : canopy cover fraction $LAI$ : leaf area index $S_L$ : stem lean from the vertical axis measured at the ground level † $PBr$ : number of primary branches (i.e. developing from the main stem; Fig. 1a) † $SBr$ : number of secondary branches (i.e. borne on the primary branches; Fig. 1a) $mxBra$ : maximum branching angle from the horizontal axis $mnBra$ : mean branch angle from the horizontal axis † $nL$ : leaf count † $L_{BM}$ : leaf biomass † $Br_{BM}$ : total branch biomass (i.e. primary and secondary branch biomass) † $C_{BM}$ : crown biomass	m $m^2$ m % $m^2$ $m^{-2}$ ° $m^{-2}$ $m^{-2}$ ° ° $m^{-2}$ $g \cdot m^{-2}$ $g \cdot m^{-2}$ $g \cdot m^{-2}$	This study
‡Soil temperature	$ST = f(Pg, Sy, Ta)$	Eq.(6)	$ST$ : soil temperature measured from June to October, 2018 $Pg$ : incident rainfall (i.e. rainfall that reaches the soil without vegetation) measured from June to October, 2018 $Sy$ : stemflow yield measured from June to October, 2018 $Ta$ : air temperature measured from June to October, 2018	° $mm$ $mL$ °	This study
‡Soil moisture	$\theta v = f(Pg, Sy, Ta)$	Eq.(7)	$\theta_v$ : soil moisture measured from June to October, 2018	/1	This study

Soil matric suction	$\psi = f(Pg, Sy, Ta)$	Eq.(8)	$\Psi$ : matric suction measured from July to August, 2018	kPa	This study
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194

#### 195 2.4. Quantification of stemflow and funnelling ratio

196

197 Stemflow was suppressed for two of the three sycamore individuals (Syc1 and Syc3, Figs.  
198 2a,b), so that the influence of aboveground tree architecture on double-funnelling (Section  
199 2.6; Fig. 3a) could be quantified. Suppressing stemflow also allowed us to determine  
200 indirectly its contribution to soil-water dynamics (Fig. 3a). This suppression was achieved by  
201 sealing one stemflow gutter (32 mm diameter, corrugated vinyl tube, with a third of its  
202 perimeter cut off to enable the collection of stemflow), starting at a height of 1.7 m up the  
203 tree stem, and revolving one and a half times around the stem (Figs. 2a,b; Gonzalez-Ollauri  
204 and Mickovski, 2017a). Each stemflow gutter terminated in a 25 l opaque plastic container  
205 where stemflow water was collected and stored until measurement (Fig. 2a). The amount of  
206 stemflow collected was measured with a graduated cylinder on a rainfall event basis from  
207 July to October, 2018. On 21/06/2018, and after trenches had been dug (Section 2.3), we  
208 cleared out the understory vegetation, and covered the ground surface below the canopies of  
209 Syc1 and Syc2 with a landscape mat. This mat prevented the infiltration of water from  
210 dripfall and throughfall (e.g. Zimmermann and Zimmermann, 2014) into the soil but allowed  
211 stemflow infiltration under Syc2 (Fig. 2c).

212

213 Stemflow yield was compared against incident rainfall ( $P_g$ ; mm d<sup>-1</sup>) by fitting linear  
214 regression models (Eq. 3, Table 1; Deguchi et al., 2006) in R v3.5.1 (R Core Team, 2018).  
215 Rainfall and air temperature time series were retrieved with a 1-minute resolution from a  
216 Davis Vantage Pro2 meteorological station located *in situ* and away from the canopy's  
217 influence (voor de Poorte, 2018; Fig. S1a). We monitored 35 rainfall events in total, with an  
218 event defined as having a minimum depth of 0.4 mm and being separated by at least 2 hours  
219 without rainfall. We strived to measure stemflow volume 2h after rainfall or the following  
220 morning when the former was not possible. When more than one rainfall event occurred  
221 before we could measure stemflow (seven events in total), we assumed a linear relationship  
222 between rainfall and stemflow, and we proceeded as follows: (i) we measured the total  
223 stemflow volume collected in the container; (ii) we then discretised rainfall events by  
224 aggregating the 1 minute rainfall time steps into hourly steps; (iii) we subset and pooled  
225 consecutive time steps with rainfall depths above 0.4 mm; (iv) we summed up the rainfall  
226 depth for the pool of unmonitored events; (v) we estimated the volume ratio for each event  
227 considering the total rainfall volume, and finally, (vi) we applied this ratio to the total

228 stemflow volume collected in the container. Once stemflow yield was known, the stemflow  
229 funnelling ratio (*SFR*) was calculated at the individual level as indicated in Eq. 4 (Table 1;  
230 Herwitz, 1986).

231

## 232 2.5. Influence of stemflow and its suppression on soil-water dynamics

233

234 After trenches had been dug for the observation of dyed water originating from stemflow  
235 (Section 2.3), we monitored soil-water dynamics under both stemflow (Syc2) and suppressed  
236 stemflow (Syc1). We also monitored soil-water dynamics in zones with and without signs of  
237 double-funnelling (i.e. with and without blue staining) (Figs. 2d,e). To do so, we measured  
238 soil temperature (*ST*, °C), soil volumetric moisture content ( $\theta_v$ , / $l_1$ ), and soil matric suction ( $\psi$ ,  
239 kPa) using automatic sensors during the growing season of 2018 (i.e. late June – early  
240 October, 2018).

241

242 Every sensor was deployed at the interface between roots larger than 5 mm in diameter and  
243 soil (Fig. 2a) at locations noted in Table 2. Soil moisture content was monitored with seven  
244 time-domain reflectometry sensors (TDR; CS616 – Campbell Scientific, UK) installed at  
245 different soil depths (Table 2) in the excavated trenches (Figs. 2c, d). Soil temperature was  
246 monitored in the excavated trenches under stemflow and suppressed stemflow by installing  
247 one temperature probe (T107 – Campbell Scientific, UK) per trench and in areas that had  
248 been stained with dye (Table 2; Figs. 2c,d). Soil matric suction was monitored with two field  
249 tensiometers/piezometers (T4 – UMS GmbH, Germany) installed vertically within the soil-  
250 root zone (i.e. 0-500 mm beneath the soil surface; Gonzalez-Ollauri and Mickovski, 2017a;  
251 Tardio et al., 2016) and, at 0.1 m from the downslope side of the tree boles of Syc1 and Syc2.  
252 All sensors were wired to a solar powered CR-1000 data logger (Campbell Scientific, UK),  
253 that collected records for *ST*,  $\theta_v$ , and  $\psi$  at 15 minute time steps. To test the operational  
254 capacity of the instrumental setup, we undertook four stemflow simulation events at the onset  
255 of the monitoring period (event 1 on 28/06/2018; event 2 on 03/07/2018; event 3 on  
256 04/07/2018; and event 4 on 09/07/2018). Each stemflow simulation event consisted of  
257 spraying 20 L of tap water at a height of 1.7 m over the downslope side of the stem of Syc1  
258 and Syc2 using a backpack sprayer for 35 minutes (i.e. rainfall intensity of 45.7 mm h<sup>-1</sup>). The  
259 results from these simulations were analysed together with the records derived from real  
260 stemflow events occurring during the monitoring period.

261

262  
263  
264

Table 2. Sensor type and location in stained/unstained soil under trees with stemflow or where stemflow was suppressed. Sensors measure soil temperature ( $ST$ ), soil moisture ( $\theta_v$ ) and matric suction ( $\psi$ ). Sensor Id refers to the sensor type and number.

Variable	Sensor	Sensor Id	Tree	Treatment	Positioned in zone previously stained with blue dye from stemflow?	Depth (mm)
Soil temperature	T107	$ST1$	Syc1	Suppressed stemflow	Yes	150
	T107	$ST2$	Syc2	Stemflow	Yes	150
Soil moisture	CS616	$\theta_v-1$	Syc1	Suppressed stemflow	Yes	100
	CS616	$\theta_v-2$	Syc1	Suppressed stemflow	No	100
	CS616	$\theta_v-3$	Syc1	Suppressed stemflow	Yes	260
	CS616	$\theta_v-4$	Syc2	Stemflow	No	400
	CS616	$\theta_v-5$	Syc2	Stemflow	Yes	100
	CS616	$\theta_v-6$	Syc2	Stemflow	No	100
	CS616	$\theta_v-7$	Syc2	Stemflow	Yes	400
Soil matric suction	T4	$\psi-1$	Syc1	Suppressed stemflow	Yes	300-400
	T4	$\psi-2$	Syc2	Stemflow	Yes	300-400

265

## 266 2.6. Framework description and implementation

267

268 We defined a cascade-style, numerical framework that incorporates a data mining workflow  
269 to evaluate the relationships between tree architecture, stemflow, and stemflow-derived soil-  
270 water dynamics (i.e. soil temperature, volumetric soil moisture content and matric suction,  
271 Fig. 3a). The framework was built using the statistical software R v3.5.1 (R Core Team.  
272 2018). Data mining was implemented twice (Figs. 3a-b): (i) to explore the effect of tree  
273 architecture on stemflow yield, and (ii) to assess the effect of stemflow yield, rainfall, and air  
274 temperature on soil-water dynamics.

275

276 The data mining workflow fits 100 boosted regression tree models (BRTs; Breiman et al.  
277 1984) without pruning, using the R package “rpart” (Therneau and Atkinson, 2018). Each  
278 BRT was fitted using a training dataset generated through a bootstrapping method with

279 replacement (Efron, 1979). Accordingly, a dataset containing 70 % of the observations (i.e.  
280 the training dataset) was extracted for each model run. The model outcomes were then cross-  
281 validated with the remaining 30 % of the data. Model quality was evaluated depending on the  
282 value of the coefficient of determination ( $R^2$ ) and the root mean square error (RMSE),  
283 between predicted and observed values, following the least-squares criterion (e.g. Bruce and  
284 Bruce, 2017). The best fitted BRT was selected on the basis of its quality and the amount of  
285 information carried by the regression tree (i.e. the number of relevant covariates portrayed in  
286 the BRT). In addition, the relative influence ( $RI$ ; %; e.g. del Campo et al., 2018) of each  
287 covariate on the response variable was examined through the evaluation of the decrease in  
288 node impurities (i.e. reduction in mean squared error), produced by splitting each regression  
289 tree on a given metric using the R package “caret” (Khun, 2018). The nature of the  
290 relationships between response and predictor variables were then evaluated on the basis of  
291 partial dependence plots (e.g. Tanaka et al., 2017), retrieved with the R package “pdp”  
292 (Greenwell, 2017).

293

294 The steps followed to implement the proposed framework (Fig. 3a) are illustrated in Fig. 3b.  
295 Firstly, the data mining workflow was implemented to fit stemflow yield BRT models using  
296 Eq.5 (Table 1) and the information collected from Syc1 and Syc3. Incident rainfall was  
297 included as covariate in the fitting of BRTs (Fig. 3a). The purpose of this was twofold: (i) to  
298 enable prediction of stemflow yield under varying incident rainfall, and (ii) to investigate the  
299 effect of tree architecture masked by the relationship between incident rainfall and stemflow  
300 yield (Deguchi et al., 2006) – i.e. how rainfall events are partitioned into stemflow by an  
301 array of steady-state, tree architectural traits at an individual level. Model quality, covariates’  
302  $RI$ , and relationship between predictors and response variables were then examined as  
303 described above (Fig. 3a). Following model cross-validation and best model selection (Fig.  
304 3a), stemflow yield was predicted for Syc2 with the best performing BRT. For this, the  
305 measured tree architectural traits in Syc2 and incident rainfall were used as inputs (Fig. 3b).

306

307 Subsequently, soil-water BRT models were fitted to the monitored soil-water variables (i.e.  
308  $ST$ ,  $\theta_v$ , and  $\psi$ ), using Eqs. 6, 7 and 8, respectively (Table 1). To this end, air temperature,  
309 incident rainfall, and predicted stemflow yield were used as inputs for Syc2 (Fig. 3b), while  
310 the stemflow yield inputs were assumed to be zero for Syc1 (i.e. tree with suppressed  
311 stemflow). Air temperature was included to investigate soil-water dynamics during drying  
312 (i.e. in the absence of precipitation), as air temperature and soil-water tend to be tightly

313 coupled (e.g. Feng and Liu, 2015). Incident rainfall was included to detect soil-water  
 314 dynamics that were not related to stemflow in the context of this study, e.g. subsurface flow  
 315 generated away from the canopy's influence, but still reaching the soil-root zone under study  
 316 (Bogaard, 2001). BRT models were fitted per monitoring sensor (Table 2) and per tree  
 317 individual where soil-water dynamics were studied (Syc1 and Syc2).

318

319 All time series were aggregated into daily time steps prior to fitting the BRT models. Model  
 320 quality was evaluated using the probability density functions from the pool of  $R^2$  values  
 321 retrieved from cross-validation (Fig. 3a). The *RI* of the covariates (i.e. air temperature,  
 322 incident rainfall, and stemflow yield), on soil-water dynamics and the relationship between  
 323 predictors and response variables were then examined as described above (Fig. 3a).

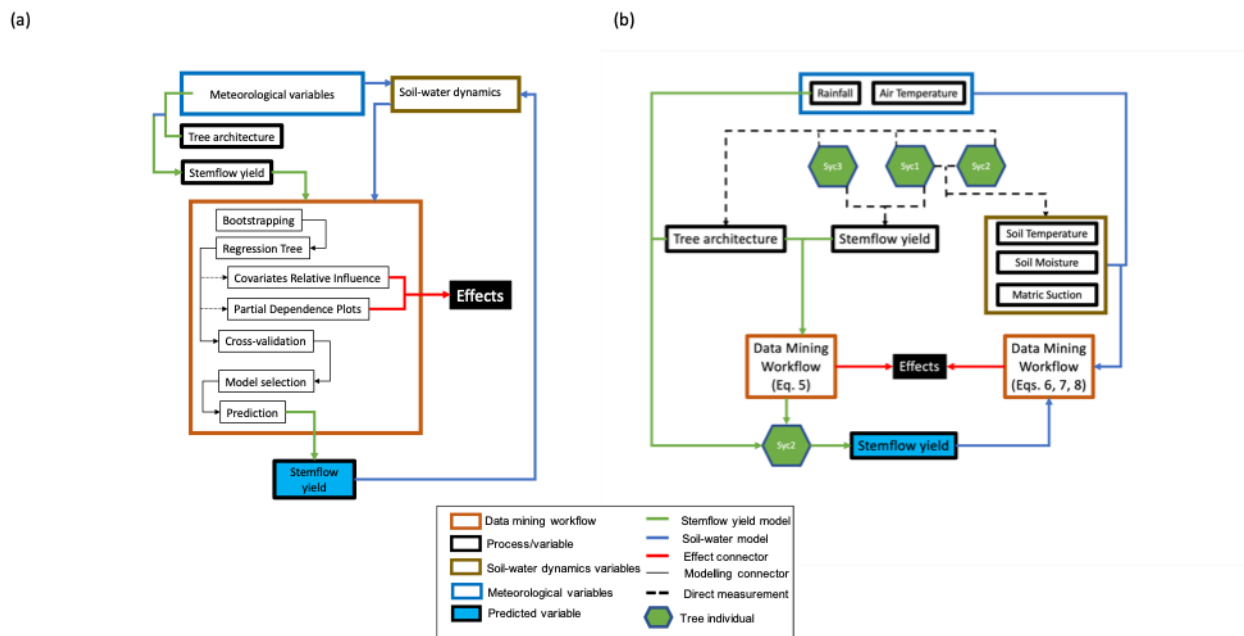


Figure 3. (a) Proposed framework to study the effect of tree architecture on stemflow yield, and the effect of stemflow yield and external meteorological variables (i.e. rainfall and air temperature) on soil-water dynamics, i.e. soil temperature, soil moisture, and matric suction. (b) Flow chart illustrating the implementation of the proposed framework in this study. See online version for colours.

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## 327 2.7. Statistical analysis

328

329 The vertical distribution of tree roots and the soil area affected by double-funnelling were  
 330 correlated using Pearson's correlation ( $r$ ) tests. Non-parametric Kruskal-Wallis ( $\chi^2$ ) tests



331 were then performed to determine differences in stemflow yield between individuals on an  
 332 event basis. Kruskal-Wallis tests were also used to evaluate differences in daily levels of  $ST$ ,  
 333  $\theta_v$ , and  $\psi$  between trees with stemflow and those where stemflow was suppressed.  
 334 Differences in model quality between the fitted BRTs (i.e.  $R^2$ ; Section 2.6) as well as  
 335 differences between covariates'  $RI$  generated for the 100 BRTs fitted to tree architectural  
 336 traits and to soil-water dynamics parameters, respectively, were also evaluated with Kruskal-  
 337 Wallis tests. Stemflow yield was excluded from statistical analyses evaluating differences  
 338 between covariate's  $RI$  on  $ST$ ,  $\theta_v$ , and  $\psi$  for Syc1, as stemflow yield was assumed to be zero  
 339 for this tree (i.e. tree with suppressed stemflow). All statistical tests were performed using the  
 340 software R v3.5.1 (R Core Team, 2018), at 95% and 99% confidence levels, following  
 341 normality testing through Shapiro-Wilk tests.

342

### 343 3. Results

344

#### 345 3.1. Aboveground tree architectural traits

346

347 Sycamore trees had smooth stems with 3 to 5 primary branches inserted above 1.7 m, from  
 348 which 60 to 80 secondary branches emerged (Table 3). The two individuals on which  
 349 stemflow yield was quantified (Syc1 and Syc3; Table 3) were similar with regard to  $DBH$  and  
 350  $C_A$  (Table 3), but they also had substantial dissimilarities in most of the remaining  
 351 architectural traits, reflected in differences in stemflow yield (Table 3). Syc3 had greater leaf  
 352 and branch biomass, with more primary and secondary branches, but exhibited less stem lean  
 353 ( $5^\circ$ ) than the other individuals ( $10^\circ$  and  $19^\circ$  from the vertical axis). The sycamore individual  
 354 where stemflow was allowed to yield freely into the soil beneath (Syc2) was larger size in  
 355 terms of  $DBH$ ,  $C_A$ , and  $Ht$ , and was more inclined, but had less leaves and less inclined  
 356 branches compared to Syc1 and Syc3 (Table 3).

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358

359 Table 3. Aboveground architectural traits and total stemflow yield for the monitoring period (July-October, 2018) for the  
 360 three sycamore individuals.  $DBH$ : diameter at breast height;  $C_A$ : projected canopy-crown area;  $c$ : canopy cover fraction;  $Ht$ :  
 361 tree height;  $LAI$ : leaf area index;  $S_L$ : stem lean;  $mxBr_a$ : maximum branch insertion angle;  $avBr_a$ : mean branch insertion  
 362 angle;  $PBr$ : number of primary branches per unit area of canopy-crown;  $SBr$ : number of secondary branches per unit area of  
 363 canopy-crown;  $nL$ : leaf count per unit area of canopy-crown;  $L_{BM}$ : leaf biomass per unit area of canopy-crown;  $Br_{BM}$ : branch  
 364 biomass per unit area of canopy crown. \* stemflow yield was predicted in Syc2 as shown in Fig. 3b.

Sycamore individual	$DBH$ (m)	$C_A$ (m <sup>2</sup> )	$c$ (%)	$Ht$ (m)	$LAI$	$S_L$ (°)	$mxBr_a$ (°)	$avBr_a$ (°)	$PBr$ (m <sup>-2</sup> )	$SBr$ (m <sup>-2</sup> )	$nL$ (m <sup>-2</sup> )	$L_{BM}$ (g m <sup>-2</sup> )	$Br_{BM}$ (g m <sup>-2</sup> )	Total Stemflow yield (mL)

														m <sup>-2</sup> )
Syc1	0.37	38.88	93	7.41	5.28	10	55	38	0.08	1.54	499.64	213.60	2557.06	2341.77
Syc2	0.49	53.84	89	11.38	4.53	19	40	28	0.09	1.30	429.53	183.63	2512.81	137.17*
Syc3	0.34	37.34	98	4.06	3.83	5	50	35	0.13	2.11	689.29	294.66	3765.61	3521.61

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366 3.2. Stemflow yield and funnelling ratio

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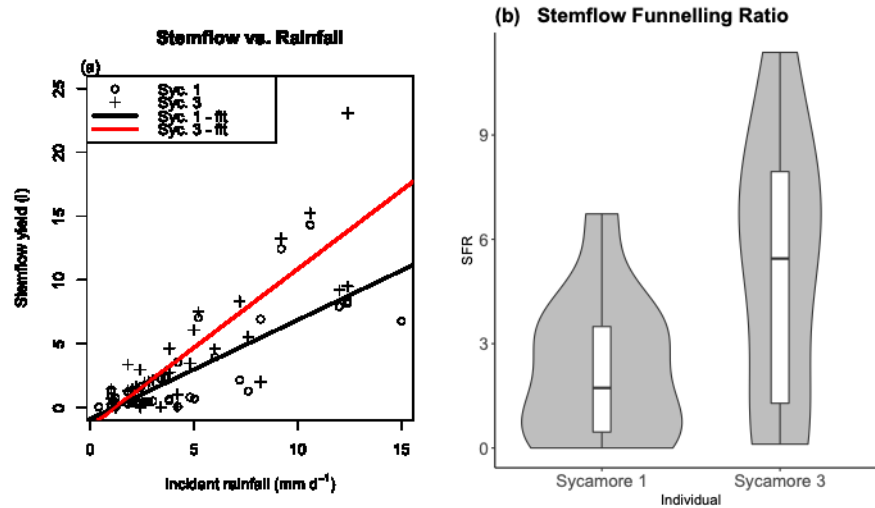


Figure 4. (a) Stemflow yield was significantly higher in sycamore Syc3 ('+' symbol and red line,  $y=1.23x-1.45$ ,  $R^2 = 0.69$ ,  $P < 0.01$ ) compared to Syc1 (empty circles and black line,  $y=0.77x-0.88$ ,  $R^2 = 0.63$ ,  $P < 0.01$ ), with respect to incident rainfall ( $\text{mm d}^{-1}$ ); (b) stemflow funnelling ratio (SFR, unitless) for Syc1 and Syc3. The lower edge of the box corresponds to the 25th percentile data point, while the top edge of the box corresponds to the 75th percentile data point. The line within the box represents the median. The grey area around the box shows the probability density of the data at different values. See online version for colours.

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377

378 Stemflow yield significantly increased with the incident rainfall in both sycamore individuals  
 379 (Fig. 4a), it being significantly greater in Syc3 when compared to Syc1. The rainfall threshold  
 380 to yield stemflow was  $1.14 \text{ mm d}^{-1}$  and  $1.18 \text{ mm d}^{-1}$  for Syc1 and Syc3, respectively. The  
 381 total stemflow yield during the monitoring period was 91.05 l and 131.50 l for Syc1 and  
 382 Syc3, respectively. For both trees and the 35 rainfall events examined, the mean stemflow  
 383 amount generated per unit projected crown area averaged 1.35 % of the incident rainfall, with  
 384 a maximum of 3.76 %. Mean stemflow funnelling ratios were above 1.0 in all cases (i.e. more  
 385 incident rainfall was concentrated around the tree bole than expected had there not been a  
 386 tree; Fig. 4b) but they did not differ statistically between the two sycamores ( $\chi^2=3.46$ ,  $df=1$ ,  
 387  $p=0.06$ ). However, the mean stemflow funnelling ratio was substantially higher in Syc3  
 388 ( $5.16 \pm 3.91$ ) than in Syc1 ( $2.23 \pm 2.11$ ).

389

390 3.3. Double-funnelling and tree root distribution

391



Figure 5. (a) Area within the soil-root zone where subsurface flow had occurred due to double-funnelling and root vertical distribution for sycamores Syc1 (full green circles and dotted line) and Syc2 (full black circles and dotted line). A negative exponential model (lines) was fitted to the measured root area (points) (Gonzalez-Ollauri and Mickovski, 2016). Soil stained with Brilliant Blue FCP dye indicated double-funnelling into soil beneath (b) Syc1 and (c) Syc2. See online version for colours.

392

393 In trees that had been sprayed with dye, zones where subsurface flow had occurred due to  
394 double-funnelling were successfully identified in the soil close to the stem (Figs. 5b and c).

395 The dye solution mostly infiltrated into the topmost soil layers, reaching maximum depths of  
396 350-400 mm b.g.l (Fig. 5a). Specific zones with signs of preferential flow were also  
397 identified, and associated with the presence of thicker roots (Figs. 5b-c). The area of soil  
398 wetted by double-funnelling (Fig. 5a) was not significantly different between Syc1 and Syc2  
399 ( $\chi^2=0.18$ ,  $df=1$ ,  $p=0.68$ ; Fig. 5a). However, we detected a strong positive correlation ( $r=0.57$ )  
400 between the stained area of soil and vertical root distribution, and both decreased with  
401 increasing soil depth (Fig. 5a). The root cross-sectional area ( $Ar$ ) of the two sycamores  
402 decreased exponentially with increasing soil depth and had mean rooting depths (i.e.  $b$ : soil  
403 depth at which 95 % of the roots are located; Gonzalez-Ollauri and Mickovski, 2016; Table  
404 1) of 258.9 mm and 275.8 mm for Syc1 and Syc2, respectively.

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### 407 3.4. Influence of stemflow and its suppression on soil-water dynamics

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#### 411 3.4.1. Soil temperature

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413 Daily soil temperature showed a clear response to stemflow (Fig. 6a) in that it was usually  
414 significantly higher ( $\chi^2=3143$ ,  $df=1$ ,  $p < 0.01$ ) under the tree where stemflow was suppressed.

415 However, under Syc2 with stemflow, a substantial increase in soil temperature was observed  
416 following heavy rainfall (i.e. > 5-10 mm d<sup>-1</sup>; Fig. 6a) that was not detected in the tree with  
417 suppressed stemflow.

418

#### 419 3.4.2. Soil moisture

420

421 Distinct daily soil moisture ( $\theta_v$ ) peaks were observed under trees with stemflow after heavy  
422 rainfall events (i.e. > 5-10 mm d<sup>-1</sup>) and following stemflow simulations (Fig. 6b). This  
423 response was more pronounced in soil where double-funnelling had occurred, but it was not  
424 detected when stemflow was suppressed. Despite this, the  $\theta_v$  time series did not show  
425 significant differences between stemflow and suppressed stemflow ( $\chi^2=2.30$ , df=1, p=0.13),  
426 not even between the locations with and without signs of double-funnelling ( $\chi^2=1.89$ , df=1,  
427 p=0.17; Table 2). However, significant differences occurred between soil depths where soil  
428 moisture probes were deployed: shallow soil (i.e. 100 mm b.g.l) had significantly higher  $\theta_v$   
429 compared to deeper soil (i.e. 260 and 400 mm b.g.l; Table 2;  $\chi^2=13.09$ , df=2, p < 0.01; Fig.  
430 6b). We excluded soil moisture records from  $\theta_{v,-1}$  (Table 2; Figs. 2c,d), as the moisture probe  
431 was dysfunctional (Fig. 6b).

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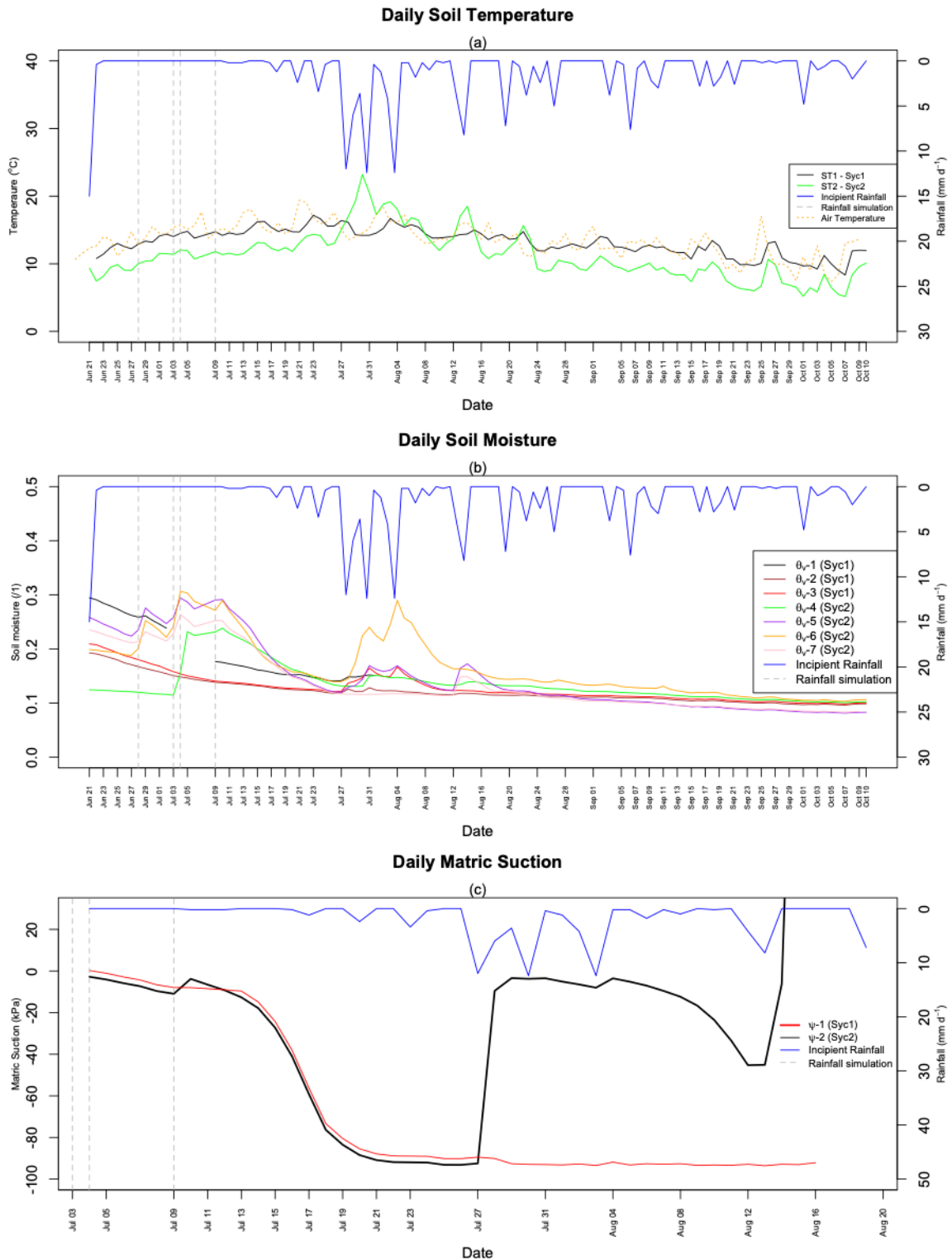


Figure 6. (a) Daily mean soil temperature time series recorded at two points (Table 2) where signs of double-funnelling had occurred under Syc1 (suppressed stemflow) and Syc2 (with stemflow), plotted together with daily mean air temperature and incident daily rainfall data. (b) Daily mean volumetric soil moisture content recorded for Syc1 (suppressed stemflow) and Syc2 (with stemflow), at different areas of the root-soil zone (Table 2), and plotted together with incident rainfall data. (c) Daily mean matric suction recorded at the root-soil zone (Table 2) under Syc1 (suppressed stemflow) and Syc2 (with stemflow). Vertical dot-dash lines indicate stemflow simulation events undertaken after trench excavation (Section 2.5). See online version for colours.

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### 3.4.3. Soil matric suction

Daily soil matric suction ( $\psi$ ) responded to stemflow markedly over the monitoring period (Fig. 6c) and increased (i.e. became more negative) in both sycamore individuals under dry conditions (i.e. in the absence of rainfall), until it reached the maximum measurable value possible with the tensiometer (-93 kPa; Fig. 6c). However,  $\psi$  decreased sharply following heavy rainfall events ( $>5 \text{ mm d}^{-1}$ ) in the sycamore individual that had double-funnelling (Syc2; Fig. 6c). However, Syc1 (i.e. suppressed stemflow) showed no change in  $\psi$  (Fig. 6c). The same effect, although of lower magnitude, was observed following stemflow simulations around Syc2 (vertical dot-dash lines in Fig. 6c). As a result,  $\psi$  was significantly different between individuals with stemflow, and those where stemflow was suppressed ( $\chi^2=44.40$ ,  $df=1$ ,  $p<0.01$ ). At the end of the observation period,  $\psi$  in soil beneath Syc2 decreased towards positive values (i.e. positive pore-water pressure; Fig. 6c). We excluded soil matric suction records after 16/08/2018 (Table 2), as the  $\psi$ -2 probe was dysfunctional after this date (Fig. 6c).

### 3.5. Framework outputs

#### 3.5.1. Effect of tree architectural traits on stemflow yield

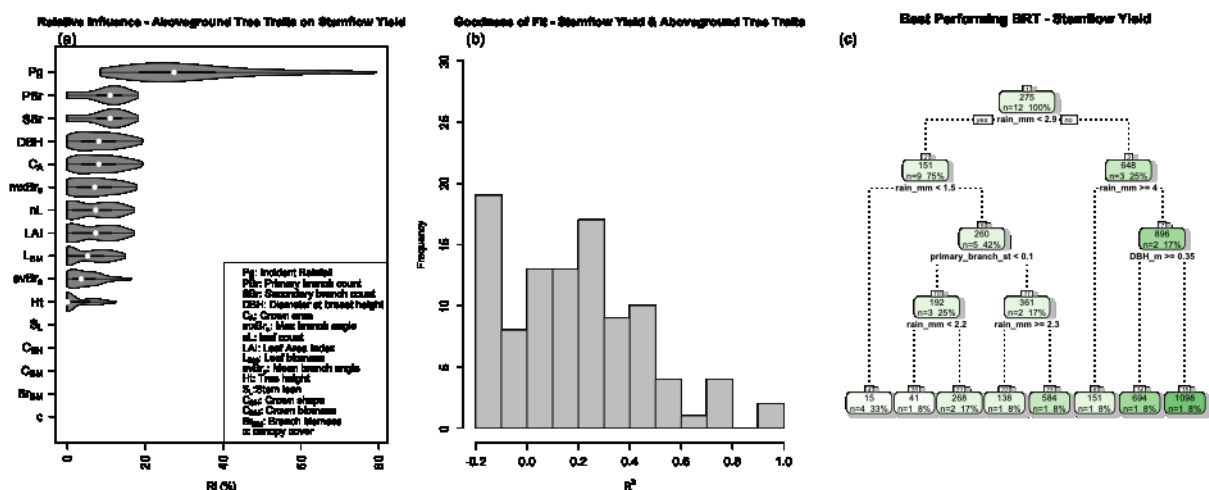


Figure 7. (a) Incident rainfall had the highest relative influence (RI) on stemflow yield for Syc1 and Syc3, followed by several architectural traits related to branch dimensions and leaf cover; the white dot within the box represents the median while the grey area around the box shows the probability density of the data at different values (b) Histogram showing the frequency of coefficients of determination ( $R^2$ ) for the 100 boosted regression trees fitted between aboveground traits against stemflow yield for sycamores Syc1 and Syc3 (c) Regression tree dendrogram for the best performing BRT model fitted to predict stemflow yield from tree architectural traits and incident rainfall. Each tree leaf (i.e. box) indicates the mean response (i.e. stemflow yield in ml), number, and percentage of observations. The darker the colour shade in the tree leaf, the higher is the mean response.

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The relative influence (*RI*) of architectural traits (Fig. 7a) on stemflow yield was significantly different ( $\chi^2=1225$ ,  $df=15$ ,  $p<0.01$ ), implying that the measured architectural traits contributed differently to the partition of rainfall into stemflow aboveground. Incident rainfall, which was included as covariate in the BRTs (Section 2.6.1; Fig. 7c), was the most important predictor (*Pg*;  $31.48\pm 16.02\%$ ; Fig. 7a). Stem lean (*S<sub>L</sub>*), crown shape (*C<sub>SH</sub>*), and biomass (*C<sub>BM</sub>*), branch biomass (*Br<sub>BM</sub>*) and canopy cover fraction (*c*) did not influence the production of stemflow yield (Fig. 7a). In the light of the best performing BRT (Fig. 7c) and partial dependence plots (PDPs; supplementary material Figs. S2a-p), incident rainfall and the number of primary branches were strongly and positively correlated with stemflow yield (Figs. 7c, S2a,f) while a strong, negative correlation was observed between stemflow yield and *DBH* (Figs. 7c, S2b). The PDP between stemflow yield and incident rainfall (Fig. S2a) indicated that there was a rainfall threshold of 3.5 mm d<sup>-1</sup> for the production of stemflow, in contrast with the thresholds of 1.14 and 1.18 mm d<sup>-1</sup> observed in Fig. 4a (Section 3.2). Beyond rainfall of 3.5 mm d<sup>-1</sup>, stemflow yield was the same. The remaining aboveground traits did not show clear correlations with stemflow yield (Figs. 7c, S2), in spite of the observed *RI* (Fig. 7a). The fitted BRTs presented a maximum  $R^2\pm RMSE$  of  $0.94\pm 19140$ , and a mean $\pm$ SD and mode  $R^2$  of  $0.19\pm 0.26$  and 0.25, respectively (Fig. 7b).

### 3.5.2. Effects of stemflow yield, incident rainfall, and air temperature on soil-water dynamics

#### 3.5.2.1. Soil temperature

The BRTs fitted to soil temperature (Eq. 6 - Table 1; Fig. 3) had a high goodness of fit overall (supplementary material Figs. S3a-b; Table 4). The  $R^2$  density function for *ST* (Figs. S3a-b) exhibited negative skewness and a mean value above 0.5 (Table 4). Model quality was significantly higher ( $\chi^2=37.94$ ,  $df=1$ ,  $p<0.01$ ) under Syc1 with suppressed stemflow (Fig. S2a) compared to Syc2 (with stemflow, Fig. S3b). The assessment of the variables' *RI* for all the BRTs fitted to soil temperature (Fig. 8a-b) suggested that air temperature was the most important covariate for predicting soil temperature (Fig. 6a), which was significantly more important than rainfall and stemflow for Syc2 ( $\chi^2=92.55$ ,  $df=2$ ,  $p<0.01$ ). However, air temperature and rainfall were equally important for predicting *ST* when stemflow was

490 suppressed ( $\chi^2=3.67$ ,  $df=1$ ,  $p=0.05$ ). The influence of incident rainfall and air temperature on  
 491 soil temperature was corroborated in the partial dependence plots for Syc2 (supplementary  
 492 material Figs. S4a-c), whereas the effect of stemflow was unclear (Fig. S4b). For Syc1,  
 493 however, the effect of rainfall on soil temperature was uncertain (Fig. S4a), while air  
 494 temperature had a more constant influence on soil temperature than that observed beneath  
 495 Syc2 (Fig. S4c).

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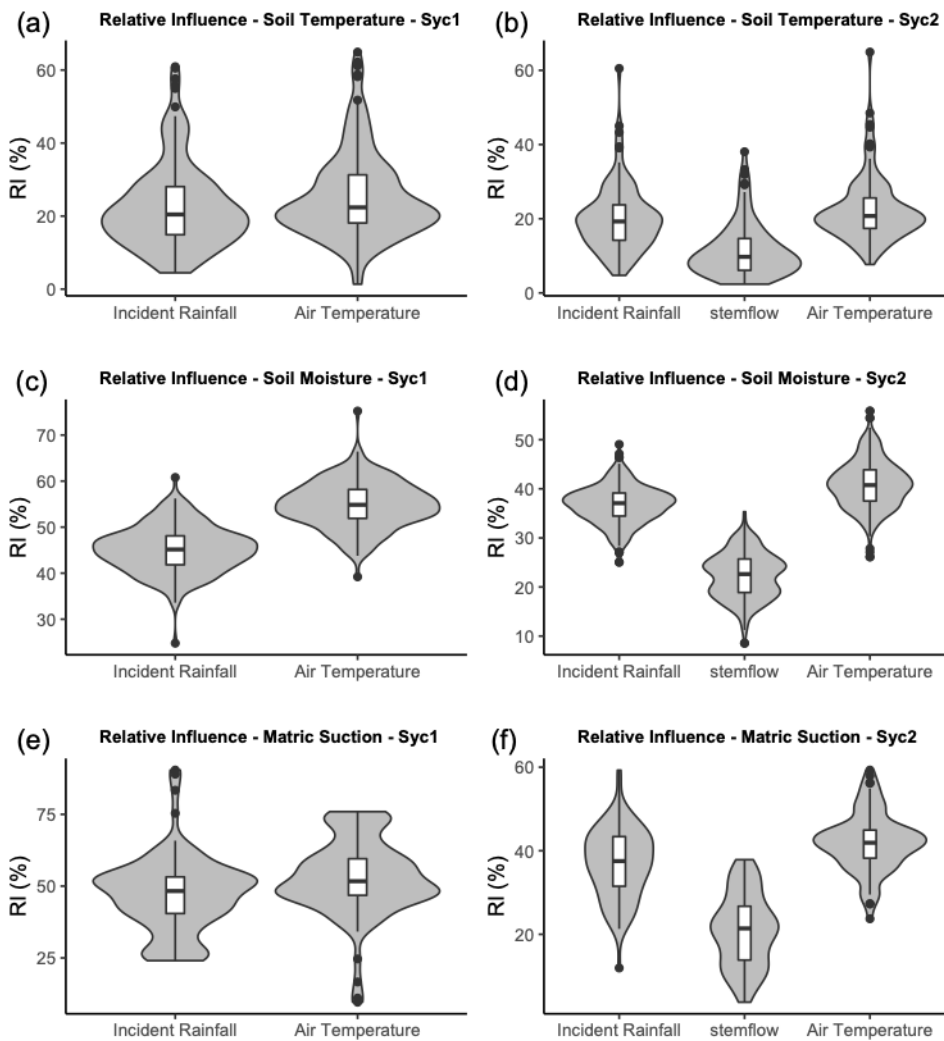


Figure 8. Relative influence (*RI*) of stemflow yield, incident rainfall and air temperature on soil-water dynamics for sycamores Syc1 (suppressed stemflow) and Syc2 (with stemflow) (a-b) soil temperature (c-d) soil moisture (e-f) matric suction. The lower edge of the box corresponds to the 25th percentile data point, while the top edge of the box corresponds to the 75th percentile data point. The line within the box represents the median. The grey area around the box shows the probability density of the data at different values.

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### 3.5.2.2. Soil moisture

The BRTs fitted to soil moisture ( $\theta_v$ ; Eq. 7 - Table 1; Fig. 3) had a satisfactory goodness of fit in almost all cases under Syc1, where stemflow was suppressed (supplementary material Figs. S3c-h; Table 4). The coefficient of determination ( $R^2$ ) was also significantly higher ( $\chi^2=194.31$ ,  $df=1$ ,  $p<0.01$ ) under Syc1 (Figs. S3c-d) compared to Syc2 (Figs. S3e-h). The assessment of the variables' *RI* for all the BRTs fitted to  $\theta_v$  (Figs. 8c-d) suggested that air temperature was the most important predictor for soil moisture (Fig. 6b), even more so than rainfall and stemflow (Syc1:  $\chi^2=205.9$ ,  $df=1$ ,  $p<0.01$ ; Syc2:  $\chi^2=851.6$ ,  $df=2$ ,  $p<0.01$ ). However and, on the basis of the PDPs (supplementary material Fig. S4), only air temperatures ranging between 10 and 11° C seemed to produce a minor, yet consistent, response on soil moisture (Fig. S4f). The PDPs also showed that the nature of the relationship between rainfall and air temperature with  $\theta_v$  was unclear for both sycamore individuals (Figs. S4a-f). The same issue was observed between stemflow yield and soil moisture (Fig. S4e).

### 3.5.2.3. Soil matric suction

The BRTs fitted to soil matric suction ( $\psi$ ; Eq. 8 - Table 1; Fig. 3) exhibited, in general, a poor goodness of fit (supplementary material Figs. S3i-j; Table 4). No significant differences occurred between the models fitted under Syc1 (suppressed stemflow) and Syc2 (with stemflow,  $\chi^2=0.14$ ,  $df=1$ ,  $p=0.71$ ). The assessment of the variables' *RI* for all the BRTs fitted to  $\psi$  (Figs. 7e-f) suggested that air temperature was the most important predictor (Fig. 8c), and was significantly more important than rainfall and stemflow (Syc1:  $\chi^2=10.54$ ,  $df=1$ ,  $p<0.01$ ; Syc2:  $\chi^2=167.2$ ,  $df=2$ ,  $p<0.01$ ). On the basis of the PDPs (supplementary material Figs. S4j-l), the influence of rainfall and air temperature on matric suction appeared constant for Syc1. However, these variables had a cyclical effect on matric suction for Syc2 (Figs. S4j-l). The PDPs for stemflow yield showed a negative relationship with matric suction in Syc2, i.e. higher stemflow yields led to lower matric suction (Fig. S4k).

551 Table 4. Summary from the cross-validation process (Fig. 2) for the 100 boosted regression trees fitted between  
 552 meteorological variables and soil-water dynamics (Table 1) for the sycamores Syc1 (suppressed stemflow) and Syc2 (with  
 553 stemflow). *ST*: soil temperature;  $\theta_v$  : soil moisture;  $\psi$ : matric suction;  $R^2$ : coefficient of determination; RMSE: root mean  
 554 square error; SD: standard deviation.

555

Variable	Tree	Probe	$R^2$			Skewness	Kurtosis	SD
			max±RMSE <sup>†</sup>	mean	mode			
Soil temperature	Syc1	ST1	0.95±0.50	0.71	0.79	-1.34	4.96	0.19
	Syc2	ST2	0.94±2.24	0.49	0.71	-0.27	2.08	0.26
Soil moisture	Syc1	$\theta_v$ - 2	0.94±0.00	0.39	0.38	0.66	-0.17	2.04
		$\theta_v$ - 3	0.84±0.01	0.35	0.38	0.38	-0.12	1.72
	Syc2	$\theta_v$ - 4	0.77±0.02	0.18	0.13	0.55	0.52	2.11
		$\theta_v$ - 5	0.80±0.02	0.19	0.18	-0.14	0.38	2.38
		$\theta_v$ - 6	0.83±0.02	0.17	0.11	-0.14	0.65	2.29
		$\theta_v$ - 7	0.60±0.03	0.04	-0.02	-0.14	1.06	3.32
	Matric suction	Syc1	$\psi$ - 1	0.99±16.92	0.04	-0.22	1.60	5.69
Syc2		$\psi$ - 2	0.95±72.71	0.08	-0.33	0.91	2.55	038

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#### 558 4. Discussion

559

##### 560 4.1. Stemflow funnelling above ground

561

562 Through our novel framework, we showed that relationships existed between stemflow yield  
 563 and aboveground tree architecture (Figs. 7a-c). In particular, we demonstrated that a thin  
 564 trunk and small crown increased stemflow yield and funnelling. Our results also showed that  
 565 stemflow yield was related to the geometry of the tree's crown, in agreement with Levia and  
 566 Frost, (2003), Levia et al., (2015) and Yuan et al., (2017). More numerous and steeply angled  
 567 branches, together with a larger surface area, also increased stemflow production, as found by  
 568 Levia et al., (2015). However, whilst stemflow yield has been found to be negatively  
 569 correlated with leaf number (Levia and Frost, 2003; Levia et al., 2015), we showed that more  
 570 leaves actually increased stemflow (Table 3). This result, which relied on a very small sample  
 571 size, suggests that leaves could deflect part of the intercepted rainfall towards the woody  
 572 parts of the canopy, thus contributing to stemflow yield (e.g. Martinez-Meza and Whitford,  
 573 1996; Deguchi et al., 2006; Liang et al., 2009; Yuan et al., 2017).

574

575 Stemflow yield in sycamores fell within commonly reported values for other woody species  
 576 across biomes (e.g. Carlyle-Moses et al., 2018) and incident rainfall was the most influential

577 variable affecting stemflow yield (Yuan et al., 2017). We detected a minimum rainfall  
578 threshold of 1.14 mm d<sup>-1</sup> required to trigger stemflow (Fig. 4a), and a maximum threshold of  
579 3.5 mm d<sup>-1</sup>, beyond which stemflow yield was constant (supplementary material Fig. S3a).

580

581 Nevertheless, the number of individuals investigated in our study was low, and a wider  
582 diversity of tree sizes and architectural traits (e.g. leaf shape and angle of insertion on host  
583 branch or bark topography) need examining, so that the model fits between stemflow yield  
584 and aboveground architectural traits can be improved. A variety of tree morphologies would  
585 also help us to better understand the influence of crown architectural traits on stemflow yield,  
586 that we could not disentangle in our study (Figs. 7c, S2). However, our framework was robust  
587 enough to account for some of the variability in the linear relationship between stemflow  
588 yield and incident rainfall (Figs. 4a, 7a, 7c, S2; Deguchi et al., 2006). Including rainfall as a  
589 covariate in the BRTs (Fig. 7c) was useful to gain insights into how rainfall events can be  
590 partitioned into stemflow by an array of tree architectural traits at the individual level, and  
591 also the hydrological boundaries at which this happens.

592

593 The poor BRT fits possibly underline the difficulty of capturing how stemflow is affected by  
594 a complex canopy structure (Levia et al., 2015), but a larger tree sample would help to reduce  
595 uncertainty. Reliable information about how tree architecture distributes precipitation within  
596 the crown to produce stemflow will be especially useful for urban foresters who need to  
597 manage stormwater flow around trees that require regular pruning. The type of pruning  
598 performed could actually alter the quantity of rainfall that reaches the soil, as well as its  
599 transfer belowground (del Campo et al., 2014).

600

601

#### 602 4.2. Double-funnelling

603

604 An effective concentration of incident rainfall occurred around the tree bole and in the  
605 uppermost soil layers, as the stemflow funnelling ratio was > 1 (Carlyle-Moses et al., 2018).  
606 Subsurface flow occurred mainly as matrix flow (Schwärzel et al., 2012; Spencer and van  
607 Meerveld, 2016), with some preferential flow observed along coarse woody roots. The dense  
608 root system in the topsoil, that was comprised chiefly of thin roots (i.e. diameter < 3 mm),  
609 was significantly and positively correlated to double-funnelling. Coarse woody roots visible  
610 on the soil surface next to the tree bole may have acted as small dams, causing stemflow to

611 pond locally and facilitating its infiltration as matrix flow (Mein and Larson, 1973). Ponding  
612 could have also been fostered by the hydrophobicity of soil organic matter (Spencer and van  
613 Meerveld, 2016), or a higher proportion of silt at the soil surface (unpublished data; Lu and  
614 Likos, 2004). The low soil moisture content that we observed, likely reduced the extent of  
615 stemflow-derived surface runoff (Liu et al., 2019), that was only noted next to the tree stems  
616 (Fig. 2b). Although some preferential flow was observed (Figs. 5b-c), it would be useful to  
617 test whether double-funnelling changes from matrix to preferential flow or to surface runoff  
618 under different soil hydrological regimes and under different stemflow rates.

619

620 Double-funnelling had a clear impact on soil temperature and moisture (Figs. 6a-b) with both  
621 variables increasing rapidly after heavy rainfall events (i.e.  $> 5 \text{ mm day}^{-1}$  in Syc2). The  
622 arrival of water to specific patches of soil, together with peaks in soil temperature could be  
623 due to enhanced matrix and preferential flow, and the subsequent increase in microbial  
624 activity and respiration (McClain et al., 2003; Kuryakov and Blagodatskaya, 2015) related to  
625 the transport of water and nutrients from the canopy to the soil through stemflow (e.g.  
626 Germer et al., 2012). Still, further work is required to quantify the effects of double-  
627 funnelling on soil respiration fluxes along with the activity of soil microbial communities  
628 (e.g. Rosier et al., 2016).

629

630 Soil matric suction was significantly modified in response to double-funnelling (Fig. 6c).  
631 Between July and August, we observed two clearly defined wetting fronts that only occurred  
632 in the soil-root zone under Syc2, suggesting that stemflow can lead to soil matric suction  
633 depletion (Liang et al., 2011). In addition, the positive pore-water pressures that developed  
634 under Syc2 after the second recorded wetting front were indicative of the formation of a  
635 perched water table at the location where the tensiometer was installed (Germer, 2013). The  
636 decrease in soil matric suction that we observed can drastically reduce the mechanical  
637 strength of plant-soil composite materials (Vanapalli et al., 1996; Gonzalez-Ollauri and  
638 Mickovski, 2017b), thus diminishing the mechanical reinforcement provided by the root  
639 system in vegetated slopes (Gonzalez-Ollauri and Mickovski, 2016, 2017b, 2017c). It is not  
640 yet known to what extent double-funnelling can alter soil hydrological regimes so that soil  
641 slippage and landslides could occur. To prevent such potential occurrences, it is necessary to  
642 make a choice on planting tree species based not only on mechanical and hydrological traits,  
643 but also taking into account aerial architecture and its potential impact on stemflow.

644

645 4.3. Effects of stemflow yield, incident rainfall and air temperature on soil-water  
646 dynamics

647

648 Our framework was useful for detecting effects of stemflow yield and meteorological  
649 variables on soil-water dynamics. Air temperature was shown to be the most influential  
650 meteorological variable (Fig. 8) and its strong positive correlation with soil temperature could  
651 have obscured the effects of rainfall and stemflow yield as predictors of soil temperature.  
652 During the summer months, the temperature-dependent, atmospheric demand for water acted  
653 as the driver regulating the soil water balance (e.g. Allen et al., 1998; Novick et al., 2016) and  
654 hence the dynamics of soil moisture and matric suction in the soil-root zone. However, the  
655 effect of rainfall on soil temperature recorded for Syc2, suggested that double-funnelling  
656 quickly brought rainfall into the root-soil matrix, and warmed the soil by triggering  
657 biogeochemical reactions (Wang et al., 2015; Lloyd and Taylor, 1994; Schindlbacher et al.,  
658 2011). In the tree with suppressed stemflow, the effect of rainfall on soil-water dynamics  
659 could be related to subsurface flow originated beyond the studied plot, based on the analysis  
660 of time lags between rainfall and soil-water dynamics (e.g. supplementary material – Fig. S5;  
661 Bogaard, 2001; Bestland et al., 2009).

662

663 Surprisingly, stemflow yield was the least important covariate influencing soil-water  
664 dynamics in Syc2. The strong correlation between rainfall and stemflow (Figs. 4a, 7a, S2a)  
665 may have obscured the relationship with stemflow in the BRTs (model covariates should be  
666 independent from each other, Bruce and Bruce, 2017). However, in our study, there were  
667 limitations to experimental design because stemflow yield was not directly measured for  
668 Syc2, but was predicted for Syc2 using BRTs fitted to a small dataset. Furthermore, Syc2 had  
669 substantial architectural differences with respect to the individuals used to fit stemflow yield  
670 BRT models (Table 3), which likely led to the poor BRT fits (Fig. S3). Therefore, to clarify  
671 the effect of stemflow on soil-water dynamics, it is essential to quantify stemflow yield for a  
672 larger sample and longer periods, using flow meters or tipping bucket gauges (e.g. Levia et  
673 al., 2010; Spencer and van Meerveld, 2016; del Campo et al., 2018) before allowing  
674 stemflow to funnel belowground.

675

676 Some limitations occurred when using BRTs, in particular, when we evaluated the  
677 relationships between predictors and response variables in the partial dependence plots  
678 (PDPs; supplementary material Figs. S2, S4). The discretisation of the response variables by

679 BRTs only enabled us to observe weak predictor-response interactions in the PDPs, as  
680 opposed to the array of effects discussed for the time series records (Section 4.2; Fig. 6) as  
681 well as for the relationships between architectural traits and stemflow yield (Section 4.1). To  
682 circumvent this issue, we encourage the incorporation of alternative statistical models able to  
683 generate continuous outputs (e.g. random forest; [Breiman, 2001](#)) in future versions of our  
684 framework.

685

## 686 5. Conclusion

687

688 We demonstrated how a novel numerical framework and experimental approach can be used  
689 to examine the effect of tree aboveground architecture on stemflow yield and its influence on  
690 soil-water dynamics. In the light of our observations and findings, it can be concluded that:

691

- 692 - The number of branches, their insertion angle, leaf number, and stem basal diameter  
693 influenced stemflow yield within specific rainfall thresholds.
- 694 - Funnelling of stemflow beneath the soil surface occurred as matrix flow and was  
695 significantly and positively correlated with the vertical root distribution.
- 696 - Soil-water dynamics were distinctly different with and without stemflow.
- 697 - Soil matric suction was negatively affected by stemflow yield, but air temperature  
698 was the most influential covariate affecting soil-water dynamics likely due to its  
699 strong correlation to evapotranspiration during the summer season.
- 700 - The discretisation of the response variables by boosted regression trees only enabled  
701 us to observe weak predictor-response interactions, as opposed to the array of effects  
702 observed in this study.

703 In spite of the study limitations discussed above, such as small sample size and differences  
704 between individuals, the proposed framework and experimental approach provide a good  
705 basis for future research contributing to our knowledge of how stemflow generated  
706 aboveground triggers major responses in soil-water dynamics belowground.

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708

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