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Evapotranspiration assessment of a mixed temperate forest by four methods: Eddy covariance, soil water budget, analytical and model

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ABSTRACT

In forest ecosystems, assessment of evapotranspiration fluxes (ET) and distinction of its components, i.e. tree transpiration (T), rainfall interception (I), and soil plus understory evapotranspiration (ETu), are a major issue. At the Vielsalm Terrestrial Observatory in Belgium (VTO, Integrated Carbon Observation System network, ICOS), covered by a mixed forest of broadleaved (mainly *Fagus sylvatica* L.) and coniferous species (mainly *Pseudotsuga menziesii* [Mirb.] Franco), the water vapor fluxes have been continuously measured by eddy covariance since 1996, without distinction of its components. Widely validated for CO2 fluxes, water vapor fluxes measured by eddy covariance still lack validation, particularly in mixed and/or heterogeneous stands. During 2010–2011, three other methods to assess ET were implemented, in order to inter-validate them and to disentangle species specific ET into its components. These methods were: (i) the analytical method which relies on measurement of each elementary flux, i.e. tree transpiration, interception loss and evapotranspiration of soil plus understory (ET_A); (ii) the soil water budget method (ET_S) and (iii) modeling of stand ET (ET_M).

Our results showed that during dry foliage conditions, stand T + ETu estimated by the analytical method or model were in very good agreement with eddy covariance ET measurements. Interception loss measured was 14% and 30% of rainfall (P) for beech and Douglas-fir respectively, leading to 19% for the whole stand. Beech interception being quite low, ET_A for the stand is probably slightly underestimated. Over 2010 and 2011, the mean seasonal value of ET was 1.9 mm d^{-1}, considering all the methods. The four methods gave close estimates, with maximum deviations from the mean being of 12%, and uncertainties, while remaining acceptable (maximum 26% with analytical method) overlap between methods. Regardless of methods, flux measurements during rainy conditions were more complex to characterize. A slight underestimation of ET by the eddy covariance method was observed at different time step, in comparison to the others implemented methods. On an annual scale, the forest water balance model estimates (BILJOU©; ET_M) were similar in beech (68% of potential evapotranspiration, PET) and Douglas-fir substands (72% of PET), despite their differences in phenology and water use patterns. Low differences were also observed between species in the water flux partitioning, with modeled ET composed of ca. 58%, 33% and 9% of T, I and ETu respectively on the annual timescale (2010–2011).

1. Introduction

Evapotranspiration (ET) is the sum of water vapor fluxes released into the atmosphere by soil and vegetation. Accurate estimations of ET and its components are needed, from the tree to the stand, in order to address water resource challenges in the 21st century and this requires a coordinated interdisciplinary approach combining soil science, ecology, forestry, hydrology and climatology (Vose et al., 2011). In forest ecosystems, ET is composed of tree transpiration (T), rainfall interception (I) and soil plus understory evapotranspiration (ETu). Evapotranspiration flux and its regulation are mostly linked to potential evapotranspiration (PET) and extractable soil water (EW), and each species' regulation of water use (Granier et al., 1999).

Measurement of ET, at the forest stand scale, is currently performed by eddy covariance, EC (Aubinet et al., 2000). This reference method, widely used since the early 1990s, allows a measurement of total ET, but without discriminating between its components.

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This methodology was developed for flux measurements on homogeneous stands, but was rapidly extended to more heterogeneous stands. Up to now, few studies have brought improvement in the eddy covariance methodology for ET flux measurements (Clement, 2005; de Ligne et al., 2010; Ibrom et al., 2007), while the comparisons of ET with other methods are more numerous (Bovard et al., 2005; Ford et al., 2007; Granier et al., 2000a; Meiresonne et al., 2003; Schwärzel et al., 2009). However, for mixed stands, the species effect on ET measurements by EC, in terms of contribution and flux partitioning (i.e. ET components) is poorly documented (Oishi et al., 2008; Unsworth et al., 2004; Wilson et al., 2001). It is therefore important to carry on the validation of EC measurements in more complex ecosystems, and compare it to independent bottom-up approaches (van der Molen et al., 2011). Besides eddy covariance, ET can be estimated by several methods (Table 1): the analytical method (ET_A), the soil water budget method (ET_S) and the modeling of ET (ET_M).

The analytical method (ET_A) consists in measuring separately T (with sap flow sensors), I (with a network of rain gauges above and below canopy) and ETu (modeled from short-term measurements with chambers). Water flux partitioning into ET strongly differs among ecosystems, depending on distribution, duration and intensity of rainfall, evaporative demand, leaf area index (LAI), species composition and tree architecture. In mature temperate forests, tree transpiration is generally the major water flux during the leafed period. Several methods have been developed in order to characterize transpiration fluxes at tree scale, then scaled up to the stand (Čermák et al., 1973; Granier, 1985; Nadezhdina et al., 1998; Oren et al., 1998). Some of these methods are based on sap flux density measurement into a part of the hydroactive xylem, such as the thermal dissipation method (Granier, 1985) widely used and validated (Ewers et al., 2007; Ford et al., 2007; Köstner et al., 1996; Saugier et al., 1997; Tournebize and Boistard, 1998). Species composition and distribution, sapwood area and radial profile of sap flux in each tree species are the main variables needed in order to upscale sap flux density measurements to stand transpiration. The second flux of importance is the interception loss of the canopy, defined as the fraction of incident rainfall that does not reach the forest floor (commonly ranging from 10% to 50%; Herbst et al., 2008). In forests, inter-annual and seasonal variability of rainfall interception can be significant, depending on rainfall and weather conditions. Variability of rainfall interception, which contributes largely to distribution of soil water content, is a function of stand density, tree species and architecture. Finally, the contribution of soil plus understory evapotranspiration in mature forests is usually low in comparison to T or I, but as it depends on energy reaching the soil surface and therefore on stand LAI, it can be significant for some ecosystems (Granier et al., 1990; Vincke et al., 2005).

The soil water budget method (ET_S) relies on the resolution of the soil water budget equation (Schume et al., 2003; Schwärzel et al., 2009; Unsworth et al., 2004; Wilson et al., 2001) using rainfall, soil water content and drainage measurements. Among the various methods of soil water content measurements (gravimetric, neutron probes, time-domain reflectometry etc.), capacitive probes are usually used, allowing precise and continuous measurements in the field (Unsworth et al., 2004; Wilson et al., 2001). For a spatial scale smaller than the watershed, drainage measurement may be measured by non-weighing lysimeters or modeled with forest water balance models, such as BILJOU© (Granier et al., 1999). Resolving the water balance equation, this kind of model also allows an estimation of daily evapotranspiration fluxes (ET_M; the third method) and soil water content.

In order to compare these different methods, their spatial and temporal scale must be similar. Fitting of analytical, soil water budget or model outputs to the footprint of EC measurements is a real challenge (Oishi et al., 2008). This difficulty increases with the heterogeneity of the ecosystem. Based on stand species distribution, footprint models can be combined to EC measurements, in order to determine sub-stand contributions to the measured fluxes, at high temporal resolution (Kormann and Meixner, 2001; Neftel et al., 2008).

Our objective is to validate ET measured by eddy covariance for two successive years in a mature mixed and heterogeneous forest located in Belgium (VTO, ICOS) and to partition its components. We therefore implemented the three methods of ET assessment described above in addition to eddy covariance (ET_{EC}), i.e. analytical (ET_A), soil water budget (ET_S) and modeling (ET_M), in order to compare them. Specific advantages and limitations of each of the methods are discussed (Table 1).

Table 1
List of the flux abbreviations with their definition, expressed in mm time^{-1}.

Abbreviations	Definitions
$\mathbf{Dr}_M$	modeled soil water drainage
ET	evapotranspiration fluxes
ET_A	analytical evapotranspiration fluxes
ET_{AB}	beech sub-stand analytical evapotranspiration fluxes
ET_{AD}	Douglas-fir sub-stand analytical evapotranspiration fluxes
ET_{AS}	stand analytical evapotranspiration fluxes
ET_{EC}	eddy covariance evapotranspiration fluxes
ET_M	modeled evapotranspiration fluxes
ET_{MB}	beech sub-stand modeled evapotranspiration fluxes
ET_{MD}	Douglas-fir sub-stand modeled evapotranspiration fluxes
ET_{MS}	stand modeled evapotranspiration fluxes
ET_S	soil water budget evapotranspiration fluxes
ET_{SB}	beech sub-stand soil water budget evapotranspiration fluxes
ET_{SD}	Douglas-fir sub-stand soil water budget evapotranspiration fluxes
ET_{SS}	reference zone soil water budget evapotranspiration fluxes
ETu	soil plus understory evapotranspiration fluxes
ETu	measurements of soil plus understory evapotranspiration fluxes
ETu_B	beech sub-stand soil plus understory evapotranspiration fluxes
ETu_D	Douglas-fir sub-stand soil plus understory evapotranspiration fluxes
ETu_S	stand soil plus understory evapotranspiration fluxes
ETu_M	modeled soil plus understory evapotranspiration fluxes
ETu_{MB}	beech sub-stand modeled soil plus understory evapotranspiration fluxes
ETu_{MD}	Douglas-fir sub-stand modeled soil plus understory evapotranspiration fluxes
ETu_{MS}	reference zone modeled soil plus understory evapotranspiration fluxes
I	Rainfall interception fluxes
I	measurements of interception fluxes
I_B	beech sub-stand interception fluxes
I_D	Douglas-fir sub-stand interception fluxes
I_S	stand interception fluxes
I_M	modeled interception fluxes
I_{MB}	beech sub-stand modeled interception fluxes
I_{MD}	Douglas-fir sub-stand modeled interception fluxes
I_{MS}	stand modeled interception fluxes
P	rainfall
P_S	stemflow
P_T	throughfall
P_{TB}	beech sub-stand throughfall
P_{TD}	Douglas-fir sub-stand throughfall
T	transpiration fluxes
T	measurements of transpiration fluxes
T_B	beech sub-stand transpiration fluxes
T_D	Douglas-fir sub-stand transpiration fluxes
T_C	mixed coniferous sub-stand transpiration fluxes
T_S	stand transpiration fluxes
T_M	modeled transpiration fluxes
T_{MB}	beech sub-stand modeled transpiration fluxes
T_{MD}	Douglas-fir sub-stand modeled transpiration fluxes
T_{MS}	stand modeled transpiration fluxes

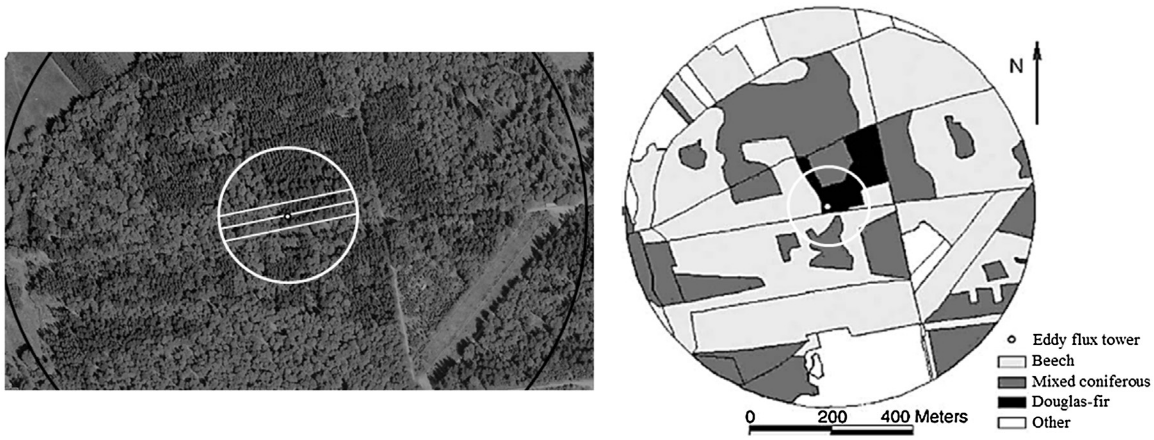

Fig. 1. Aerial picture (on the left; google map) and map (on the right; Aubinet et al., 2005) of the land use distribution around the tower (at the center). The black circle on the aerial picture corresponds to the map limit. The white circle on aerial picture and map corresponds to the reference zone. The three white lines on the aerial picture correspond to measurements transects used for throughfall, soil water content and leaf area index assessments.

2. Material and methods

2.1. The Vielsalm Terrestrial Observatory

The study site is located at Vielsalm in a Belgian Ardennes forest (50°18′18.20″N, 5°59′53.15″E; altitude: 450 m) and is part of the ICOS European network (VTO). Its topography is smoothly sloping (3%) in a north-western direction. The climate is temperate maritime. The soil is 1.3–1.5 m deep and is classified as a dystric cambisol (Longdoz et al., 2000). The vegetation in the vicinity of the EC tower is a mixture of coniferous species, mainly Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), Norway spruce (*Picea Abies* [L.] Karst.), silver-fir (*Abies alba* Miller), Hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and deciduous species, mainly European beech (*Fagus sylvatica* L.). The vegetation distribution (Fig. 1) showed within the mixed stand the presence of several types of sub-stands: two monospecific stands, beech and Douglas-fir, and one coniferous mixed stand mainly composed of Silver-fir, spruce and hemlock. The analytical method, soil water budget (SWB) method and model were developed at the sub-stand scale (beech and Douglas-fir). Then, analytical and SWB methods and model were up-scaled from the sub-stand scale to stand, in order to be compared to eddy covariance. Sub-stand characteristics (Table 2) were evaluated within a reference zone (100 m radius circle around the flux tower). This zone was assumed to be representative, in terms of species composition and density, of the type of stands generating the main fluxes measured by the EC method (Fig. 1). The understory vegetation was sparse in the conifer sub-stands and absent in the beech sub-stand. Eddy covariance (CO_2 and H_2O fluxes) and meteorological measurements were taken since 1996 (ULg-GxABT, Aubinet et al., 2001). Two wind directions predominate: south-west and north-east. From the point of view of the EC measurement, the first wind direction mainly corresponds to the beech stand while the second one mainly corresponds to the Douglas-fir stand (Fig. 1). More details about the site may be found in Aubinet et al. (2001, 2002).

Table 2
Dendrometric and LAI characteristics of the sub-stands, beech, Douglas-fir and mixed coniferous, in 2010–2011.

	Beech	Douglas-fir	Mixed coniferous
Stems per hectare	175	145	300
Basal area (m^2 ha^{-1})	20.9	58.1	40.5
Sapwood area (As/Ag; m^2 ha^{-1})	14.7	13.2	16.3
Mean tree height (m)	26	41	33
LAI_{max}	5	4.2	4.1
Age	107	80	–

2.2. Eddy covariance

Since 1996, evapotranspiration fluxes were measured using the EC method (ET_{EC}) used in the EUROFLUX – CARBOEUROFLUX – CarboEurope IP networks (Aubinet et al., 2000; Grelle and Lindroth, 1996; Moncrieff et al., 1997). This consists of a fast-response infrared gas analyzer (model LI-6262, LI-COR Inc., Lincoln, NE, USA) and a three-dimensional sonic anemometer (model SOLENT 1012R2, Gill Instruments, Lymington, UK). The system was installed on a tower at a height of 52 m above the forest floor. More technical information can be found in Aubinet et al. (2001) and de Ligne et al. (2010). Data acquisition and flux computation were performed using the EDDYFLUX (EDDY Software, Jena, Germany) software. Computation and correction procedures were standardized and defined within the EUROFLUX – CARBOEUROFLUX – CarboEurope IP networks (Aubinet et al., 2000). ET_{EC} flux calculation was performed at a 30 min timescale.

For EC measurements, correction of measured high frequencies with a closed-path infrared gas analyzer is one of the major problems (Aubinet et al., 2000; Clement, 2005). The high frequencies attenuation is a consequence of the transport of air from the sampling point to the analyzer. The correction procedure for CO_2 fluxes was used for ET fluxes (Aubinet et al., 2001), however the transfer function of water vapor fluxes was known to be dependent on air humidity (Clement, 2005; de Ligne et al., 2010; Ibrom et al., 2007; Leuning and Judd, 1996; Massman and Ibrom, 2008). Furthermore, the requirements for eddy covariance measurements are restrictive, dependents principally on atmospheric conditions of stability, transport of air by advection (night conditions), or also wet conditions for sensors. Important data gap filling could lead to incorrect seasonal evaluation of fluxes. For VTO, gap filling (by GHG-Europe database) concerned 18% of the data in 2010 and 17% in 2011, on a 30 min timescale.

The footprint analyses were performed with a two-dimensional analytical footprint software tool proposed by Neftel et al. (2008) according to the Kormann and Meixner footprint model (Kormann and Meixner, 2001). The inputs of the model are information provided by the eddy covariance system (friction velocity, Obukhov length, standard deviation of lateral wind speed, measurement height and horizontal wind speed). Based on the map of species distribution (Fig. 1), the footprint model provided the contribution of each sub-stand within the EC fluxes measurements, at a

30 min timescale. In 2010 (DOY 141–275) and 2011 (DOY 127–281), according to the footprint model, beech, Douglas-fir, and mixed coniferous sub-stands contribute on average to 62%, 11% and 25% respectively, of the fluxes measured on the tower. The footprint model covered 61% of the 30 min data; 35% of missing data occurred during low evapotranspiration rates (between 5:30 AM and 7:30 PM).

2.3. Analytical method

2.3.1. Tree transpiration

Tree transpiration was estimated from sap flow measurements. They were performed using the thermal dissipation technique (Granier, 1985, 1987) with 20 mm-long radial commercial sap flow sensors (SFS2 Type M, UP-GmbH, Ibbenbüren, Germany) installed at a height of 1.5 m in the stems of 8 beeches, 6 Douglas-firs and 3 silver-firs. The trees were initially selected so as to be representative of the circumference distribution of the species within 1 ha around the tower. The thermal dissipation technique allows the estimation of sap flux density (SFD, $g\,m^{-2}\,s^{-1}$), *i.e.* the sap flow per unit of sapwood area. Sap flow sensors measure the temperature difference (ΔT) between one heated continuously (at a constant power of 0.2 W) and one unheated probe. ΔT of each probe pair was measured at 30 s time intervals and 30 min averages were calculated and stored on a CR800 datalogger (Campbell Scientific, Logan, UT, USA). In 2010 (DOY 141–275) and in 2011 (DOY 127–281), 11% and 3% of 30 min data were missing for all trees, respectively. The missing data were gap-filled using linear regressions between trees of the same species and same circumference classes. To convert these data into water flux, the following equation was used (Granier, 1987):

$$SFD = 119 * \left(\frac{\Delta T_{max}}{\Delta T} - 1\right)^{1.23} \quad (1)$$

where ΔT_{max} is the maximum temperature difference, reached when sap flux is zero, normally during the night (Granier, 1987). ΔT_{max} was determined using Baseliner software (v3.0.7; Oishi et al., 2008; Oren et al., 1999). The probes are totally in contact with the sapwood. No significant natural temperature gradients (<0,2 °C; Do and Rocheteau 2002) were detected during measurements.

In each circumference class (i) of each tree species, mean SFD was calculated ($SFDm_i$). Each circumference class represents a sapwood area proportion (p_i) of the total stand sapwood area expressed per unit of ground area (A_S, $m^2\,m^{-2}$). Sub-stand transpiration is calculated as follows:

$$T_C = \sum_{i=1}^{i=n} (SFDm_i * p_i) * A_S \quad (2)$$

Transpiration of each sub-stand, beech (T_B), Douglas-fir (T_D) and mixed coniferous (T_C) were calculated (Table 3). For the stand, transpiration (T_S) was calculated using the footprint model (Laffineur et al., 2011; Neftel et al., 2008). On a timescale of 30 min, it provided the percentage of contribution of each sub-stand within the global measurement of ET_{EC}. T_S was then calculated as the sum of T_B, T_D and T_C, each weighted by the results of the footprint model. For missing data concerning the footprint model (cf. Section 2.2), T_S was evaluated as the mean of T_B, T_D and T_C.

In beech, the visual distinction of sapwood and heartwood is not possible, so we used the radial profile of SFD in beech trunks as fitted by Granier et al. (2000a, 2003). In Douglas-fir, the sapwood thickness was measured on cores, sampled on eight trees. We found the following relationship between sapwood radius (Rd_{SW}, cm) and tree circumference (C_{130}, cm): $Rd_{SW} = 0.04 \times C_{130} - 1.33$ ($R^2 = 0.92$). An experiment was conducted in 2010 in order to determine the radial profile of sap flow in Douglas-fir at Vielsalm (data not shown). Mobile sensors (SFS2 Type MS, UP-GmbH, Ibbenbüren, Germany) were used on three Douglas-firs, chosen in different circumference classes. SFD measurements analyzed according to relative sapwood depth, showed no differences between sampled trees. Then, the same radial profile of SFD was used to characterize the Douglas-fir sub-stand. SFD sharply decreased (by about 77%) in the first 20% of sapwood from the bark, and remained rather stable thereafter (total decrease of 86% along the sapwood). In Silver-fir (Fiora and Cescatti, 2006) and hemlock, the sapwood thickness was assumed to be 40% of the tree radius. In spruce, the sapwood radius was considered to be 45% of the tree radius (Lu et al., 1995). For these last three species, no information was found on the radial SFD profile; we assumed the same profile as for Douglas-fir. Finally, no SFD measurements were performed on hemlock and spruce. Due to their similar wood anatomy, age and aerial architecture, we assumed that their sap fluxes were similar to those measured in Douglas-fir.

2.3.2. Rainfall partitioning

In 2010–2011, incident rainfall (P, mm) was measured at the top of the tower, by two automatic rain gauges (one homemade and one model 52202, Young Company, Michigan, USA). Rainfall is partly intercepted by both leaves and woody plant surfaces and re-evaporated to the atmosphere. Interception is usually measured as the difference between the incident rainfall and rainfall reaching the ground, the latter being calculated as the sum of throughfall and stemflow (Herbst et al., 2008; Staelens et al., 2008).

For throughfall estimates (P_T, mm), seventeen manual rain gauges (funnels of 0.28 m diameter) were installed on the ground along three transects (Fig. 1). Readings were made about every two weeks and averaged separately under beech (P_{TB}) and Douglas-fir (P_{TD}). Two additional rain gauges also measured throughfall automatically, on a 30 min timescale, using a homemade tipping bucket connected to a CR800 datalogger (Campbell Scientific, Logan, UT, USA). The automatic rain gauges were used to calculate beech and Douglas-fir sub-stand throughfall on a rain event timescale. Rain events were separated by at least 6 h from each other, in order to take into account the storage capacity of the canopy. Firstly, these automatic measurements (average of the 2 automatic rain gauges) were calibrated for the beech and Douglas-fir stands, against the measurements made every two weeks (26 periods in 2010 and 2011). Secondly, P_{TB} and P_{TD}, obtained on a timescale of 30 min, were cumulated according to the rain events during the 2010 and 2011 growing seasons.

Stemflow (P_S, mm) was not measured in this study. In the literature, stemflow for beech was generally evaluated between 5% and 20% of P (Aussenac, 1968; Granier et al., 2000a; Staelens et al., 2008). For Douglas-fir, stemflow varies substantially with stand age. Rothacher (1963), found for an old Douglas-fir forest, stemflow <0.27%. Thus, considering the age and the structure of our stands, we assumed a value of 10% of rainfall (P, mm) for the beech (with a range of ±50% for the confidence interval assessment) and 1% for the Douglas-fir (with a range of ±100% for the confidence interval assessment).

Rainfall interception fluxes for the sub-stands were calculated at the rain event timescale as:

$$I_j = P - (P_{Sj} + P_{Tj}) \quad (3)$$

where the index j characterizes either beech (j = B) and Douglas-fir (j = D) sub-stands.

At the stand scale, the model of footprint was used at the rain event timescale (average of the contribution to the flux of each sub-stand for the event's duration), in view to calculate I_S (mm). As for transpiration fluxes, I_S was then calculated as the sum of I_B, I_D and I_C (use of I_D values for the mixed coniferous sub-stand), each weighted by the results of the footprint model.

Table 3
Sapwood area proportion (p), per circumference class (classes, cm) and per species (or group of species), used for the assessment of transpiration in each sub-stand (T_B, T_D, T_C). For the mixed coniferous sub-stand, Silver-firs benefiting from sap flow measurement (as beech and Douglas-fir) were separated from spruce and hemlock, for which Douglas-fir sap flow measurements were used (see text).

Beech		Douglas-fir		Mixed coniferous			
				Silver-fir		Spruce and Hemlock	
Classes	p	Classes	p	Classes	p	Classes	p
[40;110]	0.16	[110;340]	1	[40;280]	0.43	[40;300]	0.57
[110;210]	0.84						

2.3.3. Evapotranspiration of the soil and understory

In 2010–2011, the evapotranspiration of the soil and understory (ETu, mm) for beech (ETu_B) and Douglas-fir (ETu_D) were evaluated by the relationship used in BILJOU (Eq. (4); Granier et al., 1999), adapted at the 30 min timescale and using the direct evolution of the leaf area index (LAI) measured in the field. Global radiation measurements above the canopy (Rg, J cm^{-2}) and LAI were used to calculate global radiation reaching the soil (Rg_S, J cm^{-2}) using Beer-Lambert law (Monsi and Saeki, 1953).

$$ETu = 0.00055 * [Rg * e^{(-0.5 * LAI)}] \quad (4)$$

Evapotranspiration of the soil and understory at the stand scale was evaluated with the footprint model as the same way for interception. ETu_D was used for the evapotranspiration of the soil and understory of the mixed coniferous sub-stand (ETu_C).

2.4. Soil water budget method

Evapotranspiration was evaluated by the soil water budget method (ET_S, mm) as:

$$ET_{Sj} = P - Dr_{Mj} - \Delta EW_j \quad (5)$$

where ΔEW (mm) is the variation of soil water during the relevant period and the index j characterizes either beech (j = B) or Douglas-fir (j = D) sub-stands and Dr_M is the drainage modeled by BILJOU© (see Section 2.5). Indeed, this flux was not measured on the VTO site and was therefore missing for the use of the soil water budget method. At the sub-stand scale, extractable soil water was defined as the difference between actual soil water content (*W*, mm) and the minimum soil water content (W_m, the lower limit of water availability, i.e. at the permanent wilting point) in the rooted soil profile. The soil was separated into three horizontal layers according to soil horizon properties: 0–0.2, 0.2–0.6 and 0.6–1.3 m depth. In each soil layer under beech and Douglas-fir sub-stands, extractable water was calculated and then cumulated to a depth of 1.3 m. Actual soil water and minimum soil water were calculated for each layer l as:

$$W_l = \theta_l * h_l * (100 - RF_l)/100 \quad (6)$$

$$W_{ml} = \theta_{ml} * h_l * (100 - RF_l)/100 \quad (7)$$

where θ is the volumetric soil water (m^3 m^{-3}), θ_m the minimum volumetric soil water (i.e. at the permanent wilting point; pF 4.2), h the thickness of the soil layer (m) and RF its rock fraction (%). Volumetric soil water was measured under beech and Douglas-fir by means of two complementary systems, in order to characterize, *in fine*, both temporal and spatial variability. For temporal variability, θ was measured at 30 s time intervals and 30 min averages were calculated, using soil water reflectometers (CS615, Campbell Scientific, Logan, UT, USA). Sensors were placed in two vertical profiles, under both beech and Douglas-fir sub-stands. Each profile contained three sensors, at a depth of 0.2, 0.4 and 0.9 m. Data were logged and stored on a CR800 datalogger. For assessing spatial variability, a PR2 profile probe system (Delta T devices, Cambridge UK) was used. In each sub-stand, fifteen 0.4 m long access tubes were disposed vertically in the soil, spaced from 15 m on three measurement transects (5 tubes per transect and sub-stand; Fig. 1). Two 1 m-long access tubes were placed at about 1 m of the soil water reflectometer profiles. One measurement of θ (m^3 m^{-3}) was taken in the tubes every two weeks at a depth of 0.2, 0.4 and 0.9 m. In each sub-stand and at each depth, automatic measurements (daily average of CS615 measurements made at a 30 min timescale), were calibrated against a fortnightly average of PR2 system measurements (31 days in 2010–2011). Volumetric soil water in beech (θ_B) and Douglas-fir (θ_D), on a 30 min timescale was used in Eq. (6). The minimum volumetric soil water was determined in the laboratory for both beech and Douglas-fir, building a water retention curve for soil sampling (3–4 samples by depth and by sub-stands; Richards, 1941). During some rain events, automatic measurements showed some dysfunctions resulting in data loss. Variation of extractable water in soil (ΔEW) could take from one to several days, according to the occurrence of rain events and missing data and defining the SWB time step for comparison of methods. Stand evapotranspiration (ET_{SS}, mm) was calculated as the sum of ET_{SB} and ET_{SD}, weighted by the results of the footprint model (average of contribution to flux on the SWB time step). Results of Douglas-fir sub-stand were used to estimate mixed coniferous sub-stand fluxes.

The maximum extractable soil water (EW_M, mm), defined as the difference between soil water content at field capacity (W_F) and at the permanent wilting point (W_m), was estimated as 203 mm for the beech sub-stand, and 221 mm for the Douglas-fir, over a soil depth of 1.3 m for both. W_F was calculated in situ, based on θ_B and θ_D measurements made two days following significant rain events in winter (i.e. when evaporation was low, soil water content decreased from saturation to field capacity or slightly lower levels). The relative extractable water (REW), i.e. the ratio between EW and EW_M, was used as an index of water availability for trees (Granier et al., 1999). Soil water deficit was assumed to occur when REW dropped below the threshold of 0.4 (Granier et al., 1999) which induces stomatal regulation in trees.

2.5. Model: BILJOU©

The forest water balance model BILJOU© (Granier et al., 1999) was implemented at VTO for beech (broadleaved) and Douglas-fir sub-stands (coniferous). Using the above canopy daily meteorological measurements, the model calculates: (i) evapotranspiration fluxes ET_M (tree transpiration, T_M; understory evapotranspiration, ETu_M; rainfall interception, I_M) and (ii) soil water content (EW) and drainage (Dr_M). In the model, tree transpiration is calculated as a proportion of the potential evapotranspiration (Penman equation) and also depends on leaf area index (LAI). Stomatal regulation during water stress and LAI variation (the latter taking place only in the broadleaved stands) are modeled according to Granier et al. (1999, 2000b). The parameters needed to run the model characterizing the soil (three layers) and the vegetation are listed in Table 4, for both broadleaved and coniferous sub-stands. Fine root density (ρ_{roots}; diameter <3 mm) was determined over 1.3 m depth from trenches (4 repetitions for beech and 3 for Douglas-fir). For each soil profile, fine root intersects were counted using grids (100 cm × 100 cm or 120 cm × 120 cm), divided into cells of 100 cm^2 or 225 cm^2. Bulk

Table 4
Parameters of broadleaved (upper table) and coniferous (bottom table) sub-stands of the VTO, required by the BILJOU© model: dates of budburst and complete leaf fall (DOY, leafy period), maximum leaf area index (LAI_{max}) and for each soil layer, the depth (cm), the fine root density (ρ_{roots}, expressed in proportion of the total root density), the volumetric soil water content at the permanent wilting point (θm, $cm^3\,cm^{-3}$), the soil bulk density (ρ_s, $g\,cm^{-3}$) and the maximum extractable water (EW_M, mm).

Beech
Leafed period: DOY 112–310
$LAI_{max} = 5$

depth	ρ_{roots}	θ_m	ρ_S	EW_M
20	0.36	0.143	0.99	19.8
60	0.51	0.125	1.26	60.7
130	0.13	0.143	1.68	123

Coniferous
Leafed period: DOY 1–366
$LAI_{max} = 4.2$

depth	ρ_{roots}	θ_m	ρ_S	EW_M
20	0.534	0.105	1.03	30.5
60	0.454	0.107	1.13	73.2
130	0.012	0.143	1.66	117.0

soil density (ρ_s, $g\,cm^{-3}$) was assessed in the laboratory (cf. Section 2.4).

For the stand, modeled fluxes (ET_{MS}, T_{MS}, ETu_{MS} and I_{MS}) were calculated as the sum of modeled fluxes of beech (ET_{MB}, T_{MB}, ETu_{MB} and I_{MB}) and Douglas-fir (ET_{MD}, T_{MD}, ETu_{MD} and I_{MD}), weighted by the results of the footprint model (daily average of contribution to flux on a 30 min timescale). Modeled results of Douglas-fir were used for the mixed coniferous sub-stand.

2.6. Additional measurements, statistical analyses and uncertainties assessments

Leaf area index (LAI, i.e. the sum of one-sided leaf area per unit of ground area) was evaluated fortnightly, in 2010–2011, with a LAI-2200 device (Li-Cor, Lincoln, Nebraska, USA). Fifteen measurements were performed below canopy in each sub-stand, localized next to each PR2 access tubes (Section 2.4). Above-canopy reference measurements were made in a clearing localized within 500 m from the stand. The LAI-2200 considers five zenith angles simultaneously, through a fish-eye light sensor. In order to evaluate the LAI rather than the VAI (vegetation area index), only the three first zenith angles were used for data treatment (Dufrêne and Bréda, 1995). The maximum leaf area index (LAI_{max}), was calculated for each sub-stand by means of fortnightly measurements done during the month of June in 2010 and 2011 (Table 2). For the coniferous mixed stand, LAI_{max} was evaluated on one day in July 2012 (Table 2).

The meteorological measurements required for PET computation were measured at the top of the tower, at a 30 s time step and averaged over 30 min: global radiation (Rg, $J\,cm^2$; Kipp and Zonen CM5, Delft, The Netherlands), air temperature (Ta, °C) and humidity (RH, %; RHT2, Delta-T Devices Ltd, Cambridge, UK), water vapor deficit (D, hPa) and horizontal wind speed (ws, $m\,s^{-1}$; SOLENT 1012R2, Gill Instruments Ltd, Lymington, UK).

Statistical analyses of regressions and correlations between variables were performed with JMP® software (JMP® 10.0.2, SAS Institute Inc.), and R (Team, 2015). Uncertainties were computed for eddy covariance, analytic and soil water budget methods. First, major sources of uncertainties were identified (Table 5) then their impact on ET estimates were computed by using the classical error propagation law (Taylor, 1997):

$$\varepsilon_f = \sqrt{\left(\frac{\partial f}{\partial x_1}\varepsilon_1\right)^2 + \left(\frac{\partial f}{\partial x_2}\varepsilon_2\right)^2 + \left(\frac{\partial f}{\partial x_3}\varepsilon_3\right)^2 + \ldots} \quad (8)$$

Where ε_f is the uncertainty affecting the variable calculated as a function $f(x_1, x_2, x_3, x_4, \ldots)$ of variables x_j, each independently affected by an error ε_j.

3. Results

3.1. Environmental control of evapotranspiration fluxes

As expected, in the absence of soil water deficit (REW > 0.4; Fig. 2) transpiration and evapotranspiration fluxes were principally driven by meteorological factors (similar to PET; linear regression between T or ET_{EC} and PET: $R^2 \geq 0.78$, $p < 0.0001$). This correlation of fluxes with PET was clearly observed during the summer of 2010 around DOY 200, when a strong decrease in PET (Fig. 2a) induced a similar decrease in T and ET_{EC} (Fig. 2c and d). On average, for both years (Fig. 2), ET_{EC} represented 65% of PET, with a daily average of 1.8 mm per day^{-1}, while the stand transpiration (T_S) represented 50% of PET, with a daily average of 1.3 mm per day^{-1}. These results are consistent, since ET_{EC} includes, in addition to transpiration, interception plus understory evapotranspiration. At the sub-stand scale, T_B represented 58% of PET (daily average of 1.5 mm per day^{-1}), while T_D and T_C represented 40% and 38% of PET, respectively (1.1 and 1.0 mm per day^{-1}).

3.2. Evapotranspiration fluxes under dry foliage conditions

In order to test, under dry foliage conditions, the agreement between evapotranspiration fluxes either measured by EC (ET_{EC}) and the analytical method ($ET_{AS} = T_S + ETu_S$) or modeled ($ET_{MS} = T_{MS} + ETu_{MS}$), data were compared in 2010–2011 for days without rain, systematically removing the day following a rain event (Fig. 3). Estimates were close between each method, with the slopes of the regression lines of 0.91 for ET_{AS} = f (ET_{EC}) and 1.13 for ET_{MS} = f (ET_{EC}) and intercept of 0.09 and −0.23 respectively (Fig. 3a: $R^2 = 0.74$, $p < 0.0001$; Fig. 3b: $R^2 = 0.82$, $p < 0.0001$). Equality between ET_{EC} and ET_{AS} was not confirmed by statistical analysis (*t*-test; α = 0.05; p-value = 0.009), in contrary to equality between ET_{EC} and ET_{MS} (t-test; α = 0.05; p-value = 0.062). In these conditions (Fig. 3), $T_S + ETu_S$ (93% and 7% respectively) represented 95% of ET_{EC}, and $T_{MS} + ETu_{MS}$ (96% and 4% respectively) represented 108% of ET_{EC}. Equality between ET_{AS} and ET_{MS}, was not confirmed by statistical analysis, whereas considering all the days in 2010–2011, T_S and T_{MS} are statistically equal (Wilcoxon test; α = 0.05; p-value = 0.25). The error estimated on evapotranspiration fluxes measured by eddy covariance was about 9% on average, between the DOY 130 and 280. For transpiration fluxes, the error

Table 5
For eddy covariance, analytical and soil water budget methods, list of variables uncertainties and associated error estimator, taken into account for assessments of errors propagation.

Methods	Main uncertainty sources			Errors estimations
Eddy covariance	Randomness of turbulence		Richardson et al. (2012) $\varepsilon_A = 15.3 + 0.23 \times LE$ (W m^{-2})	
	High-frequency correction factor		Standard error function of relative humidity $\varepsilon_{EC} = 0.32 \times RH \times ET$ Derived from de Ligne et al. (2010)	
Analytic	Transpiration	Spatial variability of sap flux density (SFD)		Two times the standard error of the mean SFD, by sub-stand, measured on 30 min time step
		Sapwood area (As/Ag)		One unit on the last digit (Table 2)
	Interception	Incident rainfall (P)		Manufacturer margin error (Section 2.3.2.) : 2 % up to 25 mm/h, 3% up to 50 mm/h
		Stemflow (Ps)		Literature margin error (Section 2.3.2.): between 5% and 15% for beech and 0% and 2% for Douglas-fir
		Throughfall (Pt)	Spatial variability of throughfall	Two times the standard error of the mean throughfall, by sub-stand, measured on fortnightly time step
			Calibration of measurements at 30 min timescale	Two times the standard error of the regressions slopes for the mean throughfall by sub-stand in function of the mean of the 2 automatic raingauges
	Soil and understory evapotranspiration	Global radiation (Rg)		Manufacturer margin error (Section 2.6.): 5%
		Leaf area index (LAI)		Two times the standard error of the mean LAI, by sub-stand, measured on fortnightly time step
Soil water budget	Incident rainfall (P)		Manufacturer margin error (Section 2.3.2.) : 2 % up to 25 mm/h, 3% up to 50 mm/h	
	Soil water variations (ΔEW)	Spatial variability of volumetric soil water content	Two times the standard error of the mean volumetric soil water content, by sub-stand and soil layer, measured on fortnightly time step (PR2)	
		Calibration of measurements at 30 min timescale	Two times the standard error of the regressions slopes for the mean volumetric soil water content (PR2) in function of the daily mean of automatic measurement taken on 30 min time step (CS615), by sub-stand and soil layer	

proportional to the flux was evaluated at 21% of T_B, 16% of T_D and 30% of T_C. For the stand, according to species contributions on the footprint, error on transpiration was estimated at 17% of T_S. For ETu, the error was about 25% for the stand (25% for each sub-stand).

3.3. Throughfall and interception

The throughfall of the Douglas-fir sub-stand (P_{TD}) is 22% lower than in the beech sub-stand (P_{TB}), despite its lower LAI_{max} (Table 2). This results probably from a higher storage capacity of the canopy (Keim et al., 2006). On a fortnightly timescale, the throughfall coefficient of variation (CV) was larger for Douglas-fir (33% on average in 2010–2011) than for beech (22% on average), despite similar LAI CV. Coupling fortnightly measurements of throughfall with the measurements of two automatic raingauges on 30 min time step, allowed us to obtain assessments of throughfall on rain event time step. The errors (ε_{Pt}) on throughfall estimations for each sub-stand, based on this methodology, amounted to 16% and 12% for beech and Douglas-fir respectively. Errors on interception fluxes (ε_I) depended on errors on incident rainfall (ε_P), stemflow (ε_{PS}) and throughfall (ε_{PT}).

In beech, measured interception (I_B) represented 12% of cumulated rainfall over 2010 and 17% over 2011 (Table 6). We found in 2010, $\varepsilon_{IB} = 1.51 \times I_B$ and in 2011, $\varepsilon_{IB} = 0.96 \times I_B$. Interception loss, as modeled by BILJOU© for the beech sub-stand (I_{MB}), represented

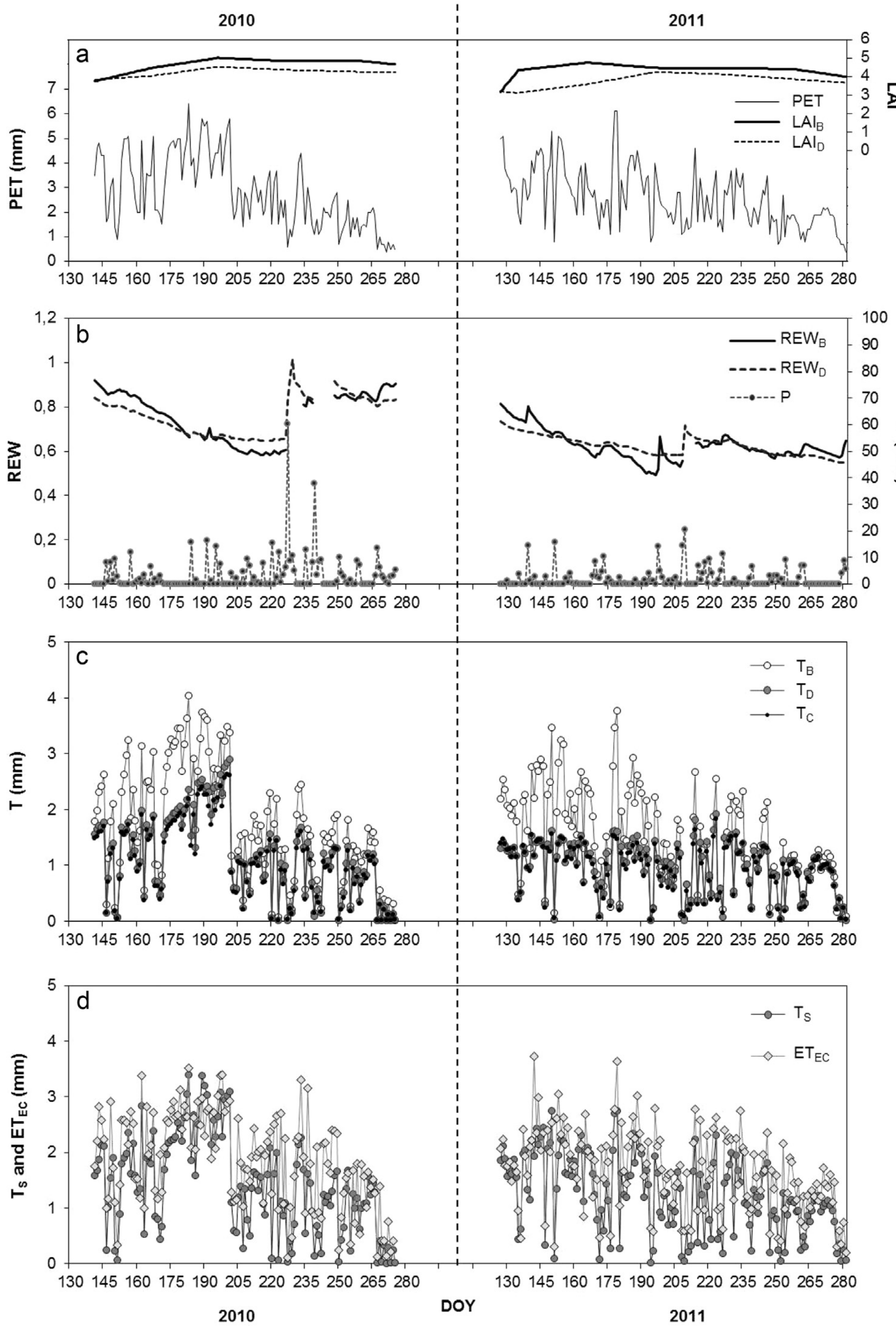

Fig. 2. Daily assessments in 2010 (DOY 141–275) and 2011 (DOY 127–281) of: (a) potential evapotranspiration (PET, mm) and leaf area index for beech (LAI_B) and Douglas-fir sub-stands (LAI_D); (b) measured relative extractable water for beech (REW_B) and Douglas-fir sub-stands (REW_D) and incident rainfall (P, mm); (c) sub-stand transpiration (T, mm) measured for beech (T_B), Douglas-fir (T_D) and mixed coniferous sub-stands (T_C); (d) stand transpiration (T_S, mm) and evapotranspiration measured by eddy covariance (ET_{EC}, mm).

+52% of I_B in 2010 and +76% in 2011 (23% of P over 2010–2011; Table 6).

In Douglas-fir, I_D represented 30% and 31% of P, with ratio ε_{ID}/I_D being respectively of 0.36 and 0.32, in 2010 and 2011 respectively. I_{MD} represented −37% of I_D in 2010 and +6% in 2011 (25% of P over 2010–2011; Table 6).

For the stand, I_S was about 18% (ε_{IS}/I_S = 0.62) in 2010 and 21% (ε_{IS}/I_S = 0.52) in 2011. I_{MS} represented +1 and +47% of I_S in 2010 and 2011 respectively. Over all the measurement period I_{MS} was of 24%.

We observed a strong effect of the intensity of incident rain on the measured interception loss at the rain event timescale. Indeed, over 2010 and 2011, I_B, I_D and I_S amounted to 22%, 40% and 28% respectively for P < 15 mm (Table 6) and to 2%, 15% and 7% respectively for P > 15 mm.

3.4. Stand scale evapotranspiration: comparison of methods

Measured stand transpiration, interception and evapotranspiration of soil and understory were added to estimate

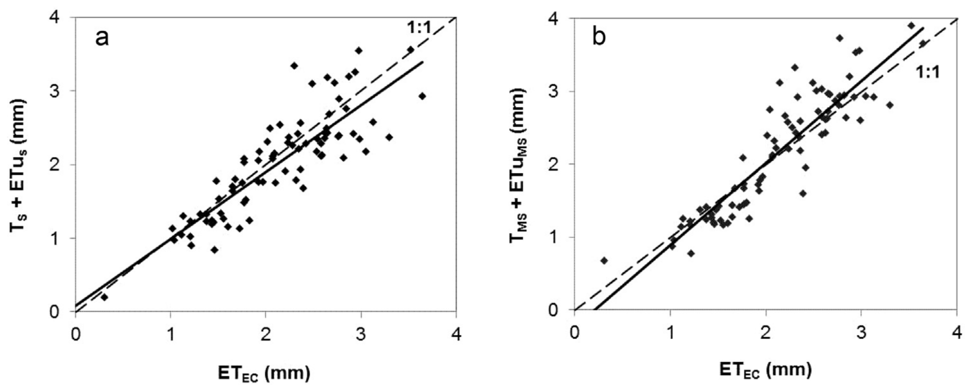

Fig. 3. Sum of the daily (a) measured stand transpiration by the thermal dissipation method (T_S, mm) and evapotranspiration of the soil and understory (ETu_S, mm) and (b) modeled transpiration (T_{MS}, mm) and evapotranspiration of the soil and understory (ETu_{MS}, mm) by BILJOU©, in relation to daily evapotranspiration fluxes measured by eddy covariance (ET_{EC}), for the days without rain and eliminating the day following a rain event, showing the linear regression line between T + ETu and ET_{EC} (see equation in the text). Periods considered: DOY 141–275 in 2010 and DOY 127–281 in 2011.

Table 6
Measured incident rainfall (P, mm), measured and modeled interception loss (mm) of beech and Douglas-fir sub-stands. Data are filtered for 2010–2011 according to P < or >15 mm. As measured interception was analyzed at the rain event timescale, and modeled interception at the daily timescale, proportions of P < or >15 mm differed according to the considered timescale. P < 15 mm concerned 61% of P at the rain events time step, and 73% of P at the daily timescale. Periods considered: DOY 171–274 in 2010, DOY 120–279 in 2011.

	Measured (rain event timescale)				Modeled (daily timescale)			
	2010	2011	2010–2011		2010	2011	2010–2011	
			P < 15 mm	P > 15 mm			P < 15 mm	P > 15 mm
Rainfall (P)	382	288	410	260	–	–	487	183
Interception beech	46	49	91	4	70	86	147	9
Interception Douglas-fir	113	89	164	38	71	95	157	9

ET_{AS}. Then, analytical and EC methods were compared on the timescale of the rain event (Fig. 4a). The regression gave $ET_{AS} = 0.90 \times ET_{EC} + 0.34$ ($R^2 = 0.90$; $p < 0.001$) and statistical analysis confirmed equality between the two estimates (Wilcoxon test; $\alpha = 0.05$; p-value = 0.087). The error on analytical assessments of ET was about 26% at the stand scale, largely influenced by the error on interception fluxes. For EC fluxes, the error was estimated for the vegetation season to 9% of ET_{EC} on average.

The SWB method was compared to the EC method at the timescale of the SWB time step (Fig. 4b) giving $ET_{SS} = 1.14 \times ET_{EC} + 0.70$ ($R^2 = 0.88$; $p < 0.001$). The difference between the two estimates was significant (*t*-test; $\alpha = 0.05$; *p*-value < 0.001). The error estimation on ET_{SS} (ε_{ETSS}), combining errors on incident rainfall (ε_P) and on variation of soil water ($\varepsilon_{\Delta EW}$), was about 9.5%. ET_{EC} and modeled evapotranspiration were compared on a daily timescale (Fig. 4c). The regression gave $ET_{MS} = 0.76 \times ET_{EC} + 0.65$ ($R^2 = 0.55$; $p < 0.001$). The difference between the two estimates was also significant (*t*-test; $\alpha = 0.05$; p-value < 0.001).

Comparison of analytical method with modeled evapotranspiration (Fig. 5a) or with SWB method (Fig. 5b) gave also consistent results. For ET_{AS} and ET_{MS}, aggregations of rain events (ET_{AS}) or of daily values (ET_{MS}) were done to obtain an equivalent timescale, at the lower temporal timescale as possible. Equality between ET_{AS} and ET_{MS} (Fig. 5a) or ET_{SS} (Fig. 5b) were confirmed by statistical analysis (*t*-test; $\alpha = 0.05$; p-value = 0.33 and p-value = 0.12 for Fig. 5a and b respectively).

Despite quite a high spatial variability in soil water content measurements, data scatter of the relationships between the SWB method and analytical or EC methods is rather low. On average, coefficients of variation of measured soil water content were 42% and 43% at a depth of 20 and 40 cm respectively in the beech sub-stand, and 49% and 37% in the Douglas-fir sub-stand. At a depth of 90 cm, the coefficients of variation were lower, at 20% and 15% respectively. There was no difference between ε_{EW} of beech and Douglas-fir, amounting respectively to 18% and 20%.

A focus was done on ET fluxes for P > 0 mm (Fig. 6) when the time step allowed it, i.e. for analytical and EC methods and model. ET_{AS} and ET_{MS} were expressed in function of ET_{EC} (Fig. 6a and b respectively). Regression obtained between ET_{MS} and ET_{EC} with $R^2 = 0.61$ is better than between ET_{AS} and ET_{EC} ($R^2 = 0.29$). Removing data for $ET_{AS} > 4$ mm, did not improve the relationship with ET_{EC}. In the two cases, ET_{EC} tent to be lower than the other estimations. Differences between the estimates of ET were mainly caused by interception fluxes estimates, measured or modeled, and the timescale used. For several rain events in Fig. 6a, values of ET_{EC} near to 0, corresponded to values of ET_{AS} until 2 mm. The discrepancy of data in Fig. 6b was lower for this range of values. At the time step of rain event, some events could occur principally during night conditions, during which measured interception seemed not to be taken taking into account by EC in some cases. Measured (I_S) and modeled (I_{MS}) were compared for aggregated rain events or daily values (Fig. 6c). I_{MS} tend to be greater than I_S. The observed higher values of I_S, were mainly due to high interception fluxes measured for Douglas-fir in 2010.

At the stand scale, the four methods were compared (Fig. 7). The ET average for all the methods was 174 mm in 2010 and 265 mm in 2011, equivalent in both years to a daily ET of 1.9 mm d^{-1}. In both years, the lowest estimate was provided by the EC method (−12% and −9% lower than average), but the values are largely contained in the errors bars of analytical method. EC remained inferior to model for the two years, even taking into account error margin of ET_{EC}. Using the model, annual values of ET_{MS} (from January to December) were 14% larger in 2010 and 9% in 2011 than ET_{EC} (354.5 mm in 2010 and 353.6 mm in 2011). In both years, the highest estimates of ET were provided by the SWB method (+6% and +9% higher than

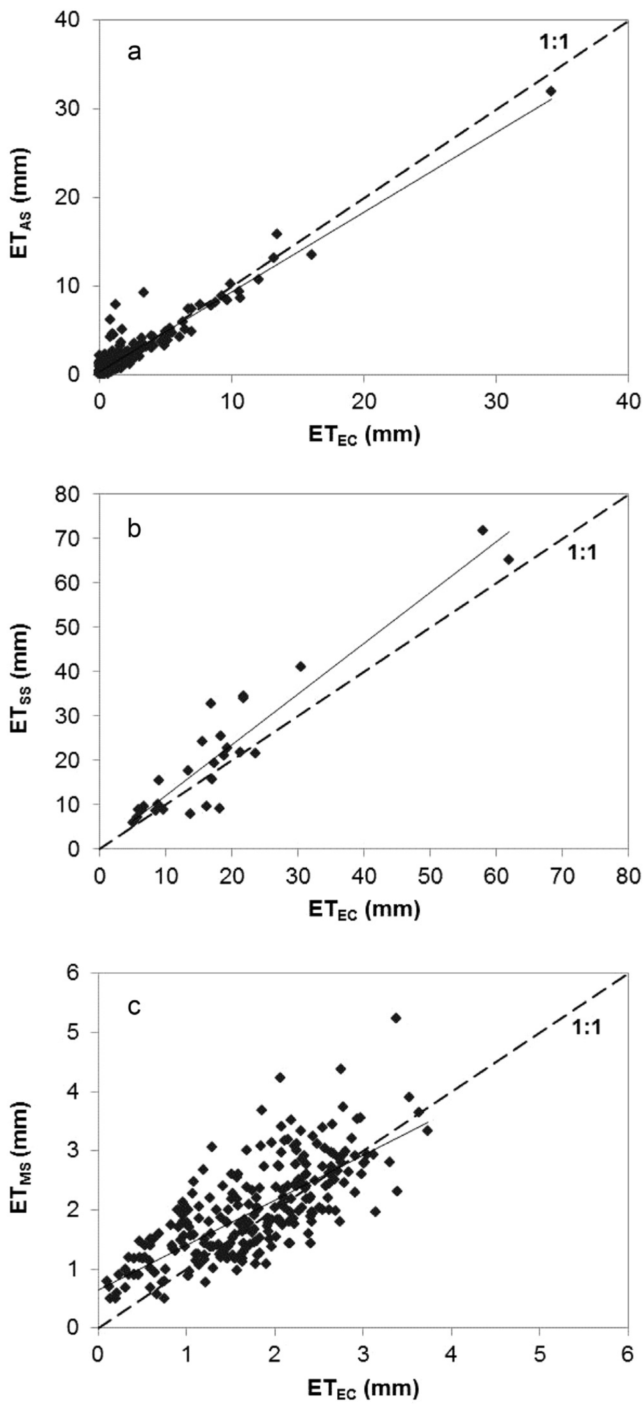

Fig. 4. Stand evapotranspiration in mm, (a) with the analytical method (ET_{AS}), (b) with soil water budget method (ET_{SS}) and (c) modeled (ET_{MS}) as a function of eddy covariance method (ET_{EC}, mm), assessed on the rain event, soil water budget and daily timescale for (a), (b) and (c) respectively. See in the text for equations of linear regressions obtained in (a), (b) and (c). Measurement periods for (a) and (c): DOY 172–275 in 2010 and DOY 130–281 in 2011; for (b): DOY 157–287 in 2010 and DOY 130–288 in 2011.

the average) equivalent in 2010 to analytical method and to model (Fig. 7).

In the analytical method, T_S, I_S and ETu_S represented 64%, 32% and 4% of ET_{AS} in 2010 and 71%, 23% and 6% in 2011 (Fig. 7). Based on modeling and on the annual timescale, T_{MS}, I_{MS} and ETu_{MS} represented 56%, 34% and 10% of ET_{MS} respectively in 2010, and 61%, 30% and 9% respectively in 2011.

4. Discussion

4.1. Tree transpiration

Our measurements of SFD were in the range of values observed for beech (daily maximum of 30–80 g m^{-2} s^{-1}) in Granier et al. (2000a), Hölscher et al. (2005), Lüttschwager and Remus (2007); for Douglas-fir (daily maximum of 29–40 g m^{-2} s^{-1}) in Domec et al. (2006), Phillips et al. (2002), Fernández et al. (2009); and for Silver-fir (daily maximum of 10–30 g m^{-2} s^{-1}) in Fiora and Cescatti (2006). Seasonal beech sub-stand transpiration was in the range of annual values reported by Schipka et al. (2005) in central Europe (from 213 to 421 mm). No similar study was found in central Europe for mature Douglas-fir. The sub-stand transpiration measurements could be improved to some extent by the measurement of SFD for other species, particularly for spruce. However, the potential error on stand transpiration was little affected with regard to the error on the mixed coniferous sub-stand, due to its moderate participation in the footprint.

Modeled transpiration fluxes were comparable to measured values and literature. The model BILJOU© was validated in several studies for beech and Douglas fir (Granier et al., 1999; Granier et al., 2002). On the sub-stand scale, excepted for the Douglas-fir in 2011 (−12% of T_{MD}), modeled transpiration is lower than measured one, but differences did not exceed −14% of measured transpiration.

4.2. Rainfall interception

Interception estimates were shown to be inferior to in other studies, in particular for beech. Indeed values around 20–25% are generally reported for beech stands (Aussenac, 1968; Aussenac and Boulangeat, 1980; Gerrits et al., 2010; Granier et al., 2000a; Staelens et al., 2008). For the Douglas-fir sub-stand, measured interception is closer to the range of 35–40% found in the literature (Aussenac and Boulangeat, 1980; Robins, 1974; Rutter et al., 1975; Tiktak and Bouten, 1994). With interception calculated for P < 15 mm of 20% and 40% for beech and Douglas-fir respectively, we obtained globally more consistent results.

However, for beech errors on measured interception fluxes remained high. For several rain events, particularly when P > 10 mm, the sum of throughfall and stemflow appeared to be superior to the incident rainfall. The interception was forced to 0. When the interception was forced to 0, but associated with non-negligible errors on throughfall, the error on I increased considerably in comparison to the cumulated I. Validity of P was checked with the data of a Belgium network meteorological station located near the VTO site (about 6 km). Taking into account to 10% of stemflow for the estimation of I, it seemed that we can assumed an overestimation of throughfall for the beech sub-stand. In case where the interception is estimated with the minimal values of throughfall (mean minus the error) we obtain a "maximal" interception. We can observe for beech that the interception estimates of BILJOU© correspond more to the maximum estimates of measured interception than to the mean estimates. For the Douglas-fir it's the opposite. Concerning the model, assessments for beech were in the range of literature and superior to measured interception. Then for beech we may assumed that in average the interception is underestimated.

For Douglas-fir, the errors found for throughfall were smaller than for beech. Associated with values of interception generally superior to 0, the ratio ε_{ID}/I_D remained high, but largely inferior to the one observed for beech. Concerning the model, as for measured interception, I_{MD} was lower than the 35–40% usually found. Globally, measurements for Douglas-fir seemed to be more consistent than for beech, despite the use of the same methodology for the two sub-stands. However, a substantial difference between mea-

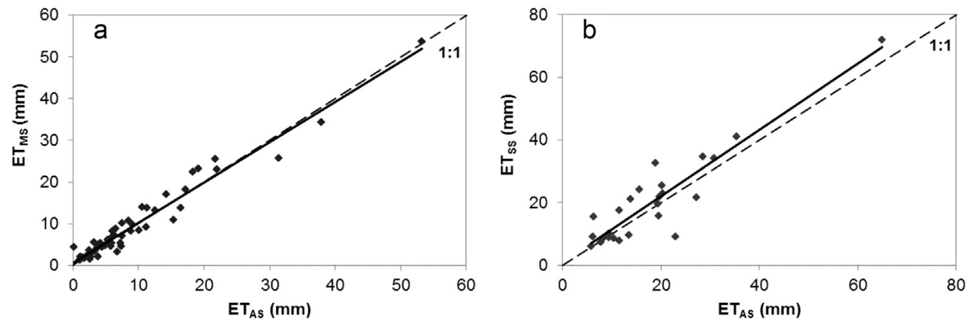

Fig. 5. Stand evapotranspiration in mm, (a) modeled (ET_{MS}) and (b) with soil water budget method (ET_{SS}) as a function of analytical method (ET_{AS}, mm), assessed (a) at time step aggregating rain event and daily values (see text) and (b) at SWB time step. The linear regression obtained is: (a) $ET_{MS} = 0.966 \times ET_{AS} + 0.601$ ($R^2 = 0.953$); (b) $ET_{SS} = 1.063 \times ET_{AS} + 0.706$ ($R^2 = 0.847$). Measurement periods for (a): DOY 172–275 in 2010 and DOY 130–281 in 2011; and (b): DOY 184–287 in 2010 and DOY 130–277 in 2011.

sured and model interception (−43 mm for model) was observed in 2010, but which was mainly due to the period from DOY 227 to DOY 243 (23 mm) during which a high amount of rainfall had been monitored (166 mm). With regards to the literature, the measurements under these extreme conditions (P > 45 mm for one rain event) seemed to be overestimated. The interception should more tend towards 0.

Taking into account all the results and literature, we conclude to an underestimation of interception for beech probably caused by a lack of spatial variability characterization of throughfall. A more intensive network of raingauges in view to decrease throughfall CV (Gerrits et al., 2010), and a spatial and temporal variability assessed both on a 30 min timescale should lead to more consistent results in interception fluxes. For stand interception at seasonal scale in 2010, modeled interception I_{MS} was equivalent to measured I_S (64 mm and 59 mm respectively). Considering modeled interception as correct, underestimation of beech and overestimation of Douglas-fir are compensated. In 2011, the difference between I_{MS} and I_S was larger (86 mm and 59 mm respectively), caused by the underestimation of beech interception. Then, at the stand scale, modeled interception is more reliable for ET assessments.

4.3. Comparison among ET estimates

Estimates of ET for the whole stand provided by the four methods were close (Figs. 2–5, 7). Based on seasonal time step and on uncertainties estimations, all the methods gave similar estimates and differences observed in the range of 5–15% can be assumed to be not significant. Granier et al. (2000a), Wilson et al. (2001), Oishi et al. (2008) and Schwärzel et al. (2009), found good agreement in the same order of magnitude, both on several days of measurements, as well as seasonally and annually, using one to several methods of ET estimates implemented in this study. In contrast, Cuenca et al. (1997) and Moore et al. (2000) reported ET_S values 60% lower than eddy covariance measurements.

For accurate stand transpiration estimates from sapflow measurements, species composition and distribution, sapwood area and radial profile of sap flux, are the key variables for upscaling. For interception fluxes, a high number of raingauges under the canopy and of collar around the trunks, remaining laborious measurements, are needed to characterize properly the throughfall and the stemflow. For the SWB method, an accurate estimate of ET depends on the degree of characterization of the soil's heterogeneity and the assessment of drainage. For the modeling approach, the limits are linked to the simplification of the components and the functioning of the ecosystems and to the relevance of the parametrization. For the EC method, they are mainly linked to the loss of fluxes and gap-filling routines.

The analytical method was previously discussed through specific analysis of transpiration and interception fluxes (Sections 4.1 and 4.2). For this method uncertainties were large, about 30% and 23% for 2010 and 2011, due principally to interception uncertainties. In 2011, in view to probable underestimation of I_S, we can assumed than ET_{AS} is probably underestimated too, and should be closer to model value. Despite that, equality was confirmed on different time step, between ET_{AS} and ET_{EC}, ET_{SS} and ET_{MS}.

The soil water budget method and modeling were not independent, since we used modeled drainage for the first one. Concerning soil water content measurements, in the first 40 cm of soil layer, the measured variability was quite large in comparison to the literature (Buttafuoco and Castrignanò, 2005; Schume et al., 2003; Schwärzel et al., 2009), probably due to the large spatial heterogeneity in such old stands. It still remains similar to that observed by Schwärzel et al. (2009) under spruce. The sampling protocol may possibly explain the higher measured variability in Vielsalm, with about 15 m between the measurement points. The uncertainties on the ET_{SS} estimates are weak, and in the same range than ET_{EC} over 2010 and 2011, but are not taking into account uncertainties on drainage. We can assume that they are in reality larger, overlap more with error on eddy covariance (Fig. 7).

The comparisons of the EC method with the other methods were very satisfactory but pointed out a slight underestimation of ET_{EC} during wet conditions. Indeed, from the rain event to the seasonal scale, ET_{EC} tends to be lower than ET_{AS}, ET_{SS} and ET_{MS} (Figs. 4, 6 and 7 and Section 3.4), whereas estimations during dry foliage conditions between ET_{EC} and ET_{AS} were similar and equality being confirmed between ET_{EC} and ET_{MS} (Fig. 3). Granier et al. (2000a) and Oishi et al. (2008) also found better relationships for days without rain between EC and analytical methods. Then, at the seasonal scale (Fig. 7), remaining similar to others ET estimates, it is likely that EC estimates are located more around the higher values of the associated errors bars. Estimates of the error on EC fluxes take into account the problem of the use of high frequency correction factor of CO_2 for water vapor fluxes.

From seasonal to annual scale, estimations of ET and flux partitioning were similar between beech and Douglas-fir substands. These results were in agreement with Aussenac (1972) and Aussenac and Boulangeat (1980), supporting the theory of conservation of evapotranspiration flux in a given site (mainly driven by weather), regardless of species, size or age of the stands (Jarvis and McNaughton, 1986; Roberts, 1983).

5. Conclusion

The methods implemented in this study provided complementary information to characterize the evapotranspiration components of a mixed forest. Good agreements were obtained

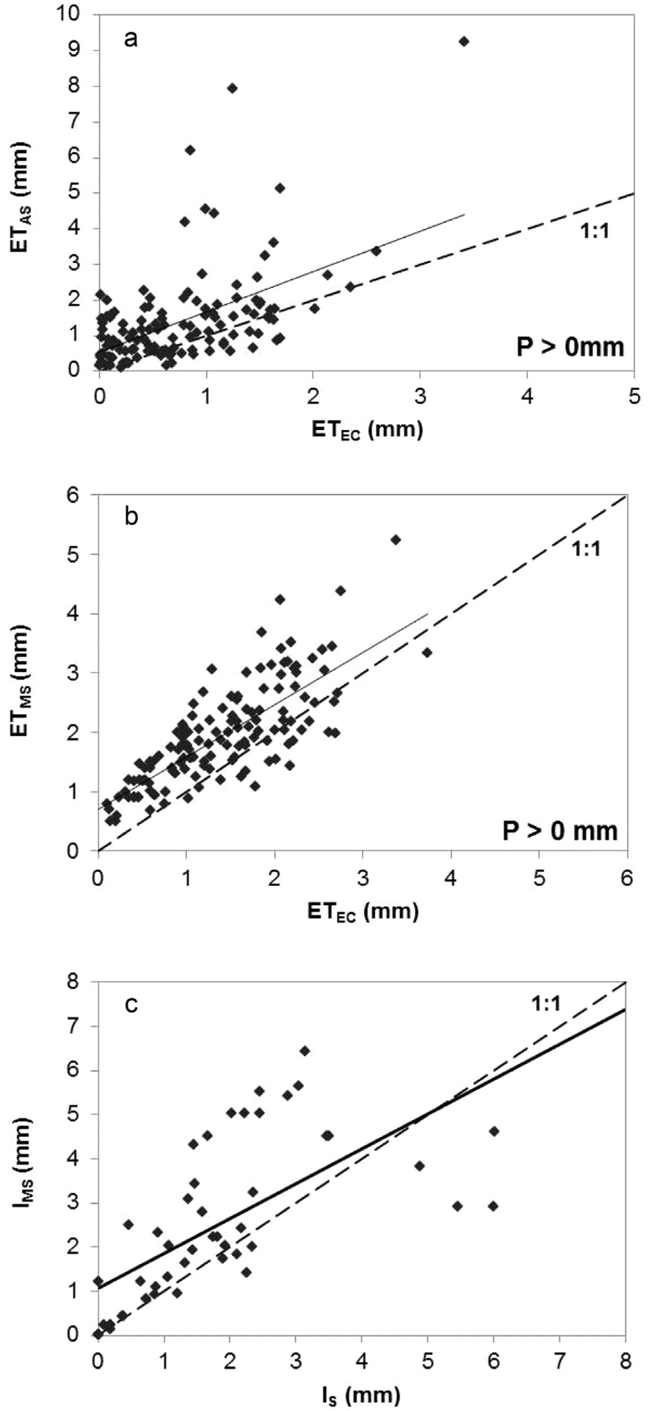

Fig. 6. Stand evapotranspiration in mm, (a) with the analytical method (ET_{AS}), and (b) modeled (ET_{MS}) as a function of eddy covariance method (ET_{EC}, mm), assessed at the rain event and daily timescale for (a) and (b) respectively, and for P > 0 mm. The linear regressions obtained are: (a) $ET_{AS} = 1.140 \times ET_{EC} + 0.526$ ($R^2 = 0.291$); (b) $ET_{MS} = 0.884 \times ET_{EC} + 0.700$ ($R^2 = 0.608$). In (c) stand modeled interception (I_{MS}, mm) is expressed in function of stand measured interception (I_S, mm) on aggregation time step of rain event and daily values (see text). Linear regression: $I_{MS} = 0.790 \times I_S + 1.071$ ($R^2 = 0.70$). Measurement period for (a) and (c): DOY 172–275 in 2010 and DOY 130–281 in 2011; for (b): DOY 157–287 in 2010 and DOY 130–288 in 2011.

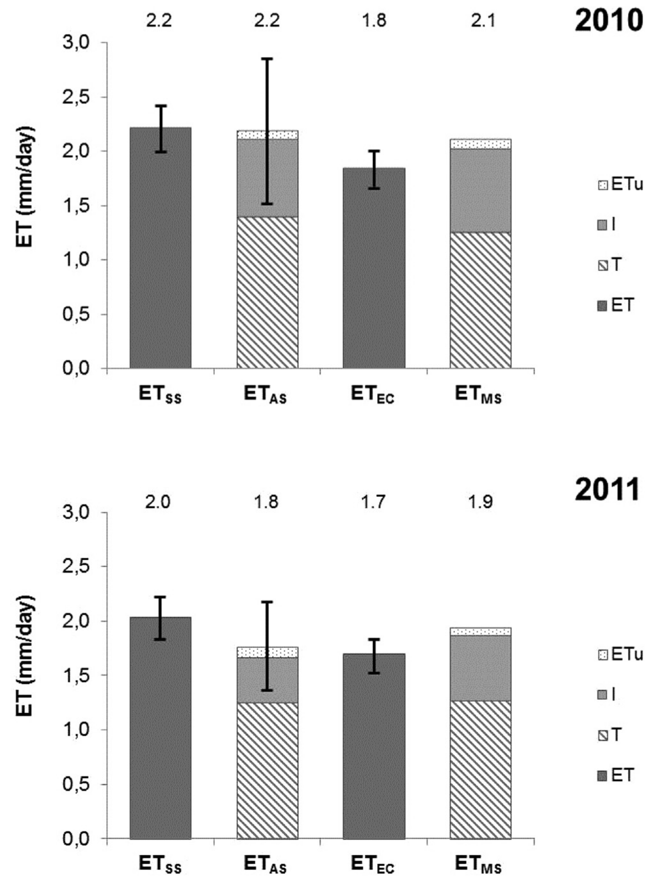

Fig. 7. Mean daily ET (mm/day) and errors (vertical bars, mm/day) in 2010 (top, DOY 184–266) and 2011 (bottom, DOY 166–277) for the stand, obtained with the different methods: soil water budget (ET_{SS}), analytical (ET_{AS}), eddy covariance (ET_{EC}) and model (ET_{MS}). When possible, ET was divided between tree transpiration (T, mm), interception loss (I, mm) and soil and understory evapotranspiration (ET_u, mm). Values of mean daily ET in each case are indicated at the top of the bars.

between the different methods of ET evaluation, whether on seasonal or annual timescales. Uncertainties on eddy covariance, analytical and soil water budget methods were calculated taking into account for each method the main sources of measurements and processing errors. Analytical method is the method with the higher uncertainties on results, 26% on average over 2010–2011, linked more to high uncertainties on interception fluxes than to transpiration. For the two other methods, uncertainties are estimated at 9–10%. Analytical method requires complex measurement systems, hardly designed for long term measurements, in particular in view to increase the estimates confidence intervals. However, this method is invaluable for the understanding of forest water cycle and to validate EC measurements.

On average over 2010–2011, ET estimates were closer between SWB method (81% of PET) and model (77% of PET), highlighting a slight underestimation of analytical method principally in 2011, due to interception fluxes (69% of PET for 83% in 2010), and also of EC method (68% of PET) most probably under rainy conditions. Indeed, during dry foliage conditions, eddy covariance measurements are mainly composed of transpiration fluxes.

Regardless of the methods, the characterization of water fluxes during rainy conditions seemed to be more complex than for dry foliage conditions. Their contribution to ET fluxes is often less important than during dry conditions, but poor evaluation during these periods may lead to significant errors in ET assessment on a seasonal or annual timescale.

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References

Čermák, J., Deml, M., Penka, M., 1973. A new method of sap flow rate determination in trees. Biol. Plantarum 15 (3), 171–178.
Aubinet, M., et al., 2000. Estimates of the annual net carbon and water exchange of forests. EUROFLUX Methodol., 113–175.
Aubinet, M., et al., 2001. Long term carbon dioxide exchange above a mixed forest in the Belgian Ardennes. Agric. For. Meteorol. 108 (4), 293–315.
Aubinet, M., Heinesch, B., Longdoz, B., 2002. Estimation of the carbon sequestration by a heterogeneous forest: night flux corrections, heterogeneity of the site and inter-annual variability. Global Change Biol. 8 (11), 1053–1071.
Aubinet, M., Heinesch, B., Perrin, D., Moureaux, C., 2005. Discriminating net ecosystem exchange between different vegetation plots in a heterogeneous forest. Agric. For. Meteorol. 132 (3–4), 315–328.
Aussenac, G., Boulangeat, C., 1980. Interception des précipitations et évapotranspiration réelle dans des peuplements de feuillu (Fagus silvatica L.) et de résineux (Pseudotsuga menziesii (Mirb) Franco). Ann. For. Sci. 37 (2), 91–107.
Aussenac, G., 1968. Interception des précipitations par le couvert forestier. Ann. Sci. For. 25 (3), 135–156.
Aussenac, G., 1972. Étude de l'évapotranspiration réelle de quatre peuplements forestiers dans l'Est de la France. Ann. Sci. For. 29 (3), 369–389.
Bovard, B.D., Curtis, P.S., Vogel, C.S., Su, H.B., Schmid, H.P., 2005. Environmental controls on sap flow in a northern hardwood forest. Tree Physiol. 25 (1), 31–38.
Buttafuoco, G., Castrignanò, A., 2005. Study of the spatio-temporal variation of soil moisture under forest using intrinsic random functions of order *k*. Geoderma 128 (3), 208–220.
Clement, R.J., 2005. Mass and Energy Exchange of a Plantation Forest in Scotland Using Micrometeorological Methods. University of Edinburgh.
Cuenca, R.H., Stangel, D.E., Kelly, S.F., 1997. Soil water balance in a boreal forest. J. Geophys. Res. 102 (D24), 29355–29365.
Do, F., Rocheteau, A., 2002. Influence of natural temperature gradients on measurements of xylem sap flow with thermal dissipation probes. 1. Field observations and possible remedies. Tree Physiol. 22 (9), 641–648.
Domec, J.C., Meinzer, F.C., Gartner, B.L., Woodruff, D., 2006. Transpiration-induced axial and radial tension gradients in trunks of Douglas-fir trees. Tree Physiol. 26 (3), 275–284.
Dufrêne, E., Bréda, N., 1995. Estimation of deciduous forest leaf area index using direct and indirect methods. Oecologia 104 (2), 156–162.
Ewers, B.E., Oren, R., Kim, H.S., Bohrer, G., Lai, C.T., 2007. Effects of hydraulic architecture and spatial variation in light on mean stomatal conductance of tree branches and crowns Plant. Cell Environ. 30 (4), 483–496.
Fernández, M.E., Gyenge, J., Schlichter, T., 2009. Water flux and canopy conductance of natural versus planted forests in Patagonia, South America. Trees Struct. Funct. 23 (2), 415–427.
Fiora, A., Cescatti, A., 2006. Diurnal and seasonal variability in radial distribution of sap flux density: implications for estimating stand transpiration. Tree Physiol. 26 (9), 1217–1225.
Ford, C.R., Hubbard, R.M., Kloeppel, B.D., Vose, J.M., 2007. A comparison of sap flux-based evapotranspiration estimates with catchment-scale water balance. Agric. For. Meteorol. 145 (3–4), 176–185.
Gerrits, A.M.J., Pfister, L., Savenije, H.H.G., 2010. Spatial and temporal variability of canopy and forest floor interception in a beech forest. Hydrol. Process. 24 (21), 3011–3025.
Granier, A., et al., 1990. Vapour flux density and transpiration rate comparisons in a stand of Maritime pine (Pinus pinaster Ait.) in Les Landes forest. Agric. For. Meteorol. 51 (3–4), 309–319.
Granier, A., Bréda, N., Biron, P., Villette, S., 1999. A lumped water balance model to evaluate duration and intensity of drought constraints in forest stands. Ecol. Modell. 116 (2–3), 269–283.
Granier, A., Biron, P., Lemoine, D., 2000a. Water balance, transpiration and canopy conductance in two beech stands. Agric. For. Meteorol. 100 (4), 291–308.
Granier, A., Loustau, D., Bréda, N., 2000b. A generic model of forest canopy conductance dependent on climate, soil water availability and leaf area index. Ann. For. Sci. 57 (8), 755–765.
Granier, A., Pilegaard, K., Jensen, N.O., 2002. Similar net ecosystem exchange of beech stands located in France and Denmark. Agric. For. Meteorol. 114 (1–2), 75–82.
Granier, A., et al., 2003. Deciduous forests: carbon and water fluxes, balances and ecophysiological determinants. In: Valentini, R. (Ed.), Fluxes of Carbon, Water and Energy of European Forests. Ecological Studies. Springer, Berlin, Heidelberg, pp. 55–70.
Granier, A., 1985. Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. Ann For. Sci. 42 (2), 193–200.
Granier, A., 1987. Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. Tree Physiol. 3 (4), 309–320.
Grelle, A., Lindroth, A., 1996. Eddy-correlation system for long-term monitoring of fluxes of heat, water vapour and CO2. Global Change Biol. 2 (3), 297–307.
Hölscher, D., Koch, O., Korn, S., Leuschner, C., 2005. Sap flux of five co-occurring tree species in a temperate broad-leaved forest during seasonal soil drought. Trees 19 (6), 628–637.
Herbst, M., Rosier, P.T.W., McNeil, D.D., Harding, R.J., Gowing, D.J., 2008. Seasonal variability of interception evaporation from the canopy of a mixed deciduous forest. Agric. For. Meteorol. 148 (11), 1655–1667.
Ibrom, A., Dellwik, E., Flyvbjerg, H., Jensen, N.O., Pilegaard, K., 2007. Strong low-pass filtering effects on water vapour flux measurements with closed-path eddy correlation systems. Agric. For. Meteorol. 147 (3–4), 140–156.
Jarvis, P.G., McNaughton, K.G., 1986. Stomatal control of transpiration scaling up from leaf to region. Adv. Ecol. Res., 1–49.
Köstner, B., Biron, P., Siegwolf, R., Granier, A., 1996. Estimates of water vapor flux and canopy conductance of Scots pine at the tree level utilizing different xylem sap flow methods. Theor. Appl. Climatol. 53 (1–3), 105–113.
Keim, R.F., Skaugset, A.E., Weiler, M., 2006. Storage of water on vegetation under simulated rainfall of varying intensity. Adv. Water Resour. 29 (7), 974–986.
Kormann, R., Meixner, F.X., 2001. An analytical footprint model for non-neutral stratification. Boundary Layer Meteorol. 99 (2), 207–224.
Lüttschwager, D., Remus, R., 2007. Radial distribution of sap flux density in trunks of a mature beech stand. Ann For. Sci. 64 (4), 431–438.
Laffineur, Q., et al., 2011. Isoprene and monoterpene emissions from a mixed temperate forest. Atmos. Environ. 45 (18), 3157–3168.
Leuning, R., Judd, M.J., 1996. The relative merits of open- and closed-path analysers for measurement of eddy fluxes. Global Change Biol. 2 (3), 241–253.
Longdoz, B., Yernaux, M., Aubinet, M., 2000. Soil CO2 efflux measurements in a mixed forest: impact of chamber disturbances, spatial variability and seasonal evolution. Global Change Biol. 6 (8), 907–917.
Lu, P., Biron, P., Breda, N., Granier, A., 1995. Water relations of adult Norway spruce (Picea abies (L.) Karst) under soil drought in the Vosges mountains: water potential, stomatal conductance and transpiration. Ann. Sci. For. 52 (2), 117–129.
Massman, W., Ibrom, A., 2008. Attenuation of concentration fluctuations of water vapor and other trace gases in turbulent tube flow. Atmos. Chem. Phys. 8 (20), 6245–6259.
Meiresonne, L., et al., 2003. Water flux estimates from a Belgian Scots pine stand: a comparison of different approaches. J. Hydrol. 270 (3–4), 230–252.
Moncrieff, J.B., et al., 1997. A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. J. Hydrol. 188–189 (1–4), 589–611.
Monsi, S., Saeki, T., 1953. Über den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung für die Stoffproduktion. J. Jpn. Bot. 14, 22–52.
Moore, K.E., Fitzjarrald, D.R., Sakai, R.K., Freedman, J.M., 2000. Growing season water balance at a boreal jack pine forest. Water Resour. Res. 36 (2), 483–493.
Nadezhdina, N., Čermák, J., Nadezhdin, V., 1998. Heat field deformation method for sap flow measurements. In: ˇCermák, J., Nadezhdina, N. (Eds.), Proceedings of the 4th International Workshop on Measuring Sap Flow in Intact Plants. Publishing House of Mendel University, Czech Republic, pp. 72–92.
Neftel, A., Spirig, C., Ammann, C., 2008. Application and test of a simple tool for operational footprint evaluations. Environ. Pollut. 152 (3), 644–652.
Oishi, A.C., Oren, R., Stoy, P.C., 2008. Estimating components of forest evapotranspiration: a footprint approach for scaling sap flux measurements. Agric. For. Meteorol. 148 (11), 1719–1732.
Oren, R., Phillips, N., Katul, G., Ewers, B.E., Pataki, D.E., 1998. Scaling xylem sap flux and soil water balance and calculating variance: a method for partitioning water flux in forests. Ann. Sci. For. 55 (1–2), 191–216.
Oren, R., Phillips, N., Ewers, B.E., Pataki, D.E., Megonigal, J.P., 1999. Sap-flux-scaled transpiration responses to light, vapor pressure deficit, and leaf area reduction in a flooded Taxodium distichum forest. Tree Physiol. 19 (6), 337–347.
Phillips, N., Bond, B.J., McDowell, N.G., Ryan, M.G., 2002. Canopy and hydraulic conductance in young, mature and old Douglas-fir trees. Tree Physiol. 22 (2–3), 205–211.
Richards, L.A., 1941. A pressure-Membrane extraction apparatus for soil solution. Soil Sci. 51 (5), 377–386.
Richardson, A.D., et al., 2012. Uncertainty Quantification, Eddy Covariance. Springer, pp. 173–209.
Roberts, J., 1983. Forest transpiration: a conservative hydrological process? J. Hydrol. 66 (1–4), 133–141.
Robins, P., 1974. A method of measuring the aerodynamic resistance to the transport of water vapour from forest canopies. J. Appl. Ecol., 315–325.
Rothacher, J., 1963. Net precipitation under a douglas-Fir forest. For. Sci. 9 (4), 423–429.
Rutter, A.J., Morton, A.J., Robins, P.C., 1975. A predictive model of rainfall interception in forests. II. Generalization of the model and comparison with observations in some coniferous and hardwood stands. J. Appl. Ecol. 12, 367–380.

Saugier, B., Granier, A., Pontailler, J.Y., Dufrêne, E., Baldocchi, D.D., 1997. Transpiration of a boreal pine forest measured by branch bag, sap flow and micrometeorological methods. Tree Physiol. 17 (8–9), 511–519.
Schipka, F., Heimann, J., Leuschner, C., 2005. Regional variation in canopy transpiration of Central European beech forests. Oecologia 143 (2), 260–270.
Schume, H., Jost, G., Katzensteiner, K., 2003. Spatio-temporal analysis of the soil water content in a mixed Norway spruce (Picea abies (L.) Karst.)–European beech (Fagus sylvatica L.) stand. Geoderma 112 (3–4), 273–287.
Schwärzel, K., et al., 2009. Soil water content measurements deliver reliable estimates of water fluxes: a comparative study in a beech and a spruce stand in the Tharandt forest (Saxony, Germany). Agric. For. Meteorol. 149 (11), 1994–2006.
Staelens, J., De Schrijver, A., Verheyen, K., Verhoest, N.E.C., 2008. Rainfall partitioning into throughfall, stemflow, and interception within a single beech (Fagus sylvatica L.) canopy: influence of foliation, rain event characteristics, and meteorology. Hydrol. Process. 22 (1), 33–45.
Taylor, J.R., 1997. An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements. University Science Books.
Team, R.C., 2015. R: A Language and Environment for Statistical Computing [Internet]. R Foundation for Statistical Computing, 2013, Vienna, Austria, Document freely available on the internet at: http://www. r-project. org.
Tiktak, A., Bouten, W., 1994. Soil water dynamics and long-term water balances of a Douglas fir stand in the Netherlands. J. Hydrol. 156 (1–4), 265–283.
Tournebize, R., Boistard, S., 1998. Comparison of two sap flow methods for the estimation of tree transpiration. Ann For. Sci. 55 (6), 707–713.
Unsworth, M., et al., 2004. Components and controls of water flux in an old-growth douglas-fir-Western hemlock ecosystem. Ecosystems 7 (5), 468–481.
Vincke, C., Breda, N., Granier, A., Devillez, F., 2005. Evapotranspiration of a declining Quercus robur (L.) stand from 1999 to 2001. I. Trees and forest floor daily transpiration. Ann. For. Sci. 62 (6), 503–512.
Vose, J.M., et al., 2011. Forest ecohydrological research in the 21 st century: what are the critical needs? Ecohydrology 4 (2), 146–158.
de Ligne, A., Heinesch, B., Aubinet, M., 2010. New transfer functions for correcting turbulent water vapour fluxes. Boundary Layer Meteorol. 137 (2), 205–221.
van der Molen, M.K., et al., 2011. Drought and ecosystem carbon cycling. Agric. For. Meteorol. 151 (7), 765–773.
Wilson, K.B., Hanson, P.J., Mulholland, P.J., Baldocchi, D.D., Wullschleger, S.D., 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. Agric. For. Meteorol. 106 (2), 153–168.