

## Evapotranspiration of a declining *Quercus robur* (L.) stand from 1999 to 2001. II. Daily actual evapotranspiration and soil water reserve

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**Abstract** – The components of actual evapotranspiration (ET) – interception (In%), tree transpiration (T) and forest floor ET – were measured from 1999 to 2001 in a mixed stand dominated by declining pedunculate oaks. Sap flux density measurements (oaks and maple) and forest floor ET [38] were extrapolated to season and stand scales by regressions with potential evapotranspiration (PET) and leaf area index (LAI). Stand ET varies between 383 and 594 mm (ET/PET: 0.75–1.23). Oak transpiration (21–38% of stand transpiration) is lower than forest floor ET: forest floor can therefore not be neglected in this stand water balance. The soil water reserve dynamics deduced from those measurements reflects the inter-annual changes of water use. No water stress have been calculated on the 1999–2001 period, but it is suspected to have occurred previously; together with soil constraints and caterpillar defoliation, it could in part explain the severe oak decline symptoms.

**transpiration / evapotranspiration / *Quercus robur* (L.) / forest decline / soil water reserve**

**Résumé** – Évapotranspiration d'un peuplement de chêne pédonculé (*Quercus robur* L.) dépérissant, de 1999 à 2001. II. Évapotranspiration réelle et réserve en eau du sol journalières. Les composantes de l'évapotranspiration réelle (ETR) – interception (In%), transpiration (T) des arbres et évapotranspiration du sous-étage herbacé – ont été mesurées de 1999 à 2001 dans un peuplement mélangé, dominé par du chêne pédonculé dépérissant. Les densités de flux de sève (chêne et érable) et l'évapotranspiration du sous-étage herbacé [38] ont été extrapolées à l'échelle de la saison et du peuplement par des régressions avec l'évapotranspiration potentielle (ETP) et l'indice foliaire (LAI). L'ETR du peuplement varie de 383 à 594 mm (ETR/ETP: 0.75–1.23). La transpiration du chêne (21–38% de la transpiration du peuplement) est beaucoup plus faible que celle de la strate herbacée: cette strate ne peut dès lors pas être négligée dans le calcul du bilan hydrique de ce peuplement à plusieurs strates. La dynamique de la réserve en eau du sol, déduite de ces mesures, reflète les changements inter-annuels d'utilisation de l'eau par le peuplement. Aucun stress hydrique n'a été calculé sur la période 1999–2001, mais ce facteur est suspecté d'avoir joué un rôle dans les années antérieures; avec les contraintes édaphiques et les défoliations de chenilles, ce facteur pourrait en partie expliquer le dépérissement observé.

**transpiration / évapotranspiration / *Quercus robur* (L.) / dépérissement forestier / réserve en eau du sol**

### 1. INTRODUCTION

The estimation of forest water use, i.e. actual evapotranspiration (ET), is the subject of numerous researches in a wide range of disciplines [42]. Several methodologies are available and their use depends on the spatial and temporal scale, the components of ET and the level of complexity that are needed [41]. One of the methods consists in measuring separately each component of ET, i.e. canopy interception, plant transpiration and soil evaporation. This gives insights into the ecosystem ecophysiology. In order to encompass a spectrum of contrasted conditions, records of forest water use during several years are necessary [29]. By proceeding in such a way, analysis of the

possible disturbances of water cycle, as a consequence of a thinning, a decline or pathogens attack can be achieved. Once ET is estimated, soil water reserve daily variations can be calculated. Effectively, the water balance method deduces soil water reserve of day  $i$  ( $R_i$ , mm  $d^{-1}$ ) by adding rainfall ( $P_i$ ) and by subtracting actual evapotranspiration ( $ET_i$ ) and surface runoff from water reserve of day  $(i-1)$ .

The present study, through water balance estimation, presents measurements of water use in two plots contrasted in density in a mixed broad-leaved stand dominated by declining 100-years-old pedunculate oaks. In both plots, oak LAI is low ( $< 3$ ) and canopies structure is heterogeneous. Oak leaves are mostly organised in clusters in the crown or developed on

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**Table I.** For each year and each plot (Th.: Thinned; C.: Control): (a) basal area (G, m<sup>2</sup> ha<sup>-1</sup>), LAI and sapwood area (SA, m<sup>2</sup> ha<sup>-1</sup>) of pedunculate oak, maple, ring- and diffuse porous species (ring porous species: *Quercus robur*, *Quercus rubra*, *Fraxinus excelsior*; diffuse porous species: *Acer pseudoplatanus*, *Prunus avium*, *Betula* sp., *Crataegus* sp., *Carpinus betulus* and *Fagus sylvatica*). Total per treatment is indicated (in m<sup>2</sup> ha<sup>-1</sup> for G and SA, in m<sup>2</sup> m<sup>-2</sup> for LAI); (b) proportion of ring- and diffuse porous species in basal area in 1999 (%G), in LAI (%LAI) and in sapwood area (%SA).

(a)	G		LAI						SA			
	Th. 1999	C. 1999	Th. 1999	Th. 2000	Th. 2001	C. 1999	C. 2000	C. 2001	Th. 1999–2001	C. 1999	C. 2000	C. 2001
<i>Q. robur</i> L.	13.8	20.9	2.8	1.9	2.45	2.8	2.3	2.45	3.2	4.2	4.1	–
<i>Acer</i>	1.7	2.24	0.2	0.12	–	0.42	0.9	–	0.24	1.45	–	–
Ring porous	15.5	24.9	3.28	2.98	–	3.42	3.7	–	3.9	6.3	6	5.8
Diffuse porous	1.9	3.5	0.32	0.12	–	0.88	1.3	–	0.4	2.6	2.6	2.6
Total	17.4	28	3.6	3.1	3.5	4.3	3.7	4.2	4.32	8.9	8.6	8.4
(b)	%G		%LAI						%SA			
	Th. 1999	C. 1999	Th. 1999	Th. 2000	Th. 2001	C. 1999	C. 2000	C. 2001	Th. 1999–2001	C. 1999	C. 2000	C. 2001
Ring porous	89	84	92.6	93.7	–	79	66.5	–	91	70.9	70.1	69.2
Diffuse porous	11	16	7.4	6.3	–	21	33.5	–	9	29.1	29.9	30.7

epicormic branches. Also, large gaps through the canopy led to the development of an abundant herbaceous cover [37]. Such a complexity in stands structure needed appropriate methodology to estimate water use.

The main objective of this paper is to estimate these plots actual evapotranspiration (ET) on a daily time step. It was therefore needed to: (i) estimate canopies water interception, (ii) detail tree (oak and secondary species) and herbaceous water use on a daily basis and (iii) quantify soil water reserve dynamic. Intra- and inter-annual changes will be commented as well as differences between plots. Drought risk occurrence will be discussed, through the estimation of the Relative Extractable Water (REW) of the soil. Effectively, several studies demonstrated that a soon as REW decreased below a threshold of about 0.4, the soil water becomes limiting for tree transpiration [6, 12, 34].

## 2. MATERIALS AND METHODS

### 2.1. Environmental settings

The study area is located in the south of Belgium. Climate is humid temperate with mean annual precipitation of 960 mm and mean temperature of 8.4 °C. Soils are dystic Cambisol [10]. Those soils present severe signs of hydromorphy: a temporary ground water table is present from late fall to late spring [39]. The forest stand is dominated by *Quercus robur* L., with also *Fraxinus excelsior* L., *Quercus rubra* L., *Betula* sp., *Acer pseudoplatanus* L. The forest floor vegetation is constituted mainly by *Circaea lutetiana* L., *Stachys sylvatica* L., *Carex pendula* Huds., *Athyrium filix femina* (L.) Roth and *Rubus fruticosus* L., the latest being the most covering. In the control plot, *Prunus spinosa* L. shrubs are found in patches. Herbaceous LAI reached values of 2.5 in the thinned plot and 2 in the control one.

### 2.2. Experimental design and environmental monitoring

The experimental design is fully described in this article's companion [38]. In 2001, below canopy global radiation ( $R_{gbc}$ , W m<sup>-2</sup>) was measured every 2-min in each plot with two tube solarimeter TSL (INRA) horizontally fixed at 1.5 m above the soil surface, in an E-W direction. That same year, below canopy Photosynthetic Active Radiation ( $PAR_{bc}$ ,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) was manually measured every hour during 4 days (Day Of Year: DOY 192-213-241-284), at 10 locations grid in each plot with the Sunscan Canopy Analysis System (Delta-T, Cambridge, UK).

An automatic weather station (PAMESEB, Libramont, Belgium) monitored hourly the local climate at 1 km from the stand. Potential evapotranspiration (PET, mm) was calculated according to the Penman formula [28].

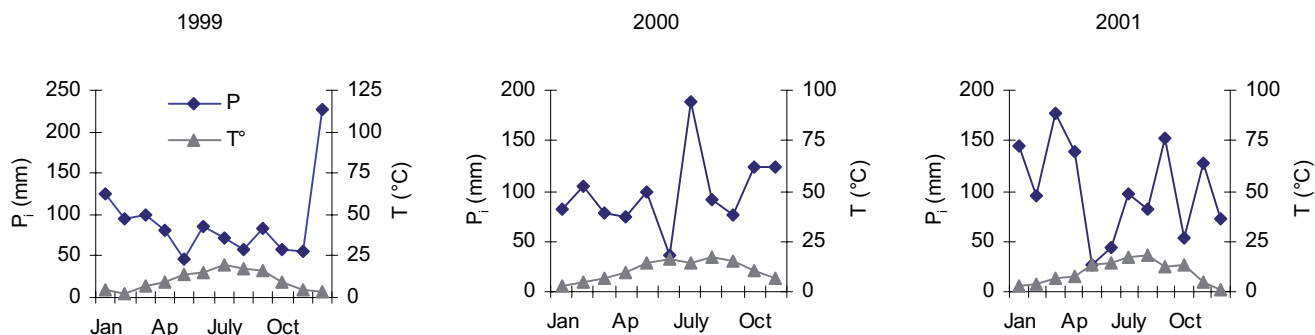
Throughfall was measured in two ways. From 1999 to 2001, two automatic tipping bucket rain gauges (GME PR12, GME, Incourt, Belgium) were installed in each plot at 1.5 m above soil surface; each couple of rain gauge was connected to an Easylog DL (GME, Incourt, Belgium). They recorded every rain event and summed them at a half-hour basis. In addition, 15 rain gauges evenly distributed along the 3 inner lines in each plot were used in 2000 and 2001 to estimate spatial variability of throughfall; water collection was realised once a week. The understorey also intercepts throughfall; this term was not measured here but Schnock [33] estimated this interception in several deciduous forests, as 1 to 12% of rainfall. Stemflow was not measured as well because different studies [1, 16, 27] found it to be very low in oak stands (< 1% of total precipitation), mainly because of the rough and moss-covered bark and branches.

Ring-porous sapwood area (SA, m<sup>2</sup>) was estimated on the basis of the in situ relationship established between oak SA and circumference at breast-height (CBH, cm):

$$SA = 0.00022 \times CBH \quad R^2 = 0.5308. \quad (1)$$

Diffuse-porous species SA was estimated with the same relationship than for maple, given in Mathieu [24].

Table I summarises each plot's basal area, LAI and SA for the 3 years and for each type of species. Total LAI was estimated from litter



**Figure 1.** Gausson ombrothermic diagrams for 1999, 2000 and 2001, on the basis of Pameseb measurements: incident rain ( $P_i$ ) and mean air temperature ( $^{\circ}\text{C}$ ) as functions of months.

collection during fall in 10 litter traps in each plot ( $0.49 \text{ m}^2$  per trap). For each trap, leaves from the different tree species were separated and dried ( $48 \text{ h}$ ,  $80 \text{ }^{\circ}\text{C}$ ). Every two weeks, and before being dried, 20 randomly selected leaves of each species were surfaced with a video camera coupled with an image analysis system (Semper 6P, Synoptics Limited). This was done to measure SLA (Specific Leaf Area,  $\text{cm}^2 \text{ g}^{-1}$ ), which was then multiplied by total dry weight to calculate total foliar surface (FS,  $\text{cm}^2$ ). Total LAI was derived from FS and litter traps sampling intensity. LAI seasonal time course was measured with the LAI-2000 Plant Canopy Analyser (Li-Cor, Lincoln, NE, USA), extensively described by Welles and Norman [40]. Caterpillar (*Tortrix viridina* L.) defoliation was observed every year during leaves budding.

Soil water balance is expressed with the following water balance equation:

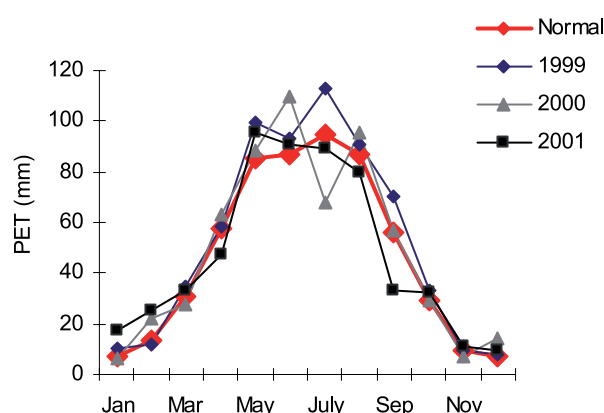
$$R_i = R_{i-1} + P_i - ET_i \quad (2)$$

where  $R_i$  is soil water reserve of day  $i$  (mm),  $R_{i-1}$  is soil water reserve of day  $(i-1)$ ,  $P_i$  is day  $i$  rainfall (mm) and  $ET_i$  is total stand evapotranspiration losses of day  $i$  (mm), i.e. the sum of tree and understory transpiration, soil evaporation and rain interception. This calculation was made in condition of no drainage (a poorly weathered schist stratum, located at  $1.7\text{--}2.1 \text{ m}$  depth, strongly reduces drainage and contributes to the formation of the water table during autumn and winter; [39]).

### 3. RESULTS

#### 3.1. Incident climate and forest interception on climate variables

Gausson's ombrothermic diagrams for the three years of this study (Fig. 1) show that May and June are often drier than the other months; nevertheless, no climatic drought ( $P < 2 \times T^{\circ}$ ) was monitored during the 3 years. In 1999, rainfall was well distributed throughout the growing season, excepted in May and August. In 2000, July was particularly wet whereas in 2001 it was September. During the 3 years, significant dry periods (10–15 days) occurred between DOY 117–126, 204–217 and 239–248 in 1999, DOY 159–172 and 262–271 in 2000 and DOY 125–133 and 139–151 in 2001. For leafy periods (DOY 91–304), rainfall was 481 mm in 1999, 688 mm in 2000, 593 mm in 2001. Over the 1971–2001 period, the normal precipitation was 552 mm. 1999 was therefore the driest year and 2000 the wettest.



**Figure 2.** Monthly normals of PET (average of each month over the 1971–2001 period) and average monthly PET for 1999, 2000 and 2001.

Potential evapotranspiration (PET) was high from May to July 1999 (Fig. 2). From 1999 to 2001, cumulative PET over the leafy periods was 510, 484 and 468 mm (Tab. IV).

As only 2 tipping buckets could not provide an accurate measurement of throughfall due to its high spatial variability within the plots, we first established the relationships between both types of measurements (tipping buckets and rain gauges; Tab. II). These relationships were applied to tipping buckets daily values, to estimate rainfall interception ( $\text{In}\%$ ).  $\text{In}\%$  during the leafy periods was always higher in the control plot, with the strongest difference observed in 2000 (Tab. III). Daily  $\text{In}\%$  varied between 18.2 and 27.7% in the thinned plot and between 22.3 and 43.4% in the control plot. In the thinned plot,  $\text{In}\%$  during winter 2000–2001 is similar between leafy and non-leafy periods, which is probably a consequence of a lack of data due to electronic breakdown. During leafy periods, throughfall amounts were 350.3, 491 and 456.6 mm in the thinned plot for 1999, 2000 and 2001 respectively. In the control plot, it reached 339, 380 and 433 mm. The relationship between LAI and  $\text{In}\%$  is shown on Figure 3. As the LAI amplitude is low, especially in the thinned plot, no clear tendency can be pointed out.

**Table II.** Rainfall measured with the tipping buckets ( $P_{tp}$ ) as a function of the measurements with rain gauges ( $P_{rg}$ ), to incorporate spatial variability.

		Leafy period		Non leafy period	
Th.	2000	$P_{tp} = 1.0014 \times P_{rg}$	$R^2 = 0.8986$	$P_{tp} = 0.8844 \times P_{rg}$	$R^2 = 0.9166$
	2001	$P_{tp} = 0.8602 \times P_{rg}$	$R^2 = 0.869$		
C.	2000	$P_{tp} = 0.9167 \times P_{rg}$	$R^2 = 0.87$	$P_{tp} = 0.7757 \times P_{rg}$	$R^2 = 0.8543$
	2001	$P_{tp} = 0.8128 \times P_{rg}$	$R^2 = 0.8082$		

**Table III.** Rain interception ( $I_n$ , %) in leafy and non leafy periods for the 3 years of measurements and for each plot (Th.: Thinned; C.: Control). Values are tipping buckets hourly measurements summed per day and corrected with equations from Table II.

Year	Leafy period		Non leafy period	
	Th.	C.	Th.	C.
1999	24.3	26.1	19.6	22.9
2000	27.7	43.4	25.5	24.9
2001	18.2	22.3	19.9	19.9

Global radiation measurements ( $W m^{-2}$ ) above ( $R_{g_o}$ ) and below ( $R_{g_{bc}}$ ) canopy demonstrated the following relationships:

Leafy period

$$(Th.) \quad R_{g_{bc}} = 0.1429 \times R_{g_o} \quad R^2 = 0.76 \quad (3)$$

$$(C.) \quad R_{g_{bc}} = 0.1164 \times R_{g_o} \quad R^2 = 0.81 \quad (4)$$

Non-leafy period

$$(Th.) \quad R_{g_{bc}} = 0.1637 \times R_{g_o} \quad R^2 = 0.81 \quad (5)$$

$$(C.) \quad R_{g_{bc}} = 0.1473 \times R_{g_o} \quad R^2 = 0.88. \quad (6)$$

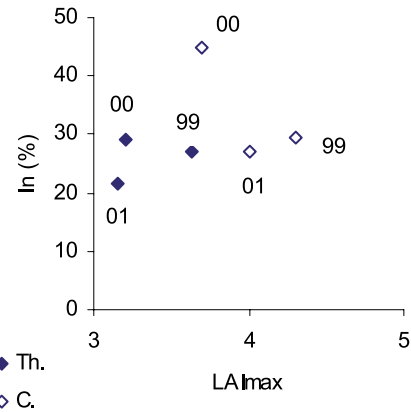
During the leafy period, below canopy Photosynthetically Active Radiation ( $PAR_{bc}$ ,  $\mu mol m^{-2} s^{-1}$ ) was related to  $R_{g_{bc}}$  by the following relationships:

$$(Th.) \quad PAR_{bc} = 1.7445 \times R_{g_{bc}} \quad R^2 = 0.59 \quad (7)$$

$$(C.) \quad PAR_{bc} = 0.612 \times R_{g_{bc}} \quad R^2 = 0.16. \quad (8)$$

### 3.2. Gap filling for tree transpiration (T)

Sapflow measurements [38] used to calculate oak and maple (daily) transpiration, had to be estimated when measurements were lacking due to electric breakdown or maintenance stop. The gaps were filled by several ways according to leaf area development. For periods of leaf area expansion and leaf fall, daily transpiration was calculated with an equation based on daily PET and on a relative LAI ( $LAI_i/LAI_{max}$ ), with  $i$  standing for the day and  $LAI_{max}$  standing for the maximum LAI of the year. For periods of constant LAI, oak transpiration was deduced by interpolation (1 missing day). If data were lacking for a tree during several consecutive days, the slope of the regression between PET and transpiration of an oak of same SA was used to rebuild the series.

**Figure 3.** Rainfall interception during the leafy period ( $I_n$ %, calculated with tipping buckets measurements corrected by equations of Tab. II) for 1999, 2000, 2001 as a function of  $LAI_{max}$  for each plot (Th.: Thinned; C.: Control).

Transpiration of ring-porous species was then estimated as follows:

$$T_{rp} = T_{oak} \times SA_{rp} / SA_{oak} \quad (9)$$

with SA in  $m^2 ha^{-1}$ .

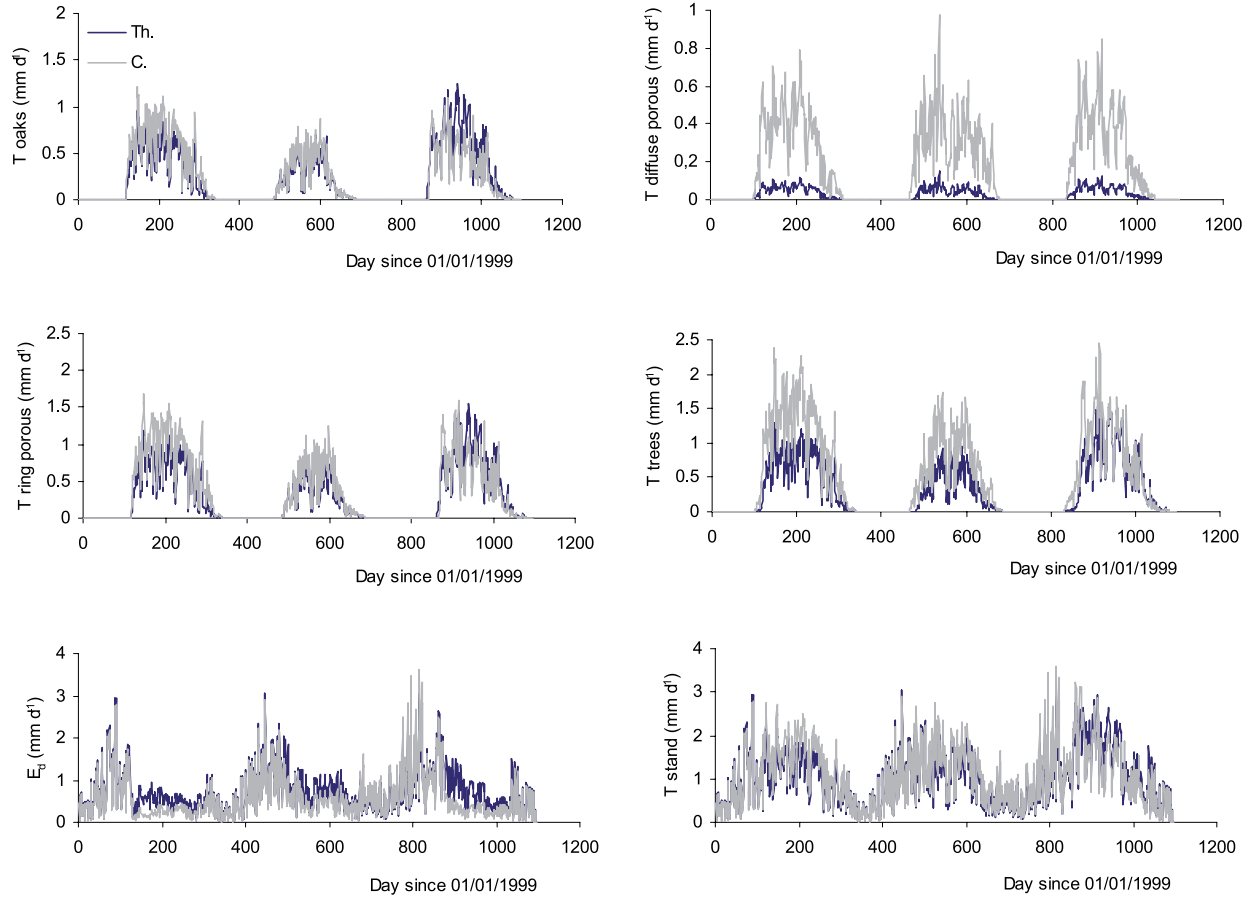
For diffuse porous species, maple SFD measurements were used to estimate  $T_{dp}$  on the basis of their SA in each plot. In the control plot,  $T_{dp}$  was dependent of PET:

$$T_{dp} = 0.14878 \times PET \quad R^2 = 0.63. \quad (10)$$

This relationship was used to fill gaps on periods with identical LAI. For leaf expansion periods and leaf fall, the same methods than for oaks have been used. In the thinned plot, maple transpiration didn't give acceptable results because of technical breakdown, so diffuse porous species transpiration was calculated as follows:

$$T_{dp(E)} = 0.14878 \times PET \times SA_{dp(Th)} / SA_{dp(C)}. \quad (11)$$

Those reconstitution give the daily variation of transpiration for oak, ring- and diffuse-porous species from 1999 to 2001 (Fig. 4). Oak and ring porous time course look similar, excepted for the maxima, which are raised by 0.3 to 0.4  $mm d^{-1}$  among plots. On the contrary, diffuse porous species transpiration showed large differences among treatments. In the thinned plot, it never exceeded 0.15  $mm d^{-1}$ , whereas in the control plot it varied between 0.5 and 0.98  $mm d^{-1}$ . Whereas diffuse porous



**Figure 4.** Daily transpiration ( $T$ ,  $\text{mm d}^{-1}$ ) for oak, ring- and diffuse-porous species, trees, forest floor ( $E_d$ ) and stand, in 1999, 2000 and 2001.

species occur in almost the same proportion in each plot in terms of basal area contribution (Th.: 11%; C.: 16%), they contribute to about 30% of LAI and SA in the control plot, and only to 6–9% of those parameters in the thinned plot. When considering all trees, in 1999 and in 2000 the control plot's transpiration is 0.35 the thinned plot's; in 2001, it is 0.20 (excepted for budbreak period).

### 3.3. Simulations of daily forest floor transpiration ( $E_d$ )

The forest floor transpiration was dependent upon LAI and  $\text{PAR}_{bc}$  [38]. Daily forest floor transpiration ( $E_d$ ,  $\text{mm d}^{-1}$ , Fig. 4), was therefore simulated with the following equations:

$$E_d = (-0.858 \times \text{LAI} + 4.001) \times f(\text{PAR}_{bc}) \quad (12)$$

with

$$f(\text{PAR}_{bc}) = \text{PAR}_{bci} / \text{PAR}_{bcmax} \quad (13)$$

where  $\text{PAR}_{bci}$  is below canopy PAR of day  $i$  and  $\text{PAR}_{bcmax}$ , the maximal below canopy PAR; both are deduced from equation (3) to (8). Each year, a different value of  $\text{PAR}_{bcmax}$  was taken for the leafy and non-leafy periods. During the leafless period, LAI is fixed to 1.1 in the thinned plot and 1.3 in the control plot, which are in fact the WAI values (Wood Area Index)

presented in Vincke [37]. The results (Fig. 4) showed that before tree budbreak, forest floor transpiration is almost identical in both plots, with maxima of  $2.2 \text{ mm d}^{-1}$  in 1999,  $2.3 \text{ mm d}^{-1}$  in 2000 and  $2.9 \text{ mm d}^{-1}$  in 2001. After, it is depending upon LAI and PAR evolution as a direct result of the calculation. As forest floor transpiration measurements were held on one location in each plot, its dependency upon LAI was used to estimate its spatial variability and differences between plots (Fig. 5). On each LAI measurements location (15 per plot),  $E_d$  was calculated with equation (14), cited in [38]:

$$E_d (\text{mm}) = -0.9574 \times \text{LAI} + 4.3701 \quad R^2 = 0.8215. \quad (14)$$

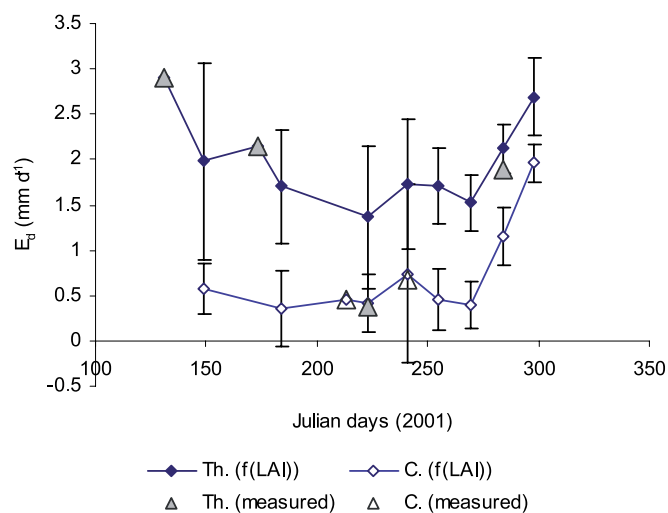
Standard deviation from the LAI-based estimation is smaller in the control plot, which canopy is more homogeneous. Effectively, only 10% of this canopy is constituted by gaps, against 27% in the thinned plot [37]. Those canopy features differences led to a forest floor development and transpiration different among plots.

### 3.4. Water use in each plot: T and ET

T and ET in each plot, for each year and each canopy layer are summarised in Table IV. Stand transpiration in both plots

**Table IV.** For each plot (Th.: Thinned; C.: Control), potential evapotranspiration (PET, mm), transpiration (T, mm), actual evapotranspiration (ET, mm) for the stand; trees transpiration, forest floor transpiration and proportion in total ET (%ET); pedunculate oak transpiration (Oak) and proportion in total ET (%ET); ring- and diffuse-porous transpiration, from DOY 91 to DOY 304 in 1999, 2000 and 2001.

Year	Plot	PET	Stand			Trees		Forest floor		Oak		Ring-Porous	Diffuse-Porous	Toaks/Tstand	Therbs/Tstand	Ttrees/Therbs
			T	ET	ET/PET	T	%ET	T	%ET	T	%ET	T	T			
1999	Th.	510	252	383	0.75	128	0.33	124	0.32	91.6	0.24	118	10	0.36	49.3	1.03
	C.		311	453	0.89	233	0.51	78	0.17	119	0.26	166	67	0.38	25.2	2.98
2000	Th.	484	248	449	0.93	74	0.16	175	0.39	51.6	0.11	65	9	0.21	70.2	0.42
	C.		282	594	1.23	149	0.25	133	0.22	59	0.10	84	65	0.21	47.3	1.11
2001	Th.	468	314	442	0.94	136	0.31	178	0.40	102	0.23	127	9.4	0.32	56.7	0.76
	C.		297	458	0.98	179	0.39	118	0.26	80.7	0.18	117.3	62	0.27	39.7	1.52



**Figure 5.** Forest floor transpiration ( $E_d$ , mm d<sup>-1</sup>) as measured with the closed chamber and as simulated with equation (14), for each plot (Th.: Thinned; C.: Control) in 2001 leafy period.

and for each year never exceeded 314 mm. Oak transpiration (Tab. IV) is between 21% and 38% of stand transpiration. Ring-porous transpiration is always higher than diffuse-porous, especially in the thinned plot. Trees transpire less water than forest floor in the thinned plot (excepted in 1999), with a minimum of 42% of forest floor ET in 2000. On the contrary, in the control plot, trees use three times more water than forest floor in 1999. From 1999 to 2001, total transpiration in the thinned plot relative to the control one increased from 81 to 106% (Tab. V). Excepted for 2001, tree transpiration in the thinned plot is about two third the transpiration in the control plot. But 2001 result could be an artefact of the variable number of functional flow-meters in the control plot. Oaks transpiration in the thinned plot increased (from 77 to 126%), relatively to the control plot. Forest floor in the thinned plot always uses more water than in the control one (from 131 to 158%). It seems to compensate what trees don't use. Diffuse porous trees water use is 85% lower in the thinned plot, as a direct effect of their lower representativeness.

**Table V.** For the stand, the trees, the forest floor (herbs), the pedunculate oaks (Oak), the ring- and the diffuse-porous species, the ratio between transpiration measured in the thinned plot and transpiration measured in the control plot (Th./C.).

Year	Stand	Trees	Herbs	Oak	Ring-porous	Diffuse-porous
1999	0.81	0.65	1.58	0.77	0.71	0.15
2000	0.88	0.66	1.31	0.87	0.78	0.13
2001	1.06	0.79	1.51	1.26	1.08	0.15

### 3.5. Soil water reserve daily seasonal variations

Using equation (2), daily variation of soil water reserve (Fig. 6) was calculated. Total soil water reserve (R, mm) was estimated by the mean of soil volumetric water content measurements (not shown) and was 600 mm out of excess water [37]. With the budding of most plants, soil water reserve decreases. A difference between plots is visible only in 1999 (starting DOY 209). Short-term variations are similar. It is also in 1999 that LAI between plots is the most contrasted. In the thinned plot, soil water depletion varied from 35.4 mm to 68.8 mm according years; in the control plot, it varied from 41.4 to 77.1 mm. Minimum reserve ( $R_{min}$ ) is reached on DOY 256 (1999), 183 (2000) and 185 (2001). The extractable water (EW) was calculated on the basis of pF-curves and was 152 mm [39] over 160 cm depth. Relative extractable water (REW) was then calculated with the following equation:

$$REW_i = (R_i - R_{min}) / (EW). \quad (15)$$

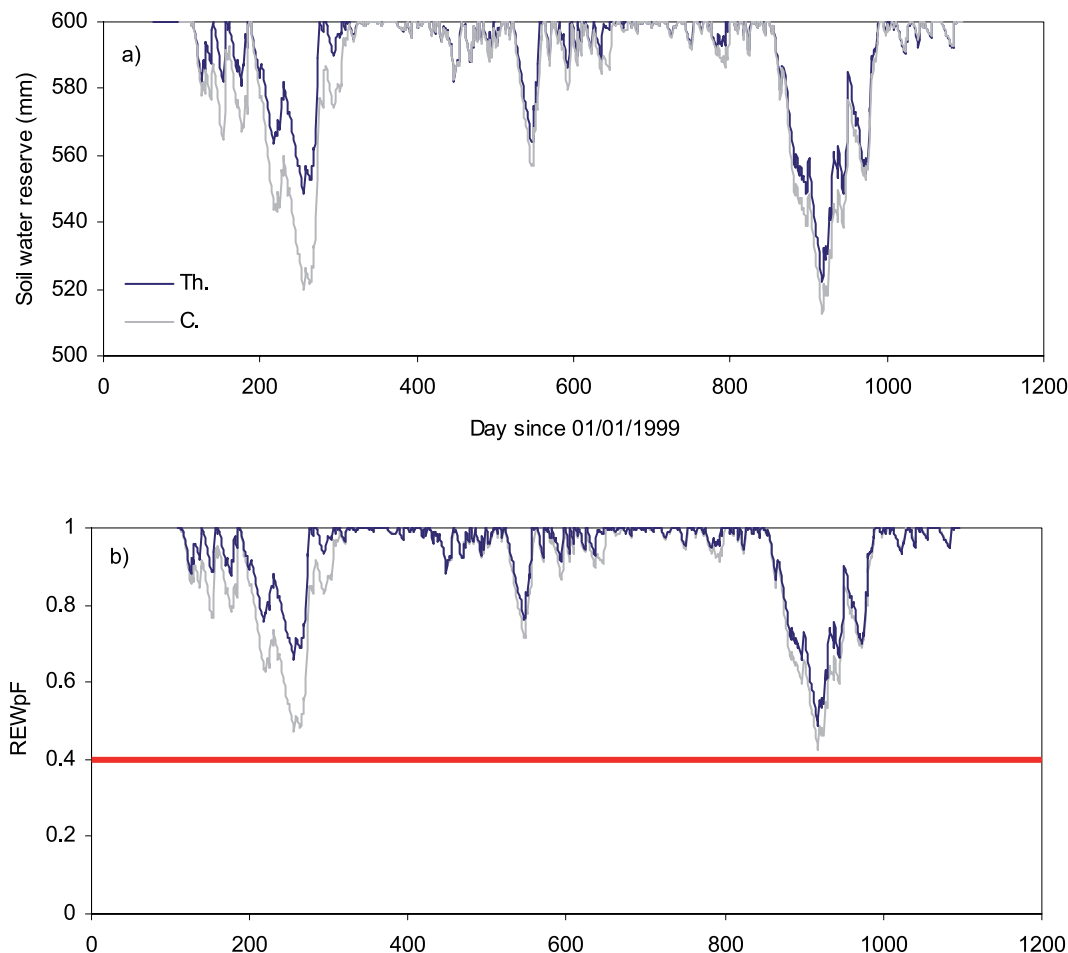
$R_{min}$  is the minimum soil water reserve.

Variation of REW (Fig. 6b) showed the same dynamic than R but allowed to discuss the eventuality of water stress. REW never dropped below 0.4, which indicates no water stress.

## 4. DISCUSSION

### 4.1. Rainfall interception

During the 3 years of measurements, no drought have been detected from estimated REW, even though in 1999 (P-PET)



**Figure 6.** For each year and each plot (Th.: Thinned; C.: Control), (a) soil water reserve (mm) as deduced from equation (2); (b) relative extractable water calculated on the basis of an EW estimated by pF-curves (REWpF).

was deficient ( $-78$  mm) in leafy period, in particular in May ( $-11.6$  mm) and July ( $-32.5$  mm). Rainfall interception (In%) during the leafy periods varied between 18% and 44% of incident rain according to the years. Nizinski and Saugier [27], in a 120 years old sessile oak stand estimated In% from 28% to 41.2%. Those values stand well with the ones cited in Aussenac [1], which varied from 20% to 40% for deciduous forests. The observed range is also close to data reported by Bréda et al. [8], who calculated In% of 16–17% in a 35 years old sessile oak stand with LAI of 3.3. The intra- and inter-annual variations, not always well correlated with LAI, probably result from (i) the type of rain and (ii) climatic conditions; for instance, slight rains are almost totally intercepted. For a same amount of rain, In% is also function of the evaporative demand (wind speed, radiation, vapour pressure deficit) and of the continuous or discontinuous pattern of the rain [2, 11, 35].

#### 4.2. Over- and understorey evapotranspiration

Sap flux density of individual trees can be extrapolated to stand by using relationship between sap flow and trees diame-

ter, or basal area, or sapwood area or leaf area [36]. In mixed stands or when there is a pronounced hierarchy in vegetation structure, this approach can be applied to sub-groups of the population, by dividing stand in classes containing plants with similar characteristics [14]. We followed this approach by classifying trees according to their type of hydroactive xylem, i.e. in ring- and diffuse-porous species. SA was used as the reference scalar to extrapolate tree water use to stand water use.

Forest floor contributes greatly to ET in each plot, ranging from 0.75 to 3.1 mm per day in the thinned plot and from 0.3 to 3.6 mm per day in the control one. Forest floor ET represented up to 40.3% of ET in the thinned plot and up to 25.8% in the control plot. The relative contribution of forest floor transpiration is lower in the control plot, which is in accordance with Rutter [32], who observed that in closed canopies, only few energy was still available below canopy. Several authors emphasised the importance of forest floor transpiration in the water and carbon balances of forests [7, 9, 15, 22, 26]. For the water balance, Granier et al. [13] cited 30% for ferns in a *Pinus pinaster* stand and 10% for *Vaccinium myrtillus* below *Pinus sylvestris*. Forest floor contributed to 49 to 57% of stand

transpiration for stands of *Pinus radiata* with a forest floor of *Hypochaeris radicata* L. and *Holcus lanatus* [19]. Lüttschwager et al. [23], in a 65 years old *Pinus sylvestris* stand measured a forest floor contribution (*Deschampsia flexuosa*) up to 50% of total water fluxes.

ET varied between 383 and 594 mm (years and plots confounded) with lower values in the thinned plot than in the control one; in 2001, ET of both plots were almost equal (Tab. IV). ET/PET varied from 0.75 to 1.23 for the stand. Ladekarl et al. [21] calculated a ET/PET ratio of 0.9 in deciduous forests. The T/PET was between 49 and 67% (plots and years confounded), which is in accordance with Wilson et al. [41], who measured a T/ET of 50% in a deciduous mixed irregular stand of oak and maple.

Following conclusions can be driven out: (i) 6–8 years after thinning, both plots use about the same amount of water besides different composition and structure and (ii) T (trees and understorey) is the main part of ET (excepted in 2000, very rainy year with low LAI).

Aussenac and Granier [3], showed also on Douglas-fir 5 years after thinning, that ET was similar in treated and non treated plots. It is possible that consequences of thinning on ET were important the 2–3 years after, as showed on Douglas-fir [4] and on oak [8]. Effectively, thinning usually implies a better water availability due to both lower T and In, and, as a consequence, a diminution of length and intensity of water stress [3, 5, 25].

One of the most important findings is that oak transpiration is lower than herbaceous transpiration; when expressed as a function of ET, it varied from 10% to 26.6%, which is low. Even if it is reasonable to state that forests developing more LAI would have higher transpiration rates, other proofs suggest that forest transpiration is a conservative hydrological process [18, 30]. One of the main causes is that understorey compensates the differences in loss of water from canopies with contrasted LAI. Our results confirm this hypothesis of a conservative use of water within forest, where transpiration tend to dampen more than to amplify the variations in evaporative demand or annual variations in water availability [17, 29]. Total stand transpiration during vegetation period is about 300 mm in both plots, even if there are big differences between them in their specific composition and structure. This is similar to the results of other studies [23, 29, 31]. Ladekarl [20] measured in a 150 years old *Q. robur* stand annual transpiration from 265 to 318 mm.

### 4.3. Soil water reserve and REW

The soil of the study site can be considered as a lysimeter. The schist (at 180 cm depth), the clayed horizons and the flat topography induce the accumulation of water. Approximately, all water that penetrates the soil only gets out by evapotranspiration. Even if no water stress have been observed, other stresses can have consequences upon trees. The first stress could be waterlogging. The water table and the soil compacity implies additive energetic costs to trees, because they need to maintain functioning roots during winter et to rebuild a part of the root system in spring. Repeated caterpillars attacks also imply energy losses and therefore contribute to tree growth limitation and mortality.

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