Evapotranspiration of a declining *Quercus robur* (L.) stand from 1999 to 2001. I. Trees and forest floor daily transpiration

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Abstract – Water use of a *Quercus robur* (L.) declining stand was estimated from 1999 to 2001 by measuring independently tree canopy and herb layer transpiration. Two plots differing in density were compared. Oak daily sap flux density kinetic is well synchronised with potential evapotranspiration (*PET*) daily time course. Despite differences in density, stand structure and LAI spatial organisation, oak transpiration (*T*, mm d–1) is quite the same between plots. The declining trees are very responsive to the *PET* fluctuations, but their daily response is low (*T* ≤ 1 mm d–1; *T* / *PET* < 0.3). A combination of soil constraints and low, disorganised LAI could induce this low transpiration capability. According to its phenology, density and the above canopy closure, the herbaceous layer contributes to at least the same but often more water consumption than the oak (up to 2.9 mm d–1). Therefore it cannot be neglected in water balance calculations.

1. INTRODUCTION

Whole-tree estimates of water use have been the subject of numerous researches since the 1930’s. Among the available techniques, heat dissipation and heat-pulse methods have been increasingly used [41, 42] because they give insight in tree physiology through sap flux radial pattern and velocity [21, 38]. Forest water use can be estimated on a ground area basis from whole-tree water use measurements if appropriate scalars are used [50]. Yet, forest heterogeneity complicate this task especially in mixed and/or multi-layered stands. For instance, according to its development, the herbaceous cover contributes to stand water use from 6% to 65% [3, 20, 28, 37].

Water use of several broad-leaved species have already been studied, among which *Quercus petraea* [7], *Quercus robur* [10] and *Fagus sylvatica* [11, 18]. But few studies treated the case of declining stands, pedunculate oak declining stands in particular [5, 44]. Whereas Becker and Lévy [1, 2] demonstrated that *Q. robur* decline was mainly due to recurrent and intense droughts, still no tree water use measurements have been done on such trees. Among the decline symptoms, a disorganised branching pattern, a foliage reduction, the clustering of leaves are usually observed [29, 33]. Tree physiology is altered as well as the overall forest structure through the impacts of a less dense canopy cover. Therefore one can reasonably assume that declining stands and/or trees present a water use regulation different from that of healthy ones.

The objectives of this paper are to estimate (i) water use of declining pedunculate oaks and (ii) forest floor water use, in two plots differing in density and canopy structure and during 3 successive years (1999–2001). On the basis of those results, a companion paper [48] estimates stand daily evapotranspiration from 1999 to 2001, and discuss the relative contribution of each layer in the stand water use.

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2. MATERIALS AND METHODS

2.1. Environmental settings

The study area is located in the South of Belgium (50° 06’ N, 4° 16’ E; Fig. 1) at an elevation of 260 m. Topography is flat. Climate is humid temperate with mean annual precipitation of 960 mm and mean temperature of 8.4 °C. Mean annual potential evapotranspiration (PET) is 526 mm, with 88% occurring between April and October (maximum in July and August).

Soils are dystric Cambisol [15]. The B structural horizon rests on a clayey substratum (up to 51.8% of clay) appearing at 30 cm depth; a temporary ground water table is present from late fall to late spring with an upper limit around 0.35–0.5 m deep. The water table reserve was estimated to be 600 mm at field capacity by the use of soil moisture measurements (Thetaprobes, Delta-T, Cambridge, UK; data not shown).

The forest stand, 2.4 km² in extent, was planted on an agricultural land in 1892 with Pinus sylvestris L. and Quercus robur L. The former was delivered as soon as it competed the oaks. During the 1940’s, different broad-leaved species were introduced in the understory (Pru- nunus avium L., Fraxinus excelsior L., Quercus rubra L., Betula sp., Acer pseudoplatanus L., Alnus sp.). The forest floor vegetation is constituted mainly by Circiaea lutetiana L., Stachys sylvatica L., Carex pendula Huds., Athyrium filix-femina (L.) Roth and Rubus fruticosus L., the last being the most covering. In the control plot, Prunus spinosa L. shrubs are found in patches.

2.2. Experimental design and environmental monitoring

A thinned plot (Th.; 1682 m²) and a control one (C.; 1323 m²) were created in 1993. In each plot, oaks are arranged in five rows; two more rows separate the plots. Thinning (May 1993) removed 32% of oak basal area. Most of the thinned trees were healthy or suffering from less than 25% of crown leaf loss according to visual assessment [43]. Decline symptoms appeared since the mid 1980’s. In 1999, oak crowns were more than 25% defoliated in 60% and 40% of the thinned and the control plots trees, respectively.

The present study started 6 years after thinning, i.e., in 1999 and up to 2001. In the thinned plot (Tab. I), oak density remained constant during the 3 years (107 trees ha⁻¹) and basal area increased from 13.8 to 14.2 m² ha⁻¹. In the control plot, density and basal area decreased respectively from 189 to 159 trees ha⁻¹ and from 20.9 to 18.3 m² ha⁻¹. The average height of oak in both plots is 24 m.

Besides pedunculate oak, forest overstory basal area is dominated by Acer pseudoplatanus L. (Th.: 10%; C.: 11.3%) and Fraxinus excelsior L. (Th.: 5.3%; C.: 8%); Prunus avium L. and Quercus rubra L. contribute respectively for 2.7% and 1.1% in the control plot and Quercus rubra L. contributed for 4.2% in the thinned plot. Total overstory basal area was 17.5 m² ha⁻¹ in the thinned plot and 28 m² ha⁻¹ in the control one (Tab. I). Quercus rubra and Fraxinus are part of the dominant canopy respectively in the thinned and the control plot; Acer is an intermediate species, reaching approximately 17 m in both plots [46].

An automatic weather station (PAMESEB, Libramont, Belgium) monitored the local climate in an open area 1 km from the stand at an hourly time step: precipitation (1 m height), wind speed (anemometer “Thermistor”, 1.8 m height), global radiation (photovoltaic sensor “solar Haeni 130”, 1.5 m height), air temperature (resistance sensor “Thermistor”, 1.5 m height), and relative humidity (psychrometer “Thermistor”, 1.5 m height) were recorded. Potential evapotranspiration (PET) was calculated according to the Penman formula [36].

2.3. Sap flux density (SFD) measurements and ligneous stand transpiration (T)

Xylem sap flux density (SFD, 1 H₂O h⁻¹ dm⁻² sapwood) was monitored on 3 (1999) and 4 (2000–2001) pedunculate oaks and on 1 maple (2000–2001) in each plot (Tab. II). Sampled oaks were representative of the plot’s mean basal area tree circumference (Th.: 125 cm; C.: 115 cm) and were suffering from less than 25% leaf loss. Radial sapflow sensors [16] were inserted 1.3 m above soil surface on the side of stems, to avoid direct solar heating. Those sensors (UP GmbH, Germany) were moni-

Table I. Oak basal area (G, m² ha⁻¹), oak mean circumference at breast-height (C₁30, cm), oak density (N ha⁻¹) and maximum LAI in 1999, 2000 and 2001; basal area (G, m² ha⁻¹) and maximum LAI when considering all tree species in each plot (All). Th.: Thinned; C: Control.

<table>
<thead>
<tr>
<th>Year</th>
<th>Oak</th>
<th>All</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G</td>
<td>C₁30</td>
<td>N ha⁻¹</td>
<td>G</td>
<td>C₁30</td>
</tr>
<tr>
<td>Th.</td>
<td>13.8</td>
<td>126.4</td>
<td>107</td>
<td>2.8</td>
<td>17.4</td>
</tr>
<tr>
<td>C.</td>
<td>20.9</td>
<td>116.2</td>
<td>189</td>
<td>2.8</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>14.2</td>
<td>128</td>
<td>107</td>
<td>2.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Table II. For 1999, 2000 and 2001, characteristics of the trees equipped with radial flowmeters, per plot (Th.: Thinned; C.: Control) and per species: tree number (No.), period during which measurements were performed (Years), circumference in 1999 (C1, cm), sapwood thickness (cm) and sapwood area (SA, cm²), crown projected area (Sc, m²), total height (H, m), height of first epicormic shoots occurrence (Hc, m), trunk height below crown (Ht, m), visual UE crown assessment (CEE) and annual circumference increment measured with dial-dendro (ic, cm).

<table>
<thead>
<tr>
<th>Species</th>
<th>No.</th>
<th>Years</th>
<th>C1 Thickness</th>
<th>SA</th>
<th>Sc</th>
<th>H</th>
<th>Hc</th>
<th>Ht</th>
<th>CEE</th>
<th>ic</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Quercus robur</td>
<td>1</td>
<td>1999–2001</td>
<td>122.8</td>
<td>4.6</td>
<td>456.2</td>
<td>36.3</td>
<td>22.7</td>
<td>3.7</td>
<td>13.3</td>
<td>0.8</td>
<td>1</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1999–2001</td>
<td>130.5</td>
<td>2.55</td>
<td>288.2</td>
<td>46.1</td>
<td>25.2</td>
<td>9.6</td>
<td>12.6</td>
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<td>0.5</td>
<td>0.75</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1999–2001</td>
<td>112.8</td>
<td>3.4</td>
<td>318.7</td>
<td>45.4</td>
<td>22.9</td>
<td>6</td>
<td>11.4</td>
<td>2</td>
<td>0.3</td>
<td>1</td>
<td>2</td>
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<tr>
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<td>58.7</td>
<td>22.9</td>
<td>3</td>
<td>10.9</td>
<td>1.05</td>
<td>0.9</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>C2</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Quercus robur</td>
<td>1</td>
<td>1999–2001</td>
<td>114.4</td>
<td>1.95</td>
<td>198.9</td>
<td>29.2</td>
<td>24.4</td>
<td>5.6</td>
<td>13.8</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>2</td>
<td>1999–2001</td>
<td>121.1</td>
<td>2.45</td>
<td>256.6</td>
<td>56.5</td>
<td>23.6</td>
<td>5.2</td>
<td>10.8</td>
<td>1.05</td>
<td>0.9</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1999–2001</td>
<td>129.9</td>
<td>2.9</td>
<td>232.2</td>
<td>57.8</td>
<td>25.9</td>
<td>12.3</td>
<td>14.3</td>
<td>1.05</td>
<td>0.9</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2000–2001</td>
<td>124.9</td>
<td>3</td>
<td>318.7</td>
<td>52</td>
<td>24.9</td>
<td>6.2</td>
<td>14.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2000–2001</td>
<td>140.5</td>
<td>3.02</td>
<td>93.9</td>
<td>25.7</td>
<td>13.9</td>
<td>5.6</td>
<td>5.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.4. Herbaceous transpiration and LAI

Herbaceous transpiration was measured during 6 days in 2001 growing season (4 in the thinned plot and 2 in the control one) with a mobile closed chamber [13]. This device is a parallelepiped chamber of 0.76 x 0.76 x 1 m (0.563 m³) composed of transparent plastic walls with movable base and top. The chamber is equipped with 4 PAR Quantum sensors (Skye instruments LTD, Powys, UK), one psychrometer H301/TR (Vector Instruments, Rhyl, UK), one air temperature probe SKTS 200 (Skye instruments LTD, Powys, UK) and 3 ven-

Cottbus, Germany) consist in a pair of probes, 2 cm long and 0.2 cm in diameter each, inserted in a radial orientation behind the cambial zone. The probes were placed into freshly bored holes vertically by 15 cm. The temperature difference between the heated and reference probes (ΔT) was recorded and by comparing it with the maximum occurring at predawn (Tmax), SFD was calculated according to Granier [16]. ΔT was recorded every minute from bud break to leaf fall and 30-min averages were stored using a DL3000 (Delta-T, Cambridge, UK). For each tree, sap flow (SF, l h⁻¹) was obtained by multiplying SFD by sapwood area (SA, dm²). Oak SA was measured on cores taken at 130 cm height at the end of the 1999 growing season. For maple, SA (cm²) was derived from an allometric relationship (Eq. (1)) with diameter at breast-height (DBH, cm), cited in Mathieu [31]:

\[
SA = 0.565 DBH^2
\]

\[
R^2 = 0.947
\]

Oak SA reached 3.2 m² ha⁻¹ (296 cm² per tree) in the thinned plot and 4.2 m² ha⁻¹ (243 cm² per tree) in the control plot. For Acer, SA was respectively 0.24 m² ha⁻¹ and 1.45 m² ha⁻¹. Sapflow sensors were replaced each year. Oak and maple daily stand transpiration (T, mm d⁻¹) were calculated as follows [7]:

\[
T = \sum T_j
\]

\[
T_j = SA/GA \cdot \prod SFD_i p_i
\]

where j stands for a species, GA is the ground area (m²), SFD is the sap flux density of tree i (l h⁻¹ dm⁻²) and p_i is the proportion of trees with sapwood area SA_i in the stand (Tab. III). Oak and maple SFD are considered as representative of the ring-porous (Quercus rubra, Fraxinus excelsior) and diffuse-porous (Betula sp., Prunus sp., Crataegus sp., Carpinus betulus, Fagus sylvatica) species, respectively.

3. RESULTS

3.1. Sap flux densities diurnal pattern

Daily time courses of mean SFD (L dm⁻² h⁻¹) per plot (Fig. 2) for DOY 162 of each year (PET = 2.7 mm d⁻¹ in all years) showed an asymmetrical bell-shaped curve, with a steep
increase in the morning until a maximum value around 8:30 a.m. (UT). For all years, mean SFD is higher in the thinned plot than in the control one. In years 1999 and 2001, mean SFD daily time course present similar curves in shape and amplitude (maximum SFD is 1.5–2 L dm$^{-2}$ h$^{-1}$ in the thinned plot, 1.5 L dm$^{-2}$ h$^{-1}$ in the control one) whereas in year 2000, both plots have mean SFD lower than 1 L dm$^{-2}$ h$^{-1}$. Mean SFD observed during 1999, 2000 and 2001 seasons (not shown) were, respectively for the thinned and the control plot and from 1999 to 2001, 2.5–2–2.75 L dm$^{-2}$ h$^{-1}$ and 1.7–1.5–2 L dm$^{-2}$ h$^{-1}$. When comparing SFD between trees with similar SA but from different plot, SFD in the control tree (No. 4 in Tab. II) was 74% SFD in the thinned one (No. 3 in Tab. II).

Oak SFD daily time course follows closely PET daily time course (Fig. 3), even if the PET curves are smoother. Maple SFD appears to be maximal later (DOY 193 in 2001), i.e. around 11:30–12:00 (UT) and to end up earlier than oak SFD, which is probably a consequence of its intermediary position in the canopy [30].

### 3.2. Inter-tree Sap Flux Density variability

Each tree relative contribution to total SFD per period (% SFD, Tab. IV) and the variation coefficient among trees.
Transpiration in a declining oak stand

Table IV. For each year and each plot (Th.: Thinned; C.: Control), percents of each oak (No.; cf. Tab. II) in the daily total sap flux density (\% SFD) and variation coefficient (cv\% = standard deviation/arithmetic mean) per period (in julian days). Periods are uniform in terms of measured trees. Periods marked with an * are leaf flushing or caterpillars attack; periods marked with an + correspond to leaf fall.

<table>
<thead>
<tr>
<th>Year</th>
<th>Plot</th>
<th>Period</th>
<th>% SFD</th>
<th>cv%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>No. 1</td>
<td>No. 2</td>
</tr>
<tr>
<td>1999</td>
<td>Th.</td>
<td>150–165*</td>
<td>35</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>166–218</td>
<td>35</td>
<td>32</td>
</tr>
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<td></td>
<td></td>
<td>219–240</td>
<td>34</td>
<td>36</td>
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<tr>
<td></td>
<td></td>
<td>241–303+</td>
<td>32</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>C.</td>
<td>150–156*</td>
<td>33.5</td>
<td>28.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>157–214</td>
<td>33.5</td>
<td>32</td>
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<td></td>
<td></td>
<td>215–240</td>
<td>30</td>
<td>33</td>
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<td></td>
<td></td>
<td>241–303+</td>
<td>28</td>
<td>34</td>
</tr>
<tr>
<td>2000</td>
<td>Th.</td>
<td>147–212</td>
<td>39</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>213–249</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>C.</td>
<td>147–249</td>
<td>24</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>139–152*</td>
<td>23</td>
<td>20</td>
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<td></td>
<td>184–283</td>
<td>32</td>
<td>–</td>
</tr>
<tr>
<td>2001</td>
<td>Th.</td>
<td>150–170*</td>
<td>37</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>184–195</td>
<td>–</td>
<td>38</td>
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<tr>
<td></td>
<td>C.</td>
<td>221–238</td>
<td>27</td>
<td>44</td>
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<tr>
<td></td>
<td></td>
<td>242–283</td>
<td>36</td>
<td>–</td>
</tr>
</tbody>
</table>

(cv\%) gave information on the representativeness of each measured tree: this is important for the up-scaling to stand. In 1999, cv\% is always lower than 0.3%, which meant that the respective contribution of each tree to total SFD per day is quite the same. Nevertheless, in both plots, a variation is observed within the trees. For example, in the thinned plot, tree No. 3 and No. 1, which are the ones with the largest LAI, contribute more per day to SFD. In the control plot, excepted for the periods of leaf flushing, the gradient was No. 3 > No. 2 > No. 1, which corresponds to a decreasing ranking of SA and crown area (Tab. II). In 2000, the tendency observed in the thinned plot is not confirmed (and cv\% are high), whereas in the control plot, the same ranking is observed between trees. In 2001, the cv\% are high but data are difficult to interpret for several reasons: (i) in the thinned plot, 2 periods out of 3 occur during leaf-flushing and caterpillars attacks, when variability is probably increased and (ii) in the control plot, sap flow measurements dysfunction rendered each period unique and impossible to compare with the others.

3.3. Tree daily transpiration

The seasonal time course of daily transpiration followed closely the fluctuations of PET (Fig. 4). In 1999, maximum oak transpiration in the control plot (1 mm d\(^{-1}\)) was higher than in the thinned plot (0.6 mm d\(^{-1}\)). In 2000, no differences were observed between plots and stand daily transpiration was around 0.6 mm d\(^{-1}\). For technical reasons, the Acer transpiration could only be measured accurately in September and daily transpiration rate reached 0.6 mm d\(^{-1}\). In 2001, frequent flowmeters dysfunction occurred during the monitoring period. The shedding of leaves is responsible for the increase of SFD up to 1 mm d\(^{-1}\). The slope of the T/PET/T/LAI relationship is always < 0.3, with a minimum in 2000 (0.16 in the thinned plot and 0.19 in the control one). The importance of PET as a limiting factor of stand transpiration has been demonstrated [19]. For each year and each plot, T/LAI was calculated in both plots and was always < 0.3. Except for 2001, T/LAI was larger in the control plot; it varied from 0.19 to 0.27 in the thinned plot and from 0.23 to 0.26 in the control one. In Figure 6, \(\Sigma(T/PET)\) (over a season) is expressed as a function of oak LAI. \(\Sigma(T/PET)\) inter-annual variation with oak LAI is larger in the thinned plot, whereas in the control one, \(\Sigma(T/PET)\) increases with oak LAI. Yet, both plots \(\Sigma(T/PET)\) relationships with LAI are consistent with the overall relationship of these parameters, as measured in other forests (Fig. 6b).

3.4. Herbaceous transpiration and driving variables

Except for DOY 131, before oak budburst, the herbaceous transpiration measurement days were characterised by a variate weather, with radiation being mainly diffuse (Tab. VI). Daily time course of transpiration rate \(E_k\) (Fig. 7) demonstrated no specific trend. \(E_k\) never exceeded 0.14 mm s\(^{-1}\) (DOY 131). A correlation was found with below canopy PAR (\(\mu\)mol m\(^{-2}\) s\(^{-1}\)):

\[
E_k = 0.000068 \times \text{PAR}_{bc} + 0.04; \quad R^2 = 0.61. \quad (4)
\]

With equation (4), \(E_k\) was calculated over the sunny hours at the end of a measurement day. No \(E_k\) calculation has been done over the first hours of the days because leaves of the understory were still wet at that time (dew deposition). By integrating \(E_k\) over the entire sunny period, we calculated \(E_d\) (mm d\(^{-1}\), Fig. 8). The maximum is observed before tree bud break, with a daily value of 2.9 mm. During the leafy period, forest floor transpiration never exceeded 0.7 mm d\(^{-1}\). At the beginning of leaf fall, daily transpiration raised up to 1.8 mm d\(^{-1}\). Forest floor LAI (Fig. 8) reached maximal values almost identical to oak LAI.
values, especially in the thinned plot. $E_d$ seasonal evolution was closely related to LAI of the upper layer, as demonstrated by the following equation:

$$E_d (\text{mm}) = -0.9574 \cdot \text{LAI} + 4.3701; \quad R^2 = 0.8215. \quad (5)$$

4. DISCUSSION

4.1. Tree SFD and transpiration ($T$)

In the thinned plot, oak trees SFD are higher than in the control plot, with exceptions for some periods in trees with large SA or crowns. The canopy in the thinned plot is more open, with SA distributed between fewer trees, with larger and more exposed crowns to light. When integrated to stand scale, the control plot transpired more, as far as oak is concerned, mainly because of that species greater density. The inter-tree variability, estimated through the relative contribution of each tree to total daily SFD, confirmed that in thinned and/or declining stands SFD is more heterogeneous [6, 25, 26]. Our results in the thinned plot showed that from year to year, despite its SA or crown area, a tree SFD may be ranking upwards or downwards depending on biological events like caterpillar attacks and their consequences on LAI.

Falge et al. [14] and Wullschleger et al. [51] stated that one of the most important aspects that emerge from sap flow
measurements in trees occupying different places in a canopy, is to estimate how a forest structure or a canopy stratification influences forest water use. Maple SFD daily time course (Fig. 3) demonstrated well that each species position in the canopy architecture has consequences upon its water use. Maple, which is an intermediate species, transpired water on a shorter day period than oak, a dominant species.

The day to day variation of $T$ suggest that oaks are very dynamic in their response to $PET$. Still, the daily rates of $T$ are very low (0.6 to 1 mm d$^{-1}$). Other studies cited daily values of 2–3 mm d$^{-1}$ in oak [6, 10]. In this case, these low values could be attributable to the low LAI or eventually local dryness. Oak LAI is effectively lower than LAI of healthy trees of same age, which are around 5–6 [8]. These low daily rates of $T$ could also be a consequence of xylem water transport impairment via xylem embolism in root and/or stems [34]. Some errors may arise from the sapflow measurement itself, associated with scaling tree estimates [9] or with ring-porous water conducting elements [22]. Some literature focused on sapflow measurement systems comparison [12, 25, 50], but no generalisation could be made on the reliability of one method among others.

Studies of inter-annual trends in water use of forests offer the opportunity to study a spectrum of biotic and abiotic conditions [37]. The interactions between transpiration, climate, LAI, can then be studied [4]. Except in 1999, no differences between oak stand transpiration have been observed between plots: in both plots, the $T/\text{PET}$ ratios were very low. Bréda and Granier [4] cited values of 0.4 to 0.89 for an oak stand; Čermák et al. [10], for hundred-years old non declining pedunculate oaks cited $T/\text{PET}$ values of 0.8, as well as Nizinski et al. [35]. This probably results from interacting biological and physical factors: soil constraints (clay content of about 46%, high bulk density, shrink-swell behaviour [39]), the low oak LAI (caterpillars and decline) can explain those low rates of transpiration, which in turn can explain the low $T/\text{PET}$. PET being relatively very much higher and therefore dampening every transpiration rise. Control trees in this case respond more to $PET$ (and LAI) than thinned ones, the reason being probably linked with LAI spatial organisation, more heterogeneous in the thinned plot. Plus, an important part of thinned trees LAI is located on epicormic branches.

$T/LAI$ are also low and coupled with $\Delta T/\Delta ETP = f (LAI)$, it reinforced the role of LAI as the main limiting factor of transpiration [6, 17, 28]. Körner [24] also pointed out that in temperate deciduous forests, the dominant factor of stand transpiration is LAI, with clear transitions between dormancy periods (leaf less) and expanding leaves during growing season. In the
thinned plot, the LAI structure inter-annual variability (due in part to caterpillar attacks) could be responsible for the apparent non correlated relationship between $T/PET$ and LAI. The Acer transpiration measurements were managed mainly to estimate the contribution of diffuse porous species in the stand transpiration. Even though they occupy an intermediate position in the canopy architecture, yet they contribute greatly to the stand water use (up to 0.6 mm d$^{-1}$).

### 4.2. Forest floor evapotranspiration

In most of forest water use studies, herbaceous transpiration is deduced as the residual term of forest water use minus tree

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**Figure 7.** Daily kinetics of forest floor transpiration ($E_k$, mm s$^{-1}$; closed symbol) and of $PAR_{bc}$ (µmol m$^{-2}$ s$^{-1}$; open symbol). Each point is the value of evapotranspiration fluxes inside the closed chamber on a 2–3 min period. The hours are expressed in decimal hours (h + min/60), in Universal Time.

**Figure 8.** $E_d$ (mm d$^{-1}$) as measured with the closed chamber during 6 days in 2001 (lozenges and dotted line). Stand (triangles and heavy line) and herbaceous (histograms) LAI seasonal dynamics are shown as well.
water use. Few authors tested the effectiveness of enclosed chamber systems [13, 45] which measure directly the water use of a small forest floor surface. In this case, forest floor (evapo-transpiration appeared to be closely related to LAI and therefore to canopy structure [23, 49] which determines the fraction of the available energy to be delivered to herbs. None of the measurement days was very warm and bright so higher transpiration rates probably occurred during the vegetation period. Still, this layer plays an important role in the forest water use, with maximal values being more than twice oak maximal daily water use. Shrubs transpiration has not been estimated (Prunus spinosa L. in the control plot) but Phillips and Oren [37] showed that their contribution to stand transpiration is < 3%. In terms of water use management, how can an understorey compete with trees? Canopy closure induces a decrease in herbaceous transpiration (as a consequence of Rsou diminution). Nevertheless, this strata stays competitive for water. During dry periods, transpiration reduction concerns more the trees than the herbs [5], those being more “coupled” with the atmosphere. Roberts et al. [40], Loustau and Cochard [27], McNaughton and Jarvis [32] also confirmed the substantial raise of herbaceous transpiration contribution to stand transpiration during dry summer. Still, some uncertainties persist: rooting depth of herbaceous is not known (and therefore its consequences upon water sources), as well as their drought tolerance and their inter-specific differences of transpiratory behaviour.

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