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Riikonen, Anu

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1 Environmental and crown related factors affecting street tree transpiration
2 in Helsinki, Finland

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4 Anu Riikonen*, Leena Järvi, and Eero Nikinmaa

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7 A. Riikonen and E. Nikinmaa, Department of Forest Sciences, University of Helsinki, P.O. Box 27, University of
8 Helsinki, Finland

9 L. Järvi, Department of Physics, University of Helsinki, P.O. Box 48, University of Helsinki, Finland

10 *Corresponding author (anu.riikonen@helsinki.fi)

11

12 **Abstract**

13 We investigated the drivers of street tree transpiration in boreal conditions, in order to better
14 understand tree water use in the context of urban tree planning and stormwater management. Two
15 streets built in Helsinki in 2002, hemiboreal zone that had been planted either with *Tilia × vulgaris*
16 or *Alnus glutinosa* f. *pyramidalis* were used as the study sites. Tree water use was measured from
17 sap flow over the 2008-2011 period by the heat dissipation method. Penman-Monteith based
18 evapotranspiration models of increasing complexity were tested against the tree water use
19 measurements to assess the role of environmental and tree related factors in tree transpiration.

20
21 *Alnus* and *Tilia* respectively used 1.1 and 0.8 liters of water per m² of leaf area per day under ample
22 water conditions, but the annual variation was high. The Penman-Monteith evapotranspiration
23 estimate and soil water status changes explained over 80% of the variation in tree transpiration
24 when the model was parameterized annually. The addition of tree crown surface area in the model
25 improved its accuracy and diminished variation between years and sites. Using single
26 parameterization over all four years instead of annually varying one did not produce reliable
27 estimates of tree transpiration. Tree transpiration, scaled to different canopy cover percentages,
28 implied that the columnar *Alnus* trees could transpire as much as all annual rainfall at or less than
29 50% canopy cover.

30

31 **Keywords:** evapotranspiration, street trees, urban, water use

32

33 **Introduction**

34 Knowledge of the water use of street trees is useful, for example, as a basis for soil resource
35 allocation when planning tree-lined streets. Increasingly urban trees are also considered as a
36 component of integrated urban stormwater management, thus an understanding of their actual and

37 potential water use and the environmental and tree related factors affecting tree water use are
38 needed.
39
40 Measuring the water use of urban trees is challenging due to their open spatial arrangements with
41 specific local environments in comparison to natural canopies. Direct transpiration measurements
42 by using micrometeorological methods available for homogeneous canopies are not necessarily well
43 suited for solitary or openly spaced urban trees with irregular spatial arrangements (Lee 2000,
44 Villegas et al. 2014). On the other hand, accurate up-scaling of leaf level transpiration
45 measurements to crown and canopy level can be difficult to achieve (Jarvis 1995) due to e.g. the
46 heterogeneous but non-random distribution of trees and also to the urban constructions in close
47 proximity to the crowns of interest. Between these scales of local and leaf level measurements, the
48 measurements of sap flow (Granier 1985) as a mean of estimating whole-tree transpiration rates are
49 readily usable for even solitary trees. However, also this method can be problematical due to e.g.
50 nonuniform sap flow within the stem (Clearwater et al. 1999), particularly with large trees.
51 Nonetheless, sap flow measurements are among the best, if not the only, practical method to
52 estimate the effects of climate and soil conditions on urban tree transpiration (e.g. Litvak et al.
53 2011, McCarthy and Pataki 2010).

54
55 Water use measurements of urban trees made *in-situ* have been published only for relatively few
56 species and climate regions and commonly over short time periods (Chen et al. 2011, Litvak et al.
57 2011, McCarthy and Pataki 2010, Pataki et al. 2011, Peters et al. 2010, Wang et al. 2011). The
58 relevance of water use measurements for natural and agricultural ecosystems in comparison to the
59 estimation of urban tree water use is complicated by different environments and species
60 composition. The interactions of tree function and environment in urban conditions differ from
61 those observed in the natural habitats of trees. For example, due to commonly observed higher air

62 temperatures and lower relative humidity, water vapor pressure deficit can be substantially higher in
63 urban areas, and soil water availability may be limited when compared to natural surroundings
64 (Nielsen et al. 2007). Such conditions can lead to stomatal regulation characteristics that are
65 different from native environments (McCarthy and Pataki 2010, Litvak et al. 2011).

66

67 The Penman-Monteith (PM) equation is commonly used to estimate potential evapotranspiration
68 (ET_0) from vegetated surfaces (Monteith 1965; Penman 1948). ET_0 considers the influence of
69 meteorological variables on transpiration. The PM equation or model is widely used in an
70 agricultural context and to estimate irrigation needs for nursery trees (e.g. Beeson 2012, Grant et al.
71 2009). In these estimations, the obtained ET_0 value is commonly multiplied by an empirically
72 derived crop coefficient k_c (Doorenbos and Pruitt 1977) or other scaling factor that summarizes the
73 influence of vegetation properties. This agriculture-based approach to determine tree water use does
74 cause some problems when applied to street trees. For example, the canopy in the urban
75 environment is often not closed, which renders the use of a general crop coefficient problematic
76 (Beeson 2012, Hagishima et al. 2007), and also soil water content may limit transpiration (Bernier
77 et al. 2006). Describing surface resistance or canopy conductance properties are more important at
78 both canopy and leaf level and need to be integrated into the model in more detail (Granier et al.
79 2000). On the other hand, the PM model is fairly robust and the application of the PM derived ET_0
80 is widespread in irrigation management, and is a familiar approach for many who work in urban
81 greening industry. Models that are used to describe and predict the transpiration of forest trees (e.g.
82 Granier et al. 2000, Medlyn et al. 2007, Mäkelä et al. 2006) are an obvious alternative to the PM
83 model. These models are also often based on the PM approach, but are more detailed, for example,
84 in describing the transpiration control by the trees, and require input variables such as
85 photosynthesis and respiration parameters or radiation components that may not be readily available
86 in an urban setting. Also in these models a continuous canopy is often assumed.

87

88 In this study, we measured and modelled street tree water use in boreal conditions in Helsinki,
89 Finland. The aim was to assess the responses of urban tree transpiration to environmental variables
90 and to examine the magnitude of tree water use in relation to annual precipitation. More
91 specifically,

92 1. Street tree sap flow was measured to attain estimates of tree water use over a four-year period.

93 2. A suitable version of PM model was developed to best describe the street tree sap flow. The
94 details of canopy properties description were varied and effects of these changes on the model
95 performance assessed.

96 3. The most important environmental variables driving tree sap flow were sought based on PM-
97 model fit against sap flow observations. Additionally, an analysis of model residuals was performed
98 against environmental variables, and sap flow observations were regressed directly against the
99 environmental variables.

100 4. PM models were applied to estimate annual tree water use and used to compare tree transpiration
101 against precipitation in an urban context assuming different canopy covers.

102

103 **Materials and methods**

104 **Study sites and measurements**

105 The study was conducted in two experimental streets situated close to the University of Helsinki
106 Viikki campus, about 9 km from the Helsinki city centre (N60°15', E25°03') (Figure 1). The two
107 streets were planted with 15 *Tilia × vulgaris* Hayne trees and 22 *Alnus glutinosa* (L.) Gaertn. f.
108 *pyramidalis* 'Sakari' trees, respectively, in late 2002. From now on the two streets are referred as
109 Tilia and Alnus site. The growing media consisted of three pre-mixed structural soils in both sites,
110 and these ranged from 32-64 mm to 64-150 mm in stone size and 65-70% in stone matrix volume.
111 The soil plot dimensions for each tree were 3 m wide, 1 m deep strips placed within the standard

112 load bearing gravel of the street. The rooting volumes ranged from 15 to 30 m³ for *Alnus* and 45 to
113 50 m³ for the *Tilia* trees and spacing between the *Tilia* trees was 15 m, 4-5 m between *Alnus* trees.
114 The underlying soil was clay and subsurface drains were installed on both sites. The level of the
115 water table at the *Tilia* site was continuously high and the street sloped towards sea at only 2 to 6 m
116 above sea level. This site collected water from a larger catchment area compared to the *Alnus* site,
117 which was fed only with local rainfall. The research sites and soils are described in detail in
118 Riikonen et al. (2011) and Table 1. Trees at both sites were irrigated weekly for the first two years
119 and they remained largely unpruned until late 2008. Thereafter, *Tilia* was pruned annually to
120 achieve necessary crown lifting. All trees had a tree grate that covered a 2.25 m² area installed
121 around the tree with open soil underneath. The street surfacing around the *Alnus* tree grate was 16 x
122 16 cm granite pavers with 10-20 mm drainage gravel grouted joints. The *Tilia* trees, had 10 x 10
123 cm granite pavers with 10 mm sand grouted joint covered an area of 4 m² around the tree grate, and
124 outside that, concrete blocks (28 x 16 cm) were installed with 2 mm sand grouted joint.

125

126 An automatic monitoring system was built on each soil mixture x tree -combination on each site
127 with a data logger (EnvicLtd., Turku, Finland) to collect data from automated measurements as
128 summarized below. The data used in this study were collected over the 2008-2011 period.

129

130 *Soil*

131 Soil volumetric water content (SWC) was measured using ML2x sensors at the depths of 10 and 30
132 cm from each tree soil surface (DeltaT Devices Ltd., Cambridge, UK, see Riikonen et al. 2011 for
133 details). The measurement interval was 2 min.

134

135 *Meteorology*

136 Air temperature and photosynthetically active radiation (PAR) at the study sites were measured at
137 the height of 8 m (radiation shielded thermistors and QS2 sensors, Delta-T Devices Ltd.,
138 Cambridge, UK, respectively). In addition to these on-site meteorological measurements,
139 observations from the nearby (4 km) SMEAR III urban measurement station (60°12', 24°57', Järvi
140 et al. 2009) were used. Relative humidity (HMP243, Vaisala Ltd, Vantaa, Finland), precipitation
141 (weighing rain gauge, Ott Pluvio, Kempen, Germany, at 4 min intervals) and wind speed (cup
142 anemometer) were measured on the roof of a building (height 52 m), and PAR, global radiation (I)
143 and downward longwave (L^-) radiation (PAR lite CNR1, Kipp & Zonen, Delft, Netherlands) from
144 top of a 31 m high measurement tower. Water vapor pressure deficits (D) at the *Tilia* and *Alnus*
145 sites were calculated using the local temperatures and relative humidity measured at the SMEAR III
146 station.

147

148 *Tree growth, leaf area and tree dimensions*

149 Tree trunk circumference at 130 cm height (in April), and tree height, live canopy height and width
150 in two approximately perpendicular directions (in August) were measured with measuring tape each
151 year. Total leaf area of the trees was estimated by fitting a linear regression to the log-transformed
152 branch leaf area and branch basal area (measured in August) and summing up over the over the first
153 degree branches of the tree (Riikonen et al. 2011) (Table 1). Leaf area index (LAI) equalled the
154 total leaf area divided by the projected canopy area. Live crown surface areas were approximated
155 from the canopy dimensions assuming the typical *Tilia* crown shape to be a cone and *Alnus* crown
156 to be an ellipsoid.

157

158 The interannual variation in LAI was derived from shoot measurements. The shoot length increment
159 was measured for 3 shoots each of 6 trees of both species from bud burst to growth cessation with

160 digital callipers two or three times per week. After the annual shoot and leaf growth had ceased the
161 leaves on five representative shoots in each of 15 *Tilia* and 22 *Alnus* trees were counted and the
162 obtained means were used to estimate the remaining number of leaves for the respective species.
163 The relative number of leaves remaining was that divided by the number of leaves at shoot growth
164 cessation.

165

166 *Tree transpiration*

167 A self-made (Hölttä et al. 2015) Granier type heat dissipation sensor pair (Granier 1985) was
168 installed in three *Tilia* and three *Alnus* trees nearest to each data logger. Prior to each growing
169 season, holes (3 mm diameter) were drilled at 10 cm apart within the range 50-100 cm height on
170 north and/or east side of the tree trunks. Brass tubes that had been filled with thermally conducting
171 silicone compound were instantly inserted into the holes and sensors (45 mm in length) into the
172 brass tubes. The sensors, measuring the first 45 mm of sapwood inwards from bark, were protected
173 from direct radiation by radiation shields that had been installed inside the trunk guards, allowing
174 free mixing of air. All sensor data obtained from each point were collected by the data loggers at 1-
175 10 min intervals.

176

177 Sap flow at 30-min intervals was calculated according to Granier's (1987) empirical calibration. A
178 five day running mean was used to estimate the temperature difference between the heated and
179 reference sensor at 0-flow conditions (at 2:30-4:30 Eastern European Time, when the lowest diurnal
180 flow rates were recorded) (T_{max}). Measured sap flow is considered to represent tree water use by
181 assuming that the whole of the sapwood cross-section conducted water, which is considered to be a
182 good estimation for young diffuse-porous trees (Gebauer et al. 2008).

183

184 Most of the sap flow sensors provided continuous data from July to August in 2008, from May to
 185 September in 2009 and from May to October in 2010 and 2011. Data obtained before bud break and
 186 after leaf fall were omitted. When a tree had more than 1/4 of the 30 min values missing for a day,
 187 that day and tree data were excluded from the data set. For a day to be included in the calculation of
 188 average daily water use, measurements of at least two of the three measured trees per species were
 189 required. Days with missing daily sums were gapfilled linearly. The missing daily sums within the
 190 used data periods for *Tilia* were in 2008: 9.5%, 2009: 18.9%, 2010: 10.2%, 2011 24.8%, and for
 191 *Alnus* in 2008: 21.8%, 2009: 19.7%, 2010:16.6% and in 2011 10.5%.

192

193 **The Penman-Monteith (PM) model**

194 The predicted evapotranspiration (ET_T) for both *Tilia* and *Alnus* sites was calculated using a
 195 modified PM model (Eq. [1]) in 30 min intervals. The model was optimized against the measured
 196 sap flow per projected canopy area (PCA), sf_{meas} ($\text{g m}^{-2} \text{s}^{-1}$) according to

$$197 \quad c \frac{\Delta R_n + \rho_a C_p (D) g_a}{(\Delta + \gamma (1 + \frac{g_a}{g_c})) \phi_v} = ET_T, \quad (\text{Equation 1.})$$

198 where c is the fitted multiplier, Δ is the rate of change of saturated air humidity with temperature
 199 (Pa K^{-1}), R_n is the net all-wave radiation (W m^{-2}), ρ_a is the dry air density (kg m^{-3}), C_p is the
 200 specific heat capacity of air ($\text{J kg}^{-1} \text{K}^{-1}$), D is the water vapor pressure deficit (Pa), γ is the
 201 psychrometric constant (Pa K^{-1}) and ϕ_v is the latent heat of vaporization (J g^{-1}). g_a and g_c are the
 202 atmospheric and canopy conductances (m s^{-1}). In Eq. [1], g_a is calculated from its inverse,
 203 aerodynamic resistance ($r_a = g_a^{-1}$, s m^{-1}) according to

$$204 \quad r_a = \frac{\ln\left(\frac{z_m - z_d}{z_{0m}}\right) \ln\left(\frac{z_m - z_d}{z_{0v}}\right)}{k^2 u}, \quad (\text{Equation 2.})$$

205 where z_m is the height of the measured wind speed (m), z_d is the displacement height (m), z_{0m} and
 206 z_{0v} are the roughness lengths for momentum and water vapor (m), k is the von Karman constant and

207 u is the wind speed (m s^{-1}). The effect of the atmospheric stability was assumed to be negligible and
 208 thus the stability functions for momentum and water vapor were omitted from the calculation of r_a .
 209 z_{0m} and z_{0d} were calculated from the mean tree height z_h ($0.1z_h$ and $2/3z_h$, respectively) and z_{0v} as a
 210 rule of thumb $z_{0v} = z_{0m}/10$ (Grimmond and Oke 1991).

211

212 Models of variable complexity were used to calculate g_c in Eq. [1]. In the simplest model (M1) g_c
 213 was a standard parameter ($1/70 \text{ m s}^{-1}$) according to FAO guidelines (Allen et al. 1998). In the more
 214 complex model (M2) g_c was calculated using a Lohammar-type function that considered the effect
 215 of I (W m^{-2}) and D (Pa) (Granier et al. 2000):

$$216 \quad g_c = \left(g_{s_{max}} \frac{I}{a+I} \frac{1}{1+bD} \right) L, \quad \text{(Equation 3.)}$$

217 where L accounts for the effects of leaf area and $g_{s_{max}}$ (m s^{-1}), a (W m^{-2}) and b (Pa^{-1}) are the fitted
 218 parameters for each species. The first parameter gives the maximum canopy conductance, a is the
 219 non-linearity of light modifier (Michaelis-Menten type saturation) and b is the vapor pressure
 220 deficit modifier (both modifiers obtain values that range from 0 to 1).

221

222 While in M2 $L = 1$, in the next model M3, L accounts for the effect of leaf area (LA):

$$223 \quad L = \min\left(1, \frac{1}{6} \text{LAI} \times L_s\right), \quad \text{(Equation 4.)}$$

224 where L_s accounts for the change within a growing season. According to Granier et al. (2000), g_c
 225 scales linearly with $\text{LAI} < 6 \text{ m}^2 \text{ m}^{-2}$ and with higher values it saturates in relation to LA. L_s was
 226 estimated from mean shoot length growth measurements, assuming the relative leaf area increase
 227 was linearly proportional to the relative shoot length increment. After the annual shoot growth had
 228 ceased, leaf area scaling followed the relative number of remaining leaves. Additionally in M3, the
 229 effect of crown surface area in relation to crown projection area were accounted for by replacing c
 230 (Eq. [1]) with a term $\text{CS}/\text{PCA} \times \beta$. CS refers to crown surface area (m^2) and β replaces c as a fitting

231 parameter; a separate symbol is used to underline the exclusion of crown dimensions from the
232 parameter.

233

234 I and R_n used in Eq. [1] and Eq. [3] were indirectly derived. PAR measured at the tree sites (μmol
235 m^{-2}) was converted to I by using a conversion factor (0.55) that had been derived from 30 min
236 means at the SMEAR III station. Furthermore, the R_n at tree surface was estimated based on
237 Loridan et al. (2010):

$$238 R_n = I(1 - \alpha_0) + \varepsilon_0(L \downarrow - \sigma T^4) - 0.08 I(1 - \alpha_0), \quad (\text{Equation 5.})$$

239 where α_0 and ε_0 are the effective surface albedo and emissivity for deciduous trees, respectively, σ
240 is the Stefan and Boltzmann constant ($\text{W m}^{-2} \text{K}^{-4}$) and T is the air temperature (K). R_n at the street
241 tree sites was further transferred from locally measured PAR by using a conversion factor from the
242 correlation between R_n calculated from Eq. [5] and measured PAR at SMEAR III. The R_n value that
243 was calculated for the Tilia site was used also for Alnus site, because the PAR sensors at the Alnus
244 site were located in the street canyon and shaded part of the time by the surrounding buildings on its
245 eastern side.

246

247 **PM model fittings**

248 The performance of modified PM model (Eq. [1]) was assessed both annually (annual models) and
249 over the whole 4-year datasets (general models) using all 30 min sap flow values from 2008-2012.
250 The similarity of the acquired PM parameter values in Eq. [1] were compared with Tukey's two-
251 sided T test. First, however, a time lag between evapotranspiration, tree sap flux and environmental
252 conditions was accounted for (Granier 1985, Burgess and Dawson 2008). The time lag that gave
253 the best fit (least squares) between the ET_T and sf_{meas} using the whole growing season for each site
254 from 2008 to 2011 (Tables 2 and 3) was chosen and used in all data analyses in this study. The
255 tested lag times ranged from 0 to 4 hours and the best fit was obtained for a time lag of 60 min in all

256 years except at the Tilia site in 2009, when the time lag was 30 min, and at the Alnus site in 2010,
257 when time lag was 90 min (Tables 2 and 3).

258

259 **Statistical tests for the effect of environmental variables**

260 Comparisons between ET_T , sf_{meas} and residuals against environmental variables were performed on
261 a daily basis for the annual M3 model with multiple linear regression (SAS procedure REG). A
262 comparison of the daily residuals ($sf_{meas} - PM\ ET_T$) was made between the SWC and all the
263 meteorological variables in the PM model in backward selection using Akaike's Information
264 Criterion. Both SWC measurement depths were initially included in the model and then the less
265 significant depth was omitted and the fitting was then completed.

266

267 Furthermore, a linear regression (with logarithmic transformation when necessary) was used to
268 study relationship between daily D , I , SWC and sap flow density (j_s , $g\ cm^{-2}\ day^{-1}$) in July-August
269 each year on the daily sum level, loosely following the approach used by McCarthy and Pataki
270 (2010). To examine the effects of D and I on j_s , a model

$$271\ j_s = i + e \ln(D) + f I \quad \text{(Equation 6.)}$$

272 with two parameters (e and f) and an intercept (i) was fitted. In the following step the residual
273 ($j_{s_{meas}} - j_{s_{pred}}$) was regressed against SWC. The linear regression model was applied with SAS
274 procedure REG and NLIN. Data was fitted separately for each year and site.

275

276 Measured weekly sap flow sums (calculated per m^2 of LA) for each year were compared between
277 sites and analyzed by using the Kruskal-Wallis test. All statistical analyses in this study used p -
278 value of 0.05 as the cut-off point below which differences were considered to be statistically
279 significant.

280

281 The annual sum of measured *Tilia* tree transpiration in relation to PCA was compared to total
282 annual precipitation measured at the SMEAR III station. Estimates of tree transpiration were made
283 for different canopy cover percentages (proportion of land area covered by horizontal projections of
284 tree crowns) by scaling the measured sap flow per PCA, Similar comparison was also performed
285 using the ET_T estimates obtained from the optimized PM model. The year 2008 was excluded from
286 this analysis due to the high percentage of missing sf_{meas} (65% of daily values over the entire
287 summer for *Tilia* and 57% for *Alnus*). In the estimates accounting for canopy interception, we
288 assumed that 38.2% of precipitation during the growing season and 27% in the wintertime was
289 intercepted by canopy area corresponding to the canopy cover percentage (Xiao and McPherson
290 2011).

291 **Results**

292 **General meteorological and hydrological conditions**

293 The study years 2008-2012 differed from each other especially in regard to their mean daily T and
294 D (Figure 2). July 2010 was clearly warmer (22 °C) than the 30-year mean (18 °C) for Helsinki
295 (Pirinen et al. 2012). Similarly, systematically higher D were measured in July 2010 than in the two
296 previous years. If considered over the entire summer, D was on average higher still in 2011, but this
297 was due to high values in early summer (June). The *Tilia* site had a higher groundwater table
298 (Riikonen et al. 2011) and higher SWC values than at the *Alnus* site throughout the entire four-year
299 period. SWC values rose from year to year at the *Tilia* site, and at the *Alnus* site, SWC was at its
300 highest also in the last year, 2011 (Figure 2).

301

302 **Tree transpiration**

303 Based on sap flow measurements, *Tilia* water use on a PCA basis in July-August was
304 approximately 1/4 of the *Alnus* water use in all studied years (Table 4), but weekly water use per m^2

305 of leaf area only showed a significant difference between species in 2009. The mean water use per
306 m^2 of leaf area was at its highest in *Tilia* in 2010 and in *Alnus* in 2009. Approximate daily water use
307 per tree was at its highest in 2010, ranging from 40 to 50 l d^{-1} for *Tilia* and 60 to 70 l d^{-1} for *Alnus*.

308

309 **The PM model**

310 *General parameterization*

311 To find the optimal PM model parameters to describe street tree sap flow, comparisons between the
312 different models against observations were made. The PM model, fitted to all the study years
313 (general parameterization), explained a minimum of 54% of the 30 min mean transpiration values at
314 its simplest (M1, Table 2). M1 however overestimated transpiration in three years out of the four
315 years studied (bias in the all years model, Table 2). In comparison to M1, the bias in the annual
316 transpiration estimates was reduced considerably (from 6 – 80% to 7 – 56%) in M2. This is
317 attributable to the *I* and *D* modifiers to describe canopy conductance (Eq. [3]) included in M2
318 model. M2 also explained slightly more (61%) of the variation in the transpiration values than M1;
319 the improvement was more notable at the *Alnus* site. The addition of varying LA and crown surface
320 area to the model (M3) improved the fit further (R^2 increased by about 0.05, Tables 2 and 3). The
321 M3 model had again smaller bias than M2, but the improvement was not as clear as the one gained
322 by the addition of canopy conductance submodel in M2.

323

324 The parameter *a* describing stomatal response to solar radiation in M3 was thrice as high and g_{smax}
325 less than half for *Tilia* in comparison to *Alnus* (Table 3). These parameter values mean that *Tilia*
326 obtained half of its maximum transpiration rate at more than double the light intensity and had only
327 one third of the maximum transpiration rate in comparison to *Alnus*. The *D* response parameter *b*
328 was only significant for *Alnus*, indicating that for *Tilia*, additional model to describe stomatal
329 reaction to *D* was not needed. Values of the scaling parameter β in M3 differed little between the

330 species. All the fitted parameters were significantly different for *Tilia* in comparison to *Alnus*
331 however.

332

333 *Annual parameterization*

334 Fitting the models separately for each year (annual parameterization, Tables 2 and 3) improved the
335 explained variation and reduced or removed the trend in the prediction bias in all model versions. In
336 M1 – M2 this was mostly because annual variation was allowed in parameter c , which mainly
337 describes the variation in canopy properties. In M1, the R^2 of individual years varied between 0.48
338 – 0.83 with generally better correlation at *Tilia* than *Alnus* site. All the models tended to slightly
339 overestimate low sap flow and underestimate high sap flow on both 30 min (Figure 3) and daily
340 (Figure 4) level. Considering the light and D modifiers for canopy conductance (M2) and the
341 within-year leaf area dynamics at annual level (M3, also Figure 3) improved the predictions further
342 (R^2 between 0.60 – 0.81 and 0.67 – 0.86, respectively). On the daily level, the differences between
343 the tested model versions were more pronounced than on the 30 min level (Figure 4).

344

345 The parameters of the g_c function in the annually fitted M3 model were fairly similar within each
346 site in 2009-2011 but with some exceptions they were either at their lowest or highest in 2008
347 (Table 3). Parameter values had less inter-annual variation in *Alnus* than in *Tilia*. The D response
348 parameter b was not significant at the *Tilia* site in 2008 and 2010. The light response parameter a
349 value was at its highest on both sites in 2008 and lowest in 2011. In the models M1-M2 the scaling
350 parameter c increased annually and was always 3-4 times higher at the *Alnus* site than at the *Tilia*
351 site. In M3, where crown surface area in relation to projected crown area is taken into account, the
352 scaling parameter β varied less, yet significantly, between sites and years but there was no similar
353 trends as in c and also the differences between the species were reduced.

354

355 *Residual correlations*

356 The residual ($sf_{meas} - ET_T$) correlations with environmental variables (I , D and SWC), used to assess
357 the model fit and effect of environmental variables on tree transpiration, ranged from fairly strong
358 ($R^2 = 0.67$) to non-existent (Table 5). Correlations with environmental variables at the Tilia site
359 were weaker than at the Alnus site and at their most obvious in 2008 when the early and late
360 summer measurements were missing. The model predicted higher transpiration than was actually
361 observed in high air temperature at the Alnus site, especially in 2010. Soil water content had a
362 notable role at the Alnus site in all years examined, especially in 2008 and 2011. Soil water content
363 regressed alone against ($sf_{meas} - ET_T$) was responsible for most of the explanatory power of the
364 residual regression model at the Alnus site each year.

365

366 **The regression model**

367 The regression model (Eq. 6), applied on daily level to find support for PM based analysis of the
368 effect of environmental variables, was significant for both sites and all years except for the Alnus
369 site in 2011. R^2 varied from 0.48 to 0.88 (Table 6). The model accounted for the observations from
370 the Tilia site better than those from the Alnus site. The results showed that D was the more
371 significant driver at the Tilia site in 2008 and Alnus site in 2009, while I dominated at the Tilia site
372 in 2010 and at the Alnus site in 2008. Correlation between SWC and the residuals of the linear
373 regression model was significant at the Tilia site only in 2008, but at the Alnus site, it was
374 significant in all years except 2010 (Figure 5).

375

376 **Comparison between tree transpiration and rainfall**

377 The measured and modelled transpiration values respective to the annual rainfall in 2009-2011 were
378 estimated with different surface fraction of vegetation scenarios (Table 7) to assess the potential
379 benefits of tree transpiration in managing e.g. stormwater from building roofs. With 20% of the

380 surface covered with *Tilia* crowns, the transpiration from the canopy cover would be 15-20% of the
381 annual rainfall. If the coverage of the canopy would be 70% the respective fraction would be 60-
382 80%. For *Alnus*, the corresponding percentages were much higher, and the annual total rainfall
383 would have been transpired with less than 50% canopy cover in an average year. M1 produced
384 higher transpiration for *Tilia* than what was measured, but the difference was only approximately
385 10%. Correcting for soil water effects (i.e. assuming no water limitation in soil) did not affect the
386 estimates for *Tilia*, but for *Alnus*, the SWC corrected estimates over all three years were slightly
387 higher than the uncorrected ones (not shown).

388

389 With the columnar *Alnus* trees, transpiration equalling rainfall was reached on average with
390 approximately 35% canopy cover. If we assume that canopy interception accounts for 35-40 % of
391 rainfall during the growing season and 27% in the wintertime (Ilvesniemi et al. 2010, Xiao and
392 McPherson 2011), the estimates of canopy cover that would produce water removal equal to rainfall
393 were about 30% for *Alnus* and 90% for *Tilia*.

394

395 **Discussion**

396 **Tree transpiration**

397 In comparison to forest tree transpiration in the boreal zone, street tree transpiration measured at the
398 study sites appeared to be similar or somewhat higher when calculated per LA (Amiro et al. 2006,
399 Arain et al. 2003, Bernier et al. 2006, Daley et al. 2007, Herbst et al. 1999, Launiainen 2010, Oishi
400 et al. 2008). As expected from the reported high values of maximal stomatal conductance of *Alnus*
401 *glutinosa* (Eschenbach and Kappen 1999) the water use of *Alnus* were generally higher than the
402 corresponding values of *Tilia*, although no direct published reference to the behavior of these
403 species in urban conditions have been found. Peters et al. (2010) observed similar or lower
404 transpiration rates for urban *Tilia americana* in Minneapolis compared to *Tilia × vulgaris* in this

405 study. However, *Tilia americana* is considered to be more shade tolerant than the *Tilia* of this study
406 (Burns and Honkala 1990) and the late successional species also have a generally lower stomatal
407 conductivity (Bazzas 1979).

408

409 The heat dissipation method used for sap flow measurements has several known sources of
410 uncertainty (Clearwater et al. 1999). There is a delay in the response of measured sap flow to
411 changes in environmental factors that is caused by both tree- and method-related factors (Tatarinov
412 et al. 2005, Wullschlegel et al. 2011). When the relationships between sap flow and transpiration
413 driven by meteorological factors are studied, this delay needs to be taken into consideration. The
414 best fit between tree water use and ET_T in the present study was obtained with a time lag of between
415 30 to 90 min, which is similar to what Granier et al. (2000) reported for coniferous and deciduous
416 forests growing in latitudes that ranged from Canada to the tropics.

417

418 Traditionally it is assumed that no sap flow occurs in predawn hours (see Granier 1987), allowing
419 for T_{max} determination from nocturnal sap flow measurements. It is well known however that this
420 assumption does not always hold true (e.g. Daley and Phillips 2006, Granier 1987, Phillips et al.
421 2003). Despite this, alternative methods for determining T_{max} (with the help of e.g. weather data,
422 Regalado and Ritter 2007) have not yet gained much popularity, and appropriate selection
423 averaging period for T_{max} is the most common method to reduce potential error. If T_{max} in this study
424 did not represent true no-flow situation, this leads to underestimation of tree sap flow, which in
425 relation to the role of trees in stormwater management would lead to less critical dimensioning error
426 than the opposite. Also, significant night time evapotranspiration seems to be rare in the boreal
427 environment (Launiainen et al. 2005), reducing further the potential error of incorrect T_{max}
428 determination.

429

430 The recorded sap flows may not represent tree transpiration accurately because these were
431 measured at the superficial 96-79% of the stem cross-section. We assumed that sap flow was
432 uniform within the whole tree trunk. Although this is not strictly true, the deviations from this with
433 relatively small diffuse porous trees can be expected to be small (Gebauer et al. 2008). The possible
434 overestimation in the measured sap flow based on trunk and sensor dimensions would be 21% at the
435 highest if there were no flow beyond the instrumented sapwood. We could not destructively sample
436 our trees and therefore we had no way of knowing whether heartwood was indeed present in our
437 study trees but in relation to tree age and size it was probably not an issue. *Tilia* sp. have been found
438 to have sapwood lying at lengths beyond the sensor dimensions we used in the present study
439 (Gebauer et al. 2008, Peters et al. 2010, Hölscher 2005). The same reasoning applies to *Alnus* sp.
440 for which sapwood depth has also been recorded to exceed our sensor length (Moore et al. 2004).

441

442 **The PM model**

443 The adaption of a Lohammar type response of canopy conductance to light and vapor pressure in
444 M2, and its linear-saturating response to leaf area (Granier et al. 2000) in M3 improved the fit
445 between sf_{meas} and ET_T for both general and annual parameterization. General parameterizations of
446 the different PM model versions gave biased predictions over time, but the bias was smaller with
447 each consecutive addition of response variables. In M3 the bias in the estimation of annual
448 transpiration was still significant (Tables 2 and 3); the average daily absolute deviation of the
449 predicted value was 35% of the measured value at the *Tilia* site and 29% at the *Alnus* site. This
450 would lead to a risk of similarly large over- or underestimation in transpiration prediction made
451 with this model without annual parameterization. In conclusion, satisfactory prediction accuracy
452 with the same parameter values across all four years could not be attained.

453

454 Accounting for leaf area and its development within a growing season improved the prediction
455 mainly in spring and autumn, when leaf area was below its annual maximum. The use of shoot
456 growth as a proxy for leaf area development appeared to cause the predicted sap flow to precede the
457 measured sap flow slightly in the spring (data not shown). This was likely because the leaf
458 development from initiation to full maturity lags behind shoot development, and the leaf level
459 functions also vary within year (Xu and Baldocchi 2003; Wilson et al. 2001). We used the approach
460 of saturating the canopy conductance in respect to leaf area index, suggested by Granier et al.
461 (2000). Iterations with our data gave the best fit with slightly higher LAI (~10) than they suggested,
462 implying that saturating leaf area index could be higher in open-grown trees.

463

464 The parameter c was fitted to scale the PM evapotranspiration to sf_{meas} in model versions M1 and
465 M2. When c was allowed to vary from year to year, the prediction bias observed in general
466 parameterization (overestimation in 2008 and 2011, underestimation in 2010-2011) was much
467 reduced. In M1, the parameter c parallels the crop coefficient (k_c) to fair extent, although crop
468 coefficient assumes well-watered crop and large uniform canopy (Doorenbos and Pruitt 1977). The
469 uniform canopy assumption is partially met by considering a single-tree crown and the former by
470 excluding the data where obvious soil water limitation was detected. Despite the deviance from
471 original description of crop coefficient, the variation in c gives us an idea about the expected
472 variation of the crop coefficient in urban setting. Divided by LAI, it can be used in urban tree soil
473 volume requirements models (Degaetano 2000; Lindsey and Bassuk 1991). The crop coefficient
474 determined here, calculated to the adjustment factor used by Lindsey and Bassuk (1991), gives
475 clearly lower value for *Tilia* than the default parameters given by the model authors, and somewhat
476 so for *Alnus* as well. Parameter c estimated for *Alnus* was some three times higher than for *Tilia*,
477 resembling the crop coefficient for irrigated fruit crops (Dragoni et al. 2005; Marsal et al. 2013).
478 More of a concern is the high annual variation in c in our dataset however. Excluding the variation

479 resulting from soil water limitation and the year 2008 with its shorter period of measurements still
480 leaves twofold variation in the value of c (Tables 2 and 3). This implies that using a set crop
481 coefficient for the case study trees could have led to water use estimation errors of similar
482 magnitude.

483

484 The PM model, often in a form closely resembling M1 in this study, has been commonly used for
485 orchard trees (e.g. Edwards and Warwick 1984, Fernandez et al. 2001, Nicolas et al. 2005, Pereira
486 et al. 2006). In these studies comparing sap flow and PM estimates, the correlations attained were
487 good and resembled more our annual parameterization than general parameterization efforts. This
488 may be due to e.g. shorter periods of data used or different scaling in terms of leaf or canopy area,
489 which may have prevented detection of possible intra-annual variation in c .

490

491 In model M2, the parameter c is not equal to crop coefficient like in M1, because the addition of the
492 explicit canopy conductance function removes the net effect of stomatal regulation from parameter
493 c . The change helped to decrease the model bias but the numerical value of the parameter did not
494 change much between model versions M1 and M2. This suggests that the between year variation in
495 the evapotranspiration levels was related to structural rather than physiological factors. In the model
496 M3, crown surface area is directly included in the model. This improved the model fit and
497 decreased the bias in the general parameterization. Also the differences in the parameter β values
498 and trends between species practically disappeared. This left similar between year variations in the
499 parameter β value in both species, which we were unable to explain with the simple tree crown
500 characterization used in this material.

501

502 Including crown surface area directly in the model is reasonable for trees growing in an open site,
503 receiving direct light also from the sun at low angles. The improvement attained in the general

504 parameterization with this addition implies that the single crown architecture needs to be considered
505 in the transpiration estimates as was suggested by Duursma and Mäkelä (2007). Airborne laser
506 scanning as described by Tanhuanpää et al. (2014) shows promise as a means of data collection for
507 a model that includes crown dimensions.

508

509 Considering the crown size and physiology of trees allows a comparison between the different
510 species and provides an explanation for the observed differences in tree water use. Canopy
511 conductance of the *Alnus* crowns responded more strongly to low light than it did for the *Tilia*
512 crowns. The *Alnus* sp. is known to favor moist sites and can have very high transpiration rates
513 (Eschenbach and Kappen 1999). The higher maximal stomatal conductance (parameter g_{Smax}) and
514 the more ready responsiveness of stomata to D (parameter b) in *Alnus* compared to *Tilia* suggests
515 that in comparison to *Tilia*, *Alnus* has a heavy water use strategy under favourable conditions. On
516 the other hand the light response differences between the species may originate from their very
517 different crown architectures, which create different penumbra influences (Stenberg 1998). The
518 columnar *Alnus* trees have very dense foliage that reduce the light penetration inside the crown
519 cylinder.

520

521 The estimated parameter values give some insight into the observed between year differences in
522 transpiration. The parameters of the canopy conductance part of the M3 model (g_{Smax} , a and b)
523 suggest higher leaf area specific transpiration in *Alnus* in 2010 than in 2009 and 2011. This can be
524 explained by g_{Smax} being higher for 2010 than for 2009, and much lower value of a in 2011 than in
525 the previous years. However, both T and D in 2010 were much higher in July-August 2010 than in
526 2009 or 2011, which reduced the transpiration rate through the lowering of the canopy conductance
527 via the D modifier (see Eq. [3]). The D response of the canopy conductance function was similar to
528 that reported by Granier et al. (2000) for several tree species. The negative correlation in (sf_{meas} -

529 ET_T) against temperature in 2010 may reflect D response but also direct acclimation to prevailing
530 temperature. High temperatures can directly lower the photosynthesis rate (Smith and Dukes 2013),
531 which may in turn lead to lower transpiration (Nikinmaa et al. 2013) without any changes in D .

532

533 The notable difference in the parameter values between year 2008 and other years may arise from
534 the poor availability of data during that year. The differences between this and the other years were
535 smaller when the parameters were estimated from the late summer data also in 2009-2011 (data not
536 shown). This suggests that the spring and autumn responses of transpiration to the climatic variables
537 differed from each other. Typically, stomatal conductance peaks just before or at leaf full maturity
538 and declines slowly thereafter, but the trend may be difficult to detect due to increasing self-shading
539 (Wang et al. 2014). Annual canopy conductance maximum may dominate more on the 2008 dataset
540 containing only July and August. Perhaps this type of intra-annual variation in leaf properties and
541 different within growing season weather patterns produce the previously mentioned between year
542 differences in parameter β and should thus be considered if general parameterization over several
543 years is attempted.

544

545 Some of the variables examined with the residual ($sf_{meas} - ET_T$) analysis (I , D and additionally T
546 influences D) were included as drivers in the PM model but other variables (SWC) were not. The
547 significance of the former set of variables indicates driver influences that the model formulation
548 cannot fully capture whereas that of SWC describes environmental influence not currently included
549 in the model. The SWC correlation with tree sap flow was confirmed by both analyses in four of the
550 eight year x site combinations, after the effects of meteorological drivers had been taken into
551 account. Lower sap flow during periods of low soil water content was clear at the *Alnus* site. Data
552 for sap flow in 2008 were only available for July-August when soil water content was fairly low,
553 and SWC effects may have been partially confounded by the fitted parameters. The lower sap flow

554 in the driest period of 2010 was attributed mainly to T and D . The D , I and T were all co-correlated
555 and soil was generally driest when the weather was at its warmest in the study period, thus it may
556 merely be a reflection of a tightening stomatal control due to dry soil.

557

558 **The regression model**

559 The examination of sf_{meas} in comparison to its main environmental drivers D and I showed that
560 these explained measured sap flow better at the *Tilia* site than at the *Alnus* site. The variation
561 explained by the regression model was comparable to street trees in Los Angeles (McCarthy and
562 Pataki 2010). Site differences and interannual variation in the variation explained by the regression
563 model are both in parallel to the PM annual models. The PM model explained some 20% more of
564 the variation than the regression model however, even if the proportion of residuals related to SWC
565 effects was taken into account.

566

567 The main conclusion from the regression model results is that the finding of SWC related PM
568 model residuals at the *Alnus* site is supported. Both models agree that SWC effects on tree sap flow
569 were seen in 2008, 2009 and 2011. The effects seen in the PM model residuals also at the *Tilia* site
570 in 2008 and *Alnus* site in 2010 were not detected in the regression analysis, which is likely related
571 to the lower level of the effect. Analysis of the PM model residuals is thus understandably stronger
572 tool in the exploration of SWC effects on tree water use.

573

574 **Comparison between tree transpiration and rainfall**

575 Assessing tree transpiration for larger areas based on the measurements from *Tilia* indicated that
576 annual rainfall and transpiration could be almost equal on years when annual rainfall is close to the
577 local average (660 - 680 mm, Pirinen et al. 2012), if the canopy cover is very high. Annual variation
578 in transpired proportion of rainfall was considerable however. In addition, scaling up the measured

579 canopy transpiration to higher canopy cover is problematic, because the transpiration per tree
580 increases as canopy cover decreases (Oke 1987). Hagishima et al. (2007) found in a plant spacing
581 experiment that transpiration from scattered vegetation was about 2.7 times higher per PCA than
582 from plants placed close together. Accounting for the effects of increasing spacing on transpiration
583 per PCA was not possible with our data, as the trees were planted in rows with nearly even spacing.
584 It appears likely however that because the columnar *Alnus* transpiration model benefited greatly
585 from including the crown surface area, the vertical dimension contributes much in total transpiration
586 and thus tighter spacing would notably lower tree transpiration.

587

588 In this study, street tree water use was similar or slightly higher than that of forest trees in
589 comparable climates. It is estimated (Peurasuo et al. 2014) that of all of the trees managed by the
590 city of Helsinki, less than 1% are street trees, and more than 95% grow in environment managed as
591 a forest, which implies that it would be feasible to use transpiration estimates of forest trees for the
592 urban canopy as a whole. Attaining accuracy in smaller scale requires data on street trees as well
593 however, because street trees dominate in the most built-up areas. This is of particular importance
594 because street trees and their transpiration is a potential factor in the urban storm water
595 management. Emerging research shows that in addition to the better known aspect of canopy
596 interception, tree transpiration can indeed contribute considerably to stormwater management of
597 e.g. parking lots (Scharenbroch et al. 2016).

598

599 Knowledge about the behaviour of different tree species in stormwater management structures such
600 as bioswales is just starting to emerge as well (Scharenbroch et al. 2016); findings here underline
601 the importance of species selection. The indication that only 30% canopy cover of *Alnus* could
602 transpire all the annual rainfall indicates quite a good potential for directing rainfall from larger

603 surface area to their growing media; allowing for example 50% decrease in tree transpiration due to
604 tighter spacing would still give similar results at about 50% canopy cover.

605

606 **Conclusions**

607 Our aim was to quantify water use by street trees and analyse how the environmental factors affect
608 it in boreal urban environment. The water use rates of the tree species studied ranged from 20-40 l
609 day⁻¹ for *Tilia* and 30-60 l day⁻¹ for *Alnus* and thus were quite dissimilar. According to our
610 expectations the Penman-Monteith model could be used to predict the water use of both species
611 accurately. However, this required both parameterization of the transpiration model annually and
612 also allowing the canopy conductance to vary with light and D , and attain different maximal
613 conductance values (different g_{smax}) for each year. Accounting for intra-annual leaf area changes
614 and including tree crown dimensions in the model improved the prediction further. The canopy
615 conductance parameterization was overall similar for each species for three out of the four years
616 examined, but the scaling parameters c and β needed to be determined for each year. The PM model
617 appears suitable for estimating urban tree water use, but overt simplifications in the model and
618 parameterization risk considerable biases in the results. Our multi-year observations and PM-model
619 analysis challenges the use of simple crop coefficient for accurate estimation of street tree
620 transpiration.

621

622 Our analysis of the factors behind the variation in the evapotranspiration showed that the PM model
623 with an additional canopy conductance and leaf area development submodels, scaled to crown
624 surface area, performed satisfactorily in relation to environmental variables included in the model.

625 Soil water status was not included in the model, but was detected to have a significant effect on tree
626 sap flow in several cases. The results of the regression model also indicated that the effects of soil

627 water status on tree transpiration were significant, supporting the need to showing that its inclusion
628 in the predictive models is necessary.

629

630 The comparison of tree transpiration and precipitation with different canopy cover percentages
631 showed that *Alnus* water use was on average more than 50% of the precipitation with only 20%
632 canopy cover. *Tilia* trees, in comparison, had such a high impact only with canopy cover of 60-
633 70%. Thus it appears that especially the columnar *Alnus* trees have high potential in stormwater
634 management.

635

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643

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857 Figure captions

858 Figure 1. Aerial view of the Viikki district in Helsinki (©Kaupunkimittausosasto 2011, Helsinki,
859 Finland). The Tilia site is marked by a cross and the Alnus site is marked by a square.

860

861 Figure 2. Daily mean global radiation (I , $W m^{-2}$) measured at the Tilia site and air temperature (T ,
862 $^{\circ}C$), water vapor pressure deficit (D , kPa) and soil volumetric water content in the fine soil fraction
863 of structural soils (SWC, % vol., mean of 10 and 30 cm measuring depths) at the tree sites (Tilia
864 site: solid light line, Alnus site: dotted black line) during May-October in 2008-2010.

865

866 Figure 3. A comparison of 30 min measured sap flow and predicted annual M3 ET_T at the a) Tilia
867 and b) Alnus site in 2009. Solid line: 1:1 relationship, dashed line: least-squares regression line
868 (Tilia site: $y = 0.85x + 0.004 g m^{-2} s^{-1}$, root-mean-square error (RMSE) $0.013 g m^{-2} s^{-1}$, $R^2 = 0.83$;
869 Alnus site: $y = 0.79x + 0.025 g m^{-2} s^{-1}$, RMSE $0.057 g m^{-2} s^{-1}$, $R^2 = 0.79$). Solid line: 1:1
870 relationship. Note the difference in scale of the axes.

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872 Figure 4. Measured daily sap flow and predicted PM ET_T with different model versions (annual
873 parameterization) for the a) Tilia and b) Alnus site in 2009. For Tilia site M1: $R^2 = 0.58$, root-mean-
874 square error (RMSE) $0.75 l m^{-2} d^{-1}$; M2: $R^2 = 0.59$, RMSE $0.74 l m^{-2} d^{-1}$; M3: $R^2 = 0.68$, RMSE $0.68 l$
875 $m^{-2} d^{-1}$. For Alnus site M1: $R^2 = 0.27$, RMSE $3.96 l m^{-2} d^{-1}$; M2: $R^2 = 0.33$, RMSE $3.80 l m^{-2} d^{-1}$; M3:
876 $R^2 = 0.65$, RMSE $2.74 l m^{-2} d^{-1}$. Solid line: 1:1 relationship. Note the difference in scale of the axes.

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878 Figure 5. Daily residual ($sf_{meas} - (i + e \ln(D) + fI)$) (Eq. [3]); i : intercept, e and f : fitted parameters)
879 compared to soil water content at the a. Tilia and b. Alnus site in July-August; at each site, the SWC
880 from the measurement depth giving better correlation is shown (the depth of 10 cm for the Tilia site
881 and the depth of 30 cm for the Alnus site). Adjusted R^2 at the Tilia site in 2008: 0.12, 2009, 2010

882 and 2011: not significant; at the Alnus site in 2008: 0.56, 2009: 0.08, 2010: not significant, and in
883 2011: 0.13.

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886 **Tables**

887 Table 1. Mean characteristics of the trees measured for sap flow in 2008-2011: DBH = trunk

888 diameter at breast height (cm), z_t = the tree height (cm), LA = estimated one-sided tree leaf area

889 (m^2), PCA = the projected canopy area (m^2) and LAI = one-sided leaf area index within the crown.

890 SD = standard deviation of the mean.

Site	<i>Tilia</i>				<i>Alnus</i>			
Year	2008	2009	2010	2011	2008	2009	2010	2011
DBH±SD	11.1 ± 2.1	11.1 ± 2.4	12.9 ± 2.4	13.9 ± 2.8	12.4 ± 0.4	13.6 ± 0.5	14.7 ± 0.6	16.1 ± 1.1
z_t ±SD	560 ± 80	570 ± 90	600 ± 120	610 ± 120	970 ± 60	1050 ± 50	1130 ± 70	1200 ± 70
LA±SD	52 ± 11	75 ± 25	70 ± 27	65 ± 19	61 ± 17	75 ± 15	100 ± 20	91 ± 18
PCA	9.1 ± 1.7	9.3 ± 2.6	8.9 ± 3.1	10.6 ± 2.9	3.5 ± 1.1	5.1 ± 1.0	4.1 ± 0.4	6.0 ± 1.4
LAI	5.7	8.1	7.9	6.2	17.4	14.17	24.4	15.3

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906 Table 2.
 907 The performance and parameters of PM M1 and M2 models with 30 min resolution data. The
 908 differences of the predicted transpiration estimates from the measured sums are shown for each
 909 year. c is the fitting parameter in Eq. [3]. Standard errors (SE) are given with the mean parameter
 910 values.

Site	Year	Adj. R ²	$c \pm SE$	Bias (% of meas.)
<i>Tilia</i> M1	2008	0.82	0.25 ± 0.002	12
	2009	0.76	0.36 ± 0.002	13
	2010	0.68	0.49 ± 0.004	12
	2011	0.80	0.22 ± 0.001	17
	All years	0.59	0.35 ± 0.002	2008:56, 2009: 10, 2010: -21, 2011:82
<i>Tilia</i> M2	2008	0.85	0.21 ± 0.004	-3
	2009	0.80	0.37 ± 0.007	-3
	2010	0.71	0.47 ± 0.008	-3
	2011	0.81	0.28 ± 0.005	-1
	All years	0.61	0.35 ± 0.005	2008: 30, 2009: 7, 2010:-33, 2011:56
<i>Alnus</i> M1	2008	0.68	0.98 ± 0.009	11
	2009	0.63	1.24 ± 0.010	12
	2010	0.72	1.84 ± 0.010	8
	2011	0.47	0.92 ± 0.007	4
	All years	0.54	1.27 ± 0.005	2008:44, 2009: 15, 2010: -25, 2011:45
<i>Alnus</i> M2	2008	0.78	0.85 ± 0.024	-4
	2009	0.68	1.34 ± 0.036	0
	2010	0.83	1.58 ± 0.020	-2
	2011	0.60	1.00 ± 0.017	0
	All years	0.61	1.32 ± 0.018	2008: 32, 2009: 6, 2010: -33, 2011:32

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919 Table 3. The performance and parameters of PM M3 model with 30 min resolution data. The
 920 differences of the predicted transpiration estimates from the measured sums are shown for each
 921 year. a , b , and g_{smax} are the parameters in Eq. [3] and β replaces c in Eq. [3] for model M3.
 922 Standard errors (SE) are given with the mean parameter values. Each parameter was compared
 923 within species between years with Tukey's t test; values indicated with the same letter (h,j,k,m) do
 924 not differ significantly.

Site	Year	Adj. R ²	$a \pm SE$	$b \pm SE$	$g_{smax} \pm SE$	$\beta \pm SE$	Bias (% of meas.)
<i>Tilia</i>	2008 (9 July - 20 Aug.)	0.85	267 ± 72 ^{hj}	ns	0.10 ± 0.025 ^k	0.06 ± 0.001 ^h	-3
	2009 (20 May - 15 Sept.)	0.83	215 ± 20 ^h	5.2·10 ⁻⁴ ± 7.4·10 ⁻⁵ ^h	0.03 ± 0.003 ^h	0.12 ± 0.002 ^j	-3
	2010 (15 May -15 Sept.)	0.75	213 ± 25 ^{hj}	ns	0.03 ± 0.003 ^h	0.14 ± 0.002 ^k	-5
	2011 (14 May-15 Sept.)	0.86	160 ± 11 ^j	8.0·10 ⁻⁵ ± 3.0·10 ⁻⁵ ^j	0.02 ± 0.001 ^j	0.08 ± 0.001 ^m	-1
	All years	0.65	163 ± 12	ns	0.02 ± 0.001	0.11 ± 0.001	2008:29, 2009: -6, 2010: -31, 2011:53
	<i>Atrius</i>	2008 (3 July - 23 Aug.)	0.78	321 ± 87 ^h	7.8·10 ⁻⁴ ± 2.4·10 ⁻⁴ ^h	0.16 ± 0.052 ^h	0.07 ± 0.002 ^h
2009 (5 May - 15 Sept.)		0.79	58 ± 5 ^j	1.1·10 ⁻³ ± 1.2·10 ⁻⁴ ^h	0.04 ± 0.003 ^j	0.13 ± 0.002 ^j	1
2010 (19 May - 15 Sept.)		0.83	61 ± 6 ^k	1.0·10 ⁻³ ± 1.6·10 ⁻⁴ ^h	0.09 ± 0.011 ^h	0.12 ± 0.002 ^k	-2
2011 (1 May-15 Sept.)		0.67	38 ± 3 ^j	4.8·10 ⁻³ ± 6.7·10 ⁻⁴ ^j	0.09 ± 0.012 ^h	0.10 ± 0.002 ^m	0
All years		0.72	51 ± 3	1.5·10 ⁻³ ± 1.1·10 ⁻⁴	0.06 ± 0.004	0.12 ± 0.001	2008:42, 2009:2, 2010:-22, 2011:24

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931 Table 4. Means of high-summer tree water use ($1 \text{ m}^2 \text{ d}^{-1}$) measured per square meter of projected
 932 canopy area and leaf area for *Tilia* and *Alnus* trees. Mean water use per tree is given for the
 933 indicated period and for all measurements available in each year in parentheses. PCA = projected
 934 canopy area, LA = one-sided leaf area, SD=standard deviation.

Tree species	<i>Tilia</i>	<i>Tilia</i>	<i>Tilia</i>	<i>Tilia</i>	<i>Alnus</i>	<i>Alnus</i>	<i>Alnus</i>	<i>Alnus</i>
Year	2008	2009	2010*	2011	2008	2009	2010	2011
Time period	9 July - 20 Aug	9 July - 20 Aug	9 July- 30 July	9 July - 20 Aug	3 July - 23 Aug	3 July - 23 Aug	3 July - 23 Aug	3 July - 23 Aug
$1 \text{ m}^2 \text{ PCA d}^{-1} \pm$ SD	2.1 ± 0.6	3.4 ± 0.8	5.5 ± 1.9	2.4 ± 0.6	7.9 ± 3.0	13.3 ± 3.5	18.4 ± 3.2	9.6 ± 2.8
$1 \text{ m}^2 \text{ LA d}^{-1}$	0.37	0.51	0.78	0.38	0.50	1.09	0.87	0.70
Mean water use per tree, 1 d^{-1}	19	32 (28)	49 (41)	22 (20)	29	68 (51)	72 (56)	52 (44)

935 * no data for August available

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952 Table 5. Parameter estimates for daily residual (sf_{meas} -PM ET_T) correlations against environmental
 953 variables (multiple linear regression) and total R² for the residual model. T = air temperature (°C), I
 954 = global radiation (W m⁻²), D = water vapor pressure deficit (Pa) and SWC = soil water content (%
 955 volume). All environmental variables used were daily mean except for I (daily sum of PAR
 956 radiation). All parameters except those listed as not significant (ns) had a p value <0.05.

Year	Tilia site				Alnus site			
	2008	2009	2010	2011	2008	2009	2010	2011
Number of days	42	109	123	125	52	126	119	134
Intercept	-1.55	ns	ns	ns	-15.26	3.99	23.66	ns
T	ns	ns	ns	0.017	-0.27	ns	-0.83	ns
I	-2.9×10^{-3}	ns	ns	ns	ns	ns	ns	-0.022
M	1.0×10^{-3}	ns	ns	ns	ns	-1.7×10^{-3}	3.2×10^{-3}	ns
SWC 10 cm	0.10	ns	ns	ns	1.17	ns	ns	0.27
SWC 30 cm	ns	0.35	ns	ns	ns	-0.29	-0.98	ns
Adj. R ²	0.34	0.10	0.00	0.02	0.67	0.09	0.05	0.32
Adj. R ² , SWC as only explanatory variable	0.00	0.10	0.00	0.00	0.61	0.06	0.05	0.15

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977 Table 6. Significant terms in the linear regression $j_s = i + e \ln(D) + fI$, (Eq. [6]), which compares measured
 978 tree transpiration (j_s) to water vapor pressure deficit (D) and global radiation (I). * = $p \leq 0.05$.

	Tilia site				Alnus site			
Time period	2008 (9 July - 20 Aug.)	2009 (1 July - 31 Aug.)	2010 (1 July - 31 Aug.)	2011 (1 July - 31 Aug.)	2008 (3 July - 23 Aug.)	2009 (1 July - 31 Aug.)	2010 (1 July - 31 Aug.)	2011 (1 July - 31 Aug.)
<i>D</i>	*	*		*		*	*	
<i>I</i>		*	*	*	*		*	
adj. R ²	0.74	0.75	0.52	0.88	0.48	0.48	0.66	ns

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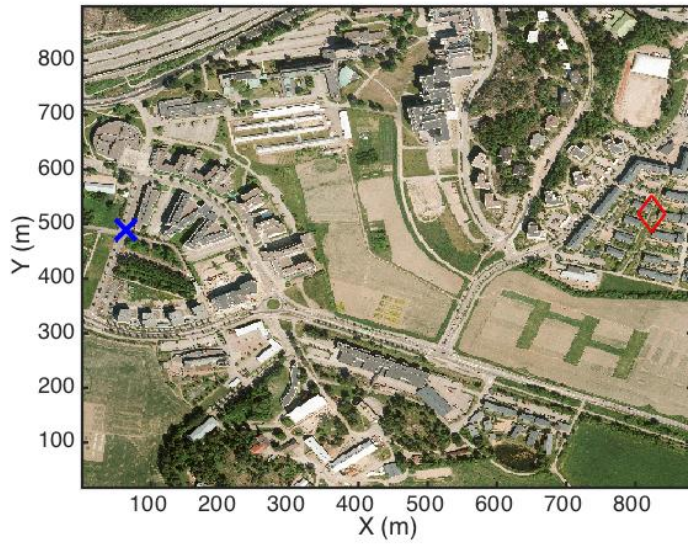
998

999 Table 7. Estimated and measured effective tree water removal in relation to annual rainfall with varying
 1000 canopy cover percentages. The estimates were calculated with the least (PM M1 general parameterization)
 1001 and most accurate model (PM M3 annual parameterization), and the latter was also corrected for SWC effect
 1002 ($ETT\ M3 \times SWC_{high}/SWC_{meas}$). Additionally, in the last column for each tree species, estimated canopy
 1003 interception (37.5% in summer, 27% in winter) is summed to the estimate of water transpired.

Removed water on average (2009-2011), % of annual rainfall								
<i>Tilia</i>					<i>Alnus</i>			
Canopy cover %	Measured transpiration	PM M1	PM M3 + SWC correction	PM M3 + SWC corr.+ canopy interception	Measured transpiration	PM M1	PM M3 + SWC correction	PM M3 + SWC corr.+ canopy interception
20	16	18	16	22	58	57	65	72
50	41	46	40	56	144	142	163	179
70	57	64	56	78	202	198	228	250

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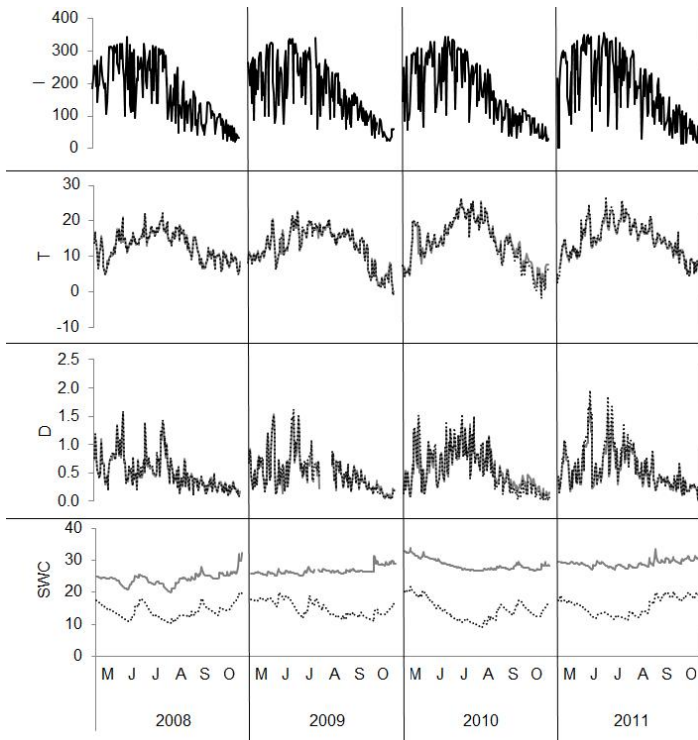


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Figure 1.

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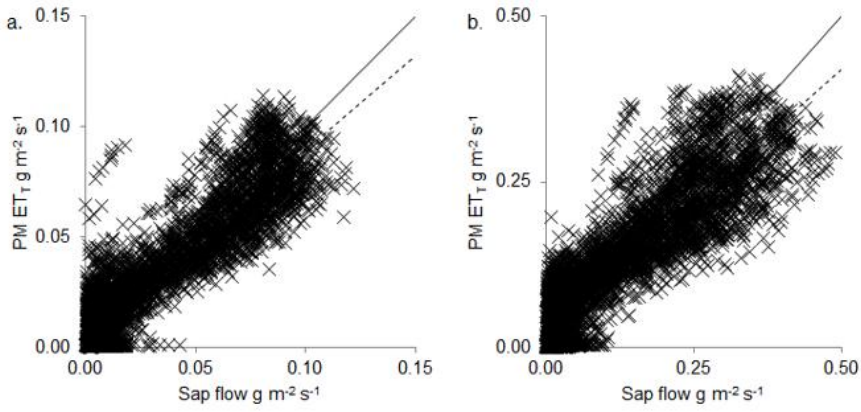
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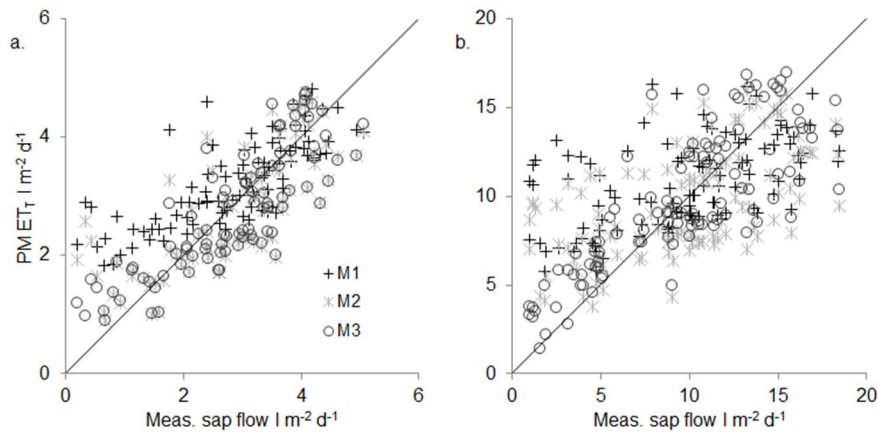
Figure 2.

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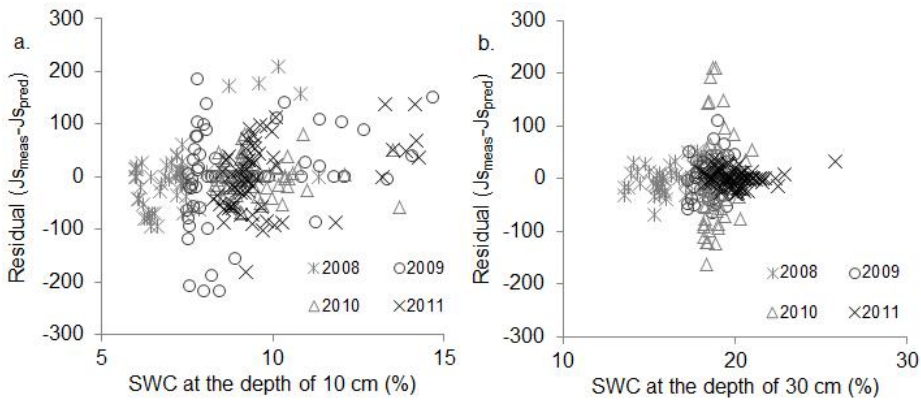
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