Journal of Hydrology 400 (2011) 244–254

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Spatial and temporal patterns of throughfall volume in a deciduous mixed-species stand

F. André [*], M. Jonard, F. Jonard [1], Q. Ponette

Université catholique de Louvain, Earth and Life Institute, Croix du sud 2/009 1348 Louvain-la-Neuve, Belgium

ARTICLE INFO

Article history:
Received 20 March 2010
Received in revised form 16 January 2011
Accepted 24 January 2011
Available online 1 February 2011

This manuscript was handled by L. Charlet, Editor-in-Chief, with the assistance of Bernhard Wehrli, Associate Editor

Keywords:
Throughfall
Rainfall partitioning
Quercus petraea
Fagus sylvatica
Mixed-species stand

SUMMARY

The effects of canopy structure on the spatial and temporal patterns of throughfall (TF) in deciduous mixed-species stands remains poorly documented. TF was collected on a rain event basis in an oak–beech stand, within 12 structural units of contrasting densities (low, LD; high, HD) and species composition (beech, oak, mixture) delimited by three neighbouring trees. A roof was installed at the centre of each unit, and gutters were placed at the periphery of the LD units. Based on selected rain events, a simplified mass balance approach was used to describe water fluxes reaching and leaving the canopy. During the leafed season, the proportions of incident rainfall (RF) collected as TF on the roofs steadily increased with increasing RF up to a RF volume of about 5 mm; for larger RF volumes, TF proportions stabilised around 55% under pure (LD, HD) beech and HD mixture, and around 65% under pure (LD, HD) oak and LD mixture. During the leafless period, TF proportions (on average 60%) were independent of RF but were still affected by local stand characteristics (HD mixture < HD beech < HD oak < LD beech and mixture < LD oak). At canopy saturation, lateral transfers as branch flow (BF) were substantial ($35 \leqslant (BF/RF)\% \leqslant 46$) in all plots, and were significantly higher in the HD units compared to the LD plots in the leafless period; part of BF falled down as indirect TF before reaching the trunks, except in the HD units during the leafless season where stemflow and BF were similar. A mechanistic numerical model using rainfall partitioning parameters determined in this study allowed to successfully describe real-time throughfall measurements.

1. Introduction

During the last decades, a strong renewed interest appeared for mixed stands given their greater biodiversity (Levine and D'Antonio, 1999), the potential reduction of financial risk they offer (Lilieholm, 1991) as well as their more optimal use of resources (Forrester et al., 2005; Kelty, 2006) and their likely greater productivity (Forrester et al., 2005; Kelty, 2006) by comparison with corresponding pure stands. Nevertheless, because of their greater complexity compared to single-species stands, mixed stands remain poorly documented on other aspects and notably regarding the influence of their canopy structure on rainfall partitioning (Davie and Durocher, 1997a,b; Zirlewagen and von Wilpert, 2001).

Rainfall partitioning in forest is influenced by both meteorological and biological factors. Meteorological factors are rainfall amount and intensity, evaporation rate, wind speed, and time intervals between successive events (Aussenac, 1970; Crockford and Richardson, 2000; Gash, 1979). Biological factors correspond to forest canopy structure, which is affected by stand density and species composition. Indeed, leaf characteristics, foliage spatial distribution and density, branch architecture, bark texture and, in the case of deciduous species, phenophase are all factors influencing rainfall interception and its partitioning under forest (Aussenac, 1970; Herwitz, 1987; Návar, 1993).

Spatial redistribution of precipitation by tree canopy has potential effects on physico-chemical and biological processes within forest. For instance, by influencing the distribution of fine roots within soil (Ford and Deans, 1978), it is likely to affect water use by trees. In addition, high amounts of stemflow funnelled on a small area at the base of the trunk of some species may modify physical and chemical properties of forest soils as well as vegetation species composition (Falkengren-Grerup, 1989; Gesper and Holowaychuck, 1970). Moreover, spatial variability of rainfall interception by forest canopies is known to have effects on soil moisture distribution (Eschner, 1967), a parameter affecting amongst others litter decomposition (Cortez, 1998; Jonard et al., 2007, 2008) and nitrification in forest soils (Killham, 1990). Furthermore, a detailed understanding of the rainfall partitioning

---

[*] Corresponding author. Present address: IBG-3 Agrosphere, Institute of Bio- and Geosciences, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany. Tel.: +49 2461 61 1882; fax: +49 2461 61 2518.

E-mail addresses: f.andre@fz-juelich.de (F. André), Mathieu.Jonard@uclouvain.be (M. Jonard), f.jonard@fz-juelich.de (F. Jonard), Quentin.Ponette@uclouvain.be (Q. Ponette).

[1] Present address: IBG-3 Agrosphere, Institute of Bio- and Geosciences, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany.

0022-1694/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2011.01.037

process in forest is of prime importance for studies concerning atmospheric deposition in such ecosystems (e.g., André et al., 2008a,b; Whelan et al., 1998; Zirlewagen and von Wilpert, 2001).

Rainfall partitioning through forest canopies has been intensively studied for more than one century in both coniferous and broad-leaved stands (Horton, 1919; Levia and Frost, 2006), considering intra-event (Dolman, 1987; Massman, 1983), event (Loescher et al., 2002; Robson et al., 1994; Staelens et al., 2006, 2008), at weekly (Böttcher et al., 1997), monthly (Morris et al., 2003), seasonal (Ford and Deans, 1978; Kukla, 2002; Stout and McMahon, 1961), and annual (Huber and Iroumé, 2001) timescales. The presence of a nonnegligible spatial variability of below canopy water fluxes was observed in several studies. On one hand, rainfall interception and partitioning was found to be affected by distance from forest edges (Devlaeminck et al., 2005; Herbst et al., 2007; Klaasen et al., 1996). On the other hand, inside forests, several authors reported a systematic spatial pattern of rainfall partitioning under the influence of canopy structure at the stand level (Bouten et al., 1992; Carleton and Kavanagh, 1990; Crockford and Richardson, 2000; Gerrits et al., 2010; Robson et al., 1994; Whelan et al., 1998) as well as at the tree level (Staelens et al., 2006, 2008).

Rainfall volume, duration and intensity as well as wind speed and direction were shown to influence both spatial and temporal variability of water fluxes under forest (Bouten et al., 1992; Llorens et al., 2003; Robson et al., 1994; Staelens et al., 2008; Vrugt et al., 2003).

For deciduous forests, a supplemental temporal component adds to the variability of rainfall partitioning due to the important seasonal evolution of canopy characteristics (Dolman, 1987; Gerrits et al., 2010; Staelens et al., 2008).

Several authors focused on the modelling of rain partitioning processes using physically based (Gash, 1979; Gash et al., 1995; Rutter et al., 1972, 1975; Whelan and Anderson, 1996), stochastic (Calder, 1986; Hall, 2003) or statistical (Bouten et al., 1992; Gerrits et al., 2010; Loescher et al., 2002) methods. In the case of mixed forests, fine spatial and temporal resolutions are especially requested for thorough understanding of rain partitioning processes and for accurate determination of aboveground hydrological fluxes, particularly in broad-leaved stands which present strong spatio-temporal variations of canopy characteristics. However, very few studies concerned with rainfall partitioning in forests have investigated simultaneously the influence of both stand density and species composition together with the effects of meteorological and phenological factors. In this respect, comparing data from monospecific stands located within a restricted area, some authors showed a substantial effect of species composition and density on rainwater partitioning (Huber and Iroumé, 2001; Mahendrappa, 1990; Nordén, 1991). Davie and Durocher (1997a,b) developed a spatially variable rainfall partitioning model allowing to reproduce the spatial distribution of water fluxes within a mixed deciduous stand. More recently, Herbst et al. (2008) applied the model of Gash et al. (1995) to a mixed deciduous woodland allowing to analyse and predict the seasonal variability in canopy interception loss, while Bittner et al. (2010) successfully parameterised the same model for three mixed temperate broad-leaved stands of different species diversity levels. Finally, studying rainfall partitioning along a tree diversity gradient in a deciduous forest, Krämer and Hölscher (2009) showed that species diversity explained a large part of inter-stand differences of below canopy water fluxes.

The objective of this study is to evaluate the influence of local stand density and species composition, rainfall characteristics and phenophase on the partitioning of incident rainfall, including vertical and lateral components, when passing through the canopy of a mixed oak (*Quercus petraea* Liebl.)–beech (*Fagus sylvatica* L.) forest. To reach this goal, the complex structure of the canopy of the mixed stand was subdivided into more homogeneous units delimited by three neighbouring trees and the pattern of throughfall volume was examined at two spatial scales: (i) amongst units of contrasted canopy structure and (ii) within units. This paper is complementary and integrates the results of previous works focusing on the modelling of stemflow generation and on the determination of water storage capacities within the same forest (André et al., 2008c,d).

2. Materials and methods

2.1. Site description

This research was carried out from May 2002 to October 2004 within a 60 ha mixed oak–beech forest located near Chimay, in the western part of the Belgian Ardennes (50°01′N, 4°24′E) on a plateau at about 300 m elevation.

The climate is temperate. The mean annual precipitation volume is about 1044 mm with 411 mm (39% of total) falling during leaf cover period (May–September). Fog rarely occurs at this site and input of occult precipitation is assumed to be negligible. Due to its very low contribution as well as because of the specific instrumentation needed for snow measurement, snow events were not considered in this paper.

The mean annual air temperature is around 8 °C and mean monthly temperature ranges from 0.4 °C in January to 15.8 °C in July. The prevailing wind direction is south to southwest.

Stand selection was strongly motivated by the great diversity of canopy structures (density and species composition). During the 20th century, the stand was treated as an oak coppice that was reproduced vegetatively from stump-sprouts in 1880. It was then progressively converted to a high-forest and invaded by beech. The area is now covered by even-aged (≈120 years) oak trees and uneven-aged beech trees.

2.2. Measurements and sampling

2.2.1. Throughfall sampling zones

The complex canopy structure of the study stand was subdivided into more homogeneous units, so-called ‘structural units’, defined as triangular zones with angular points constituted by three direct neighbouring trees. The structural units were characterised in terms of density and species composition, assessed on the basis of the basal area (BA) of their delimiting trees (see André et al. (2008c) for computation details). This delimitation and this characterisation were performed with ArcGIS® software (version 9.2) based on position data (*x*, *y* coordinates) and trunk circumferences at breast height (C130).

Throughfall collectors (see below) were installed in structural units of contrasted canopy structures: three levels of species composition (pure oak, pure beech, and mixture of both species) crossed with two density levels. Two structural units with similar values for density and tree species composition were selected for each of those six cover situations, resulting into 12 ‘throughfall sampling zones’. Later, once data were made available, the tree species composition and the density of the sampling zones were also characterised based on leaf area index (i.e., one-sided leaf area per unit ground area, $m^2\ m^{-2}$) and canopy cover (i.e., proportion of the ground area covered by branches and leaves, %) as these parameters appeared more relevant than basal area to study the interaction of canopy with rain interception (see André et al. (2008c) for measurement and computation details). The characterisation of the sampling zones on the basis of leaf area index and canopy cover resulted in a deformation of the initial experimental domain due to the contrasted shade-tolerance of both species.

Major characteristics of the selected structural units as well as of their delimiting trees are reported in Table 1 and the configuration of a sampling zone is schematized in Fig. 1.

2.2.2. Throughfall volume

A roof (c.a. 5.9 m^2: 3 m × 2 m, slope ≈ 20°) was installed in the centre of each throughfall sampling zone (Fig. 1), which allowed us to collect small rainfall events (down to 1 mm depth) and to integrate the local spatial variability. From 6 May 2002 to 29 October 2002, throughfall volumes were determined at the rain event time scale (see Section 2.3.1 for definition) by measuring the height of water in two barrels (120 L total capacity) connected to the roof and converting it into volume, using a calibration performed in the laboratory. From 28 February 2003 to 24 October 2004, home-made tipping buckets connected to data loggers (Easylog 3000, GME, Incourt, Belgium) provided real-time measurements of throughfall volume with a resolution of about 0.015 mm.

In order to account for throughfall spatial variability at the scale of the structural unit, total throughfall volume was measured at the periphery (i.e., close to the stems) of the six low density sampling zones between 5 August 2004 and 24 October 2004. Three gutters (c.a. 0.78 m^2 total horizontal surface; c.a. 0.26 m^2 individual surface: 2.2 m × 0.12 m, slope ≈ 10°) connected to a unique barrel were installed around the roof in each zone (Fig. 1). Gutters had 0.10 m height vertical lateral sides allowing us to minimise splashing out. High density sampling zones were not equipped with gutters because their area was highly covered by the roof collector (Table 1, Fig. 1).

In the following, throughfall collected on the roof and in the gutters will be denominated as 'central' and 'peripheral' throughfall, respectively.

2.2.3. Meteorological measurements

Incident rainfall volume was measured in a grassland 200 m away from the study stand using a tipping bucket (GME PR12, GME, Incourt, Belgium; resolution of 0.2 mm, open area of 201 cm^2). These measurements were compared with a manual rain gauge as a control. Both methods gave similar results: relative difference did not exceed 10% and 5% below and above 20 mm of total single-event rainfall, respectively.

Air temperature and air relative humidity (combined temperature/humidity sensor HXFW10, GME, Incourt, Belgium; recording frequency of 15 min) as well as incident rainfall were measured at 1.5 m height while the measurement height of solar radiation

Table 1
Major characteristics of the throughfall sampling zones.

Species	Density	Rep.[a]	Surface[b] (m^2)	BA[c] ($m^2\ ha^{-1}$)	LAI[d] (–)		Cover [e] (–)		Oak[f] (%)	Delimiting trees			
					Zone	Roof	Leafed	Leafless		No.	Species	C130 (cm)	Height (m)
Oak	Low	1	32.4	12.5	3.0	1.8	0.84	0.20	100	1	Oak	77	18.0
			(18%)			*4.2*			(100)	2	Oak	76	21.1
										3	Oak	75	18.1
		2	50.5	16.9	5.9	5.8	0.83	0.23	100	1	Oak	149	22.7
			(12%)			*4.4*			(100)	2	Oak	140	23.2
										3	Oak	170	24.6
	High	1	9.9	34.2	4.8	3.7	0.84	0.25	100	1	Oak	93	21.7
			(58%)			*3.5*			(100)	2	Oak	134	23.2
										3	Oak	84	22.1
		2	9.3	42.6	4.4	3.7	0.87	0.26	100	1	Oak	73	19.3
			(62%)			*5.0*			(100)	2	Oak	101	20.2
										3	Oak	117	21.6
Mixed	Low	1	35	11.2	5.3	5.4	0.91	0.26	46	1	Beech	50	16.9
			(17%)			*6.5*			(15)	2	Beech	124	22.4
										3	Oak	121	23.2
		2	36.5	11.9	4.8	3.5	0.87	0.24	40	1	Beech	108	24.9
			(16%)			*5.8*			(76)	2	Beech	86	24.5
										3	Oak	112	25.3
	High	1	8.5	40.4	8.8	8.9	0.93	0.36	66	1	Oak	103	25.8
			(68%)			*8.4*			(31)	2	Oak	83	24.3
										3	Beech	95	23.3
		2	15.6	38.5	6.8	7.1	0.94	0.35	56	1	Oak	129	26.6
			(37%)			*9.2*			(40)	2	Beech	61	21.2
										3	Beech	149	25.3
Beech	Low	1	40.6	14.5	5.8	6.1	0.90	0.23	0	1	Beech	116	25.6
			(14%)			*6.3*			(0)	2	Beech	113	23.8
										3	Beech	156	27.1
		2	31.2	14.7	6.8	7.2	0.89	0.29	0	1	Beech	124	23.8
			(19%)			*6.9*			(0)	2	Beech	96	22.2
										3	Beech	110	23.2
	High	1	14.6	47.5	11.3	13.3	0.93	0.33	0	1	Beech	105	23.6
			(40%)			*12.3*			(0)	2	Beech	144	24.6
										3	Beech	154	24.3
		2	12.5	44.1	10.6	10.9	0.92	0.32	0	1	Beech	115	24.2
			(46%)			*9.5*			(0)	2	Beech	125	24.6
										3	Beech	114	24.5

[a] Repetition number of structural units in similar canopy situations.

[b] Value between brackets is the proportion of the zone covered by the roof collector.

[c] Local basal area.

[d] Upper values are leaf area index estimated from foliage biomass allometric equations (Jonard et al., 2006); bottom values are averages of LAI-2000 measurements carried out throughout the leafy season.

[e] Proportion of canopy cover estimated from vertical upwards photographs.

[f] Oak percentage for the sampling zone. Above values are computed from local basal area; values between brackets are computed from leaf area estimates of the cover above the zone.

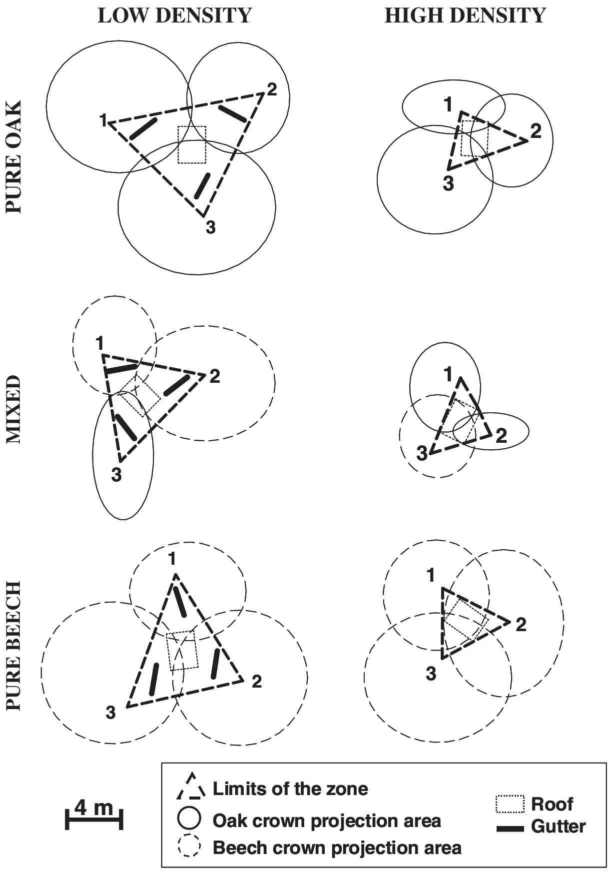

Fig. 1. Configuration of the throughfall sampling zones. Only repetition 1 of each species × density modality is represented (Table 1); numbers correspond to tree numbering in Table 1.

(pyranometer SKS1110, GME, Incourt, Belgium; recording frequency of 15 min) and wind speed (anemometer MDL33, GME, Incourt, Belgium; recording frequency of 15 min) was 2.5 m.

2.3. Data processing

2.3.1. Time subdivision

To study the effects of rain event characteristics on incident rainfall partitioning under forest, throughfall was collected at the scale of the rain event defined as a rainfall of at least 1 mm preceded by a dry period of minimum 12 h. Within a rain event, rainfall occurring after an interruption larger than 1 h was not considered to avoid bias due to water evaporation from the canopy during rainless periods. The leafed (1 June–15 September) and the leafless (1 December–15 April) periods were studied individually to take the season effect into account. The intermediate periods of leaf development and leaf falling were not analysed in details because of lack of data.

2.3.2. Canopy water balance

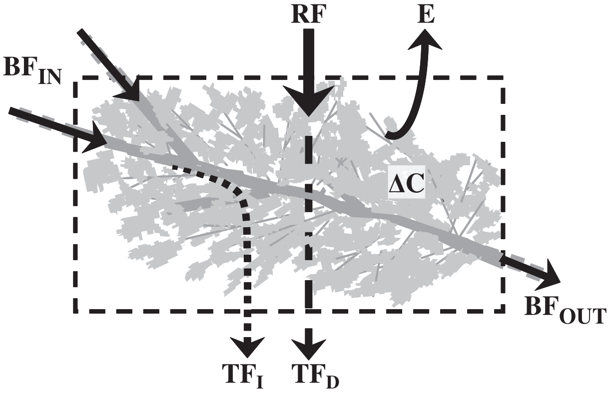

Fig. 2. Diagram of local canopy water balance. RF: incident rainfall; $\mathrm{BF_{IN}}$: branch flow inputs; $\mathrm{BF_{OUT}}$: branch flow outputs; $\mathrm{TF_I}$: indirect throughfall; $\mathrm{TF_D}$: direct throughfall; E: evaporation; ΔC: variation of rainfall amount stored on aerial organs.

For each rainfall event and each location within the structural unit, a canopy water balance may be established by considering that the change in rainfall amount stored on tree aerial organs (ΔC) is equal to the difference between water inputs and outputs (Fig. 2). While water reaches a point of the tree canopy by two main pathways, namely incident rainfall (RF) and branch flow inputs ($\mathrm{BF_{IN}}$), four water outputs may be distinguished: direct throughfall ($\mathrm{TF_D}$), indirect throughfall ($\mathrm{TF_I}$), branch flow outputs ($\mathrm{BF_{OUT}}$) and evaporation (E). The canopy water balance may be formulated as follows:

$$\Delta C = \mathrm{RF} + \mathrm{BF_{IN}} - \mathrm{TF_D} - \mathrm{TF_I} - \mathrm{BF_{OUT}} - E \tag{1}$$

Branch flow (BF) is the fraction of the rain intercepted by the canopy which flows along the branches toward the trunks. For a given point of the canopy, the difference between branch flow inputs and outputs provides the net branch flow (ΔBF). A proportion of BF may drip onto the ground before reaching the trunks, forming ‘indirect throughfall’ ($\mathrm{TF_I}$). The remaining part of branch flow reaches the trunks and forms stemflow (SF) at the base of the trees. The sum of $\mathrm{TF_D}$ and $\mathrm{TF_I}$ is the total throughfall (TF), which was collected at the centre (roof collectors) and at the periphery of the structural unit (gutters). Finally, a part of the water stored on canopy organs will be evaporated (E) throughout the rain event.

For the low density structural units, the sampling design allows us to establish the canopy water balance at two places, in the centre and in the periphery of the unit.

For each structural unit, branch flow may be estimated using real-time measurements of throughfall (15-min sub-periods) selected according to three criteria: (i) low potential evaporation at canopy level (below 2% of rainfall volume), (ii) sub-periods after 10 mm (leafed period) or 6 mm (unleafed period) of rainfall to ensure canopy saturation (see below, Fig. 3a), and (iii) rain intensity and wind speed lower than $3\ \mathrm{mm\ h^{-1}}$ and $2\ \mathrm{m\ s^{-1}}$ respectively, limiting variation of water amount stored on foliage as a consequence of branch and leaf shaking. The first criterion implies that $E \cong 0$ mm while the two others allowed us to assume that $\Delta C = 0$ mm.

Rearranging and simplifying terms of Eq. (1) based on the above conditions, we obtain:

(i) for the centre of the structural unit:

$$\mathrm{BF_{OUT}} = \mathrm{RF} - \mathrm{TF} \tag{2}$$

since $\mathrm{BF_{IN}} = 0$ at the branch extremities and RF is therefore the only water input to the canopy at this location,

(ii) for the periphery of the structural unit:

$$\Delta\mathrm{BF} = \mathrm{BF_{OUT}} - \mathrm{BF_{IN}} = \mathrm{RF} - \mathrm{TF} \tag{3}$$

For all plots, branch flows from the centre of the structural unit were compared with stemflow to evaluate if indirect throughfall is significant or not. For this comparison, stemflow volume was assessed during the selected sub-periods of rainfall defined above. The stemflow volume of structural unit was assumed to be the

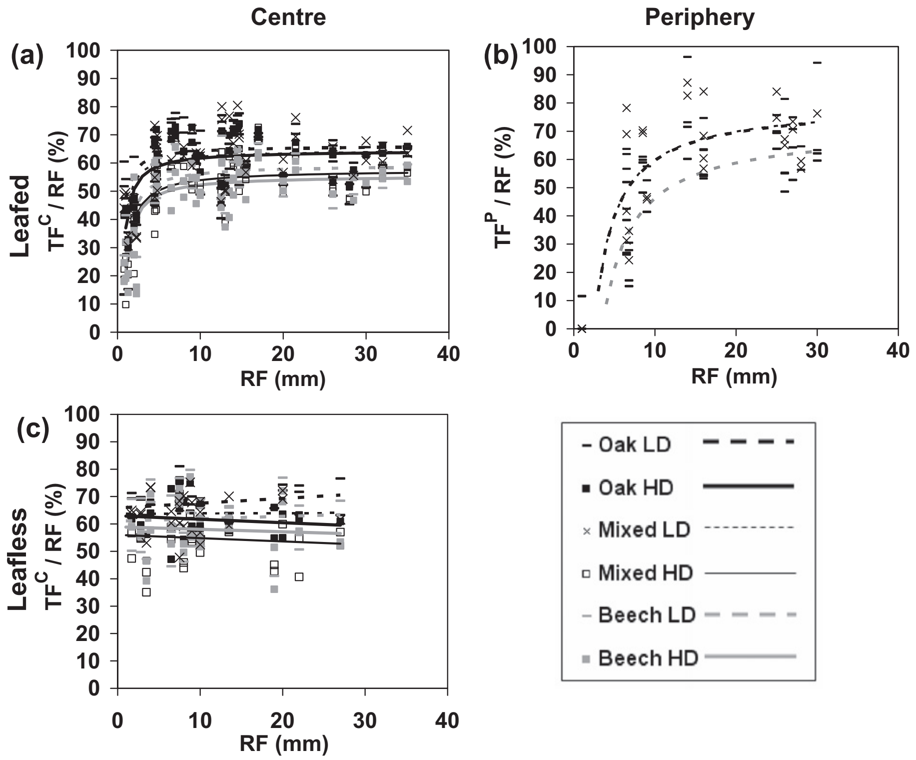

Fig. 3. Variation of the proportion of incident rain collected as throughfall with single-event rainfall volume (average by canopy situation; see Table 2 for fitting results). LD: low density; HD: high density; TF^C: throughfall volume at the centre of the sampling zones (i.e., collected on the roof); TF^P: throughfall volume at the periphery of the sampling zones (i.e., collected in the gutters); RF: incident rainfall volume.

sum of the contribution of each delimiting tree, each contribution being a proportion of the tree stemflow computed based on the fraction of its crown projection area intersecting the unit:

$$\mathrm{SFfrac}_i = (\mathrm{CPAint}_i/\mathrm{CPAtot}_i) \times \mathrm{SF}_i \tag{4}$$

where indices 'i' refer to the ith delimiting tree of the sampling zone (i ranging from 1 to 3), SF (L) is the stemflow volume generated by the tree during the sub-period, SFfrac_i (L) is the part of stemflow volume contributing to structural unit water balance, CPAint (m^2) is the surface of the crown projection area included in the sampling zone, CPAtot (m^2) is the total surface of the crown projection area. CPAint and CPAtot were determined based on the representation of the sampling zones using AutoCAD® software (Fig. 1). SF was estimated using the models established by André et al. (2008d).

Total stemflow was computed by summing the contribution of each delimiting tree (SFfrac_i, Eq. (4)) and dividing by the surface area of the unit for conversion in millimetres of water.

2.3.3. Numerical model

A mechanistic canopy water budget model was applied on real-time throughfall data collected from the roofs in order to describe throughfall dynamic during the course of rain events, using rainfall partitioning parameters determined in this paper and by André et al. (2008c). The model is based on the canopy water balance (see Eq. (1)) formulated for the centre of the structural units (i.e., $\mathrm{BF_{IN}} = 0$, see above) and for any Δt period:

$$\Delta C_{\Delta t} = C_{t0+\Delta t} - C_{t0} = \mathrm{RF}_{\Delta t} - \mathrm{TF}_{\mathrm{D}\Delta t} - \mathrm{TF}_{\mathrm{I}\Delta t} - \mathrm{BF}_{\mathrm{OUT}\Delta t} - E_{\Delta t} \tag{5}$$

with C_{t0} and $C_{t0+\Delta t}$ being, respectively, the amounts of water stored on the canopy at the beginning and at the end of the period considered. For this modelling exercise, 5-min time steps were considered.

For the leafed season, the model considers three assumptions for the early stages of rain events, i.e. before saturation is reached:

(i) No indirect throughfall occurs from the canopy ($\mathrm{TF}_{\mathrm{I}\Delta t} = 0$) and throughfall correspond exclusively to direct throughfall ($\mathrm{TF}_{\mathrm{D}\Delta t}$), estimated as the product of rainfall volume ($\mathrm{RF}_{\Delta t}$) and canopy gap fraction ($1 - c$).

(ii) As hypothesised by several authors (Rutter et al., 1972; Aboal et al., 1999) and validated by Teklehaimanot and Jarvis (1991), the part of the canopy subject to evaporation is proportional to the amount of water stored on the canopy; actual canopy evaporation ($E_{\Delta t}$) can therefore be obtained by multiplying the Penman–Monteith evaporation rate (see André et al. (2008c)) by the ratio between the amount of water stored on the canopy and the storage capacity (C_{t0}/S).

(iii) The part of rainfall diverted along the branches ($\mathrm{BF}_{\mathrm{OUT}\Delta t}$) increases proportionally to the amount of water accumulated on leaves until reaching a maximum value (p_t) at saturation.

Substituting terms according to these assumptions, Eq. (5) may be rewritten as follows for the unsaturated phase:

$$C_{t0+\Delta t} - C_{t0} = \mathrm{RF}_{\Delta t} - (1 - c) \times \mathrm{RF}_{\Delta t} - p_t \times (C_{t0}/S) \times \mathrm{RF}_{\Delta t} - (C_{t0}/S_L) \times E_{P\Delta t} \tag{6}$$

where c is the canopy cover, S (mm) is the canopy storage capacity determined by André et al. (2008c), $E_{P\Delta t}$ (mm) is the Penman–Monteith evaporation at canopy level during the Δt period and p_t is the maximum proportion of incident rainfall diverted along the branches, constant for a given sampling zone and determined analysing selected 15-min rain event sub-periods as described in the preceding section.

At saturation ($C_{t0}/S = 1$), indirect throughfall is estimated as the amount of intercepted water exceeding the storage capacity. Therefore, for the saturated phase, Eq. (6) becomes:

$$0 = \mathrm{RF}_{\Delta t} - (1 - c) \times \mathrm{RF}_{\Delta t} - p_t \times \mathrm{RF}_{\Delta t} - \mathrm{TF}_{\mathrm{I}\Delta t} - E_{P\Delta t} \tag{7}$$

Total throughfall collected on the roof is then given by:

$$\mathrm{TF}_{\Delta t} = (1 - c) \times \mathrm{RF}_{\Delta t} + \mathrm{TF}_{\mathrm{I}\Delta t} \tag{8}$$

Regarding the leafless season, analysis of the data (see below) indicates that the proportion of rainfall intercepted by the canopy at the centre of the structural units is independent of rainfall volume for a given canopy situation and equals to the part of incident precipitation (p_t) diverted along the branches. Therefore, for this season, modelling of the amount of throughfall collected on the roofs becomes:

$$\mathrm{TF}_{\Delta t} = (1 - p_t) \times \mathrm{RF}_{\Delta t} \tag{9}$$

where, as previously, p_t (–) was determined analysing selected 15-min rain event sub-periods.

As a result of the absence of real-time data for throughfall at the periphery of the sampling zones (i.e., in the gutters) and for stemflow of their delimiting trees, the numerical model could only be applied and validated for throughfall collected on the roofs. Yet, as mentioned above, a more qualitative analysis was carried out comparing branch flows from the centre of the structural units with stemflow estimates for their delimiting trees; the aim of this analysis was to highlight the occurrence of indirect throughfall at the periphery.

2.3.4. Statistics

Simple and multiple linear models were tested to establish relationships between throughfall volume (or proportion) and selected rain event characteristics (e.g. incident rainfall volume, wind speed, rain intensity; Fig. 3, Table 2), using a stepwise procedure. Similarly, linear models were developed to quantify the relationship between throughfall volume (or proportion) in the centre of the low density structural units and throughfall volume (or proportion) at their periphery (Fig. 4). All models were fitted using SAS Proc Reg procedure (SAS institute, version 9.1), and residual homoscedasticity as well as residual normality were checked in all cases.

Statistical tests were performed at a 0.05 significance level.

Table 2
Relationships between throughfall proportion (TF/RF, %) and rainfall volume (RF, mm).

Canopy structure		Effects		R^2	*n*
Species	Density	*a*	*b*		
Leafed season, centre					
Oak	Low	66.02 (±2.95)	−18.60 (±8.26)	0.24	63
	High	64.45 (±2.49)	−27.44 (±7.05)	0.47	65
Mixed	Low	63.94 (±3.09)	−22.36 (±8.08)	0.37	51
	High	57.53 (±2.63)	−36.05 (±7.22)	0.62	58
Beech	Low	59.47 (±2.97)	−32.15 (±8.21)	0.50	58
	High	55.56 (±2.53)	−34.22 (±6.99)	0.62	56
Leafed season, periphery					
Oak	Low	79.51 (±10.11)	−198.42 (±107.52)	0.35	26
Mixed	Low	79.87 (±12.06)	−199.65 (±126.09)	0.30	25
Beech	Low	71.23 (±9.58)	−250.16 (±96.44)	0.58	21
Leafless season, centre					
Oak	Low	67.86 (±2.51)	–	–	22
	High	61.63 (±2.72)	–	–	30
Mixed	Low	63.80 (±2.80)	–	–	25
	High	54.00 (±2.04)	–	–	25
Beech	Low	62.18 (±4.00)	–	–	27
	High	58.04 (±3.45)	–	–	30

Values between brackets are 95% confidence intervals. Model: TF/RF = $a + b \times \mathrm{RF}^{-1} + \varepsilon$; see Fig. 3 for model graphical representation.

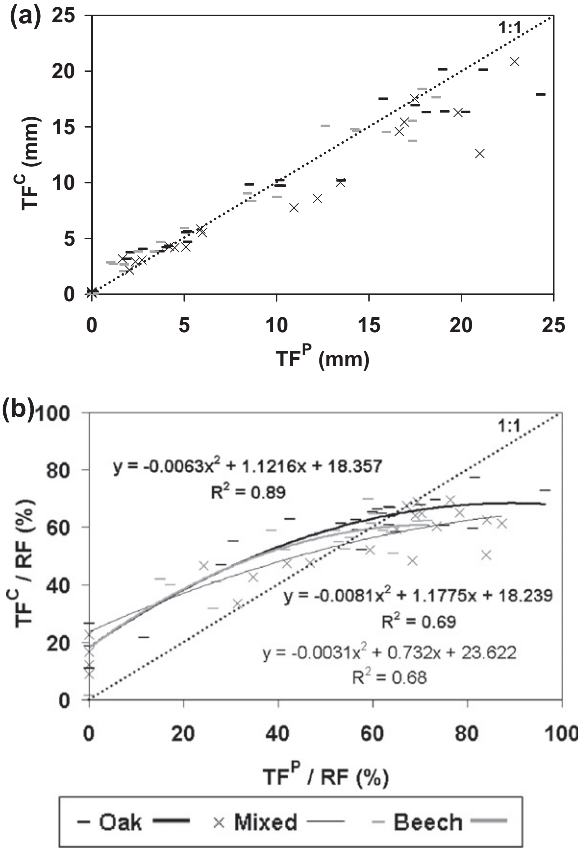

Fig. 4. Comparison of throughfall (a) volumes and (b) proportions of incident precipitation collected as throughfall in the centre and at the periphery of the throughfall sampling zones (low cover density situations). TF^{C}: throughfall volume at the centre of the sampling zones (i.e., collected on the roof); TF^{P}: throughfall volume at the periphery of the sampling zones (i.e., collected in the gutters); RF: incident rainfall volume.

3. Results

3.1. Throughfall

For the leafed season, the proportions of incident rainfall collected as total throughfall in the centre of the sampling zone (i.e., on the roof of LD and HD units) increased sharply with increasing rainfall volume for the smallest events and tended to stabilise progressively for events larger than 5 mm rainfall volume; the level of stabilisation ranged from around 55% for the beech and the high density mixture situations to around 65% for the oak and the low density mixture zones (Fig. 3a, Table 2). In contrast, for the leafless period, central throughfall proportions were not significantly affected by rain event volume, whatever species composition and local density (Fig. 3c, Table 2); moreover, for each canopy situation, average throughfall proportions during this period were close to corresponding throughfall percentages found for the largest events of the leafed season.

The variation of peripheral throughfall proportions with rain event volume during the leafed period (LD plots only) was similar to that of central throughfall proportions for the same period. However, the inflexion of the curve began at higher rainfall volumes (around 15 mm) than in the centre and stabilisation was not achieved for the investigated rain volumes; the average maximum values amounted to 73% for oak and mixture while beech throughfall proportion was around 10% lower (Fig. 3b).

Besides rainfall volume, no significant effect of any other rain event characteristics such as wind speed and rain intensity could be detected on throughfall volume (results not shown).

The comparison of throughfall volumes collected on the roof and in the gutters showed that, for the smallest rain events, throughfall volume tended to be higher in the centre than at the periphery, while the reverse was observed beyond 5–10 mm throughfall volume (Fig. 4a). This tendency was still clearer when representing throughfall percentage in the centre as a function of throughfall percentage at the periphery (Fig. 4b). The throughfall percentage in the centre ranged between 10% and 25% for a null proportion of throughfall collected at the periphery. Central throughfall percentage remained higher than peripheral throughfall proportion up to values around 55–65% of the latter; beyond these values, throughfall percentage tended to stabilise in the centre.

3.2. Branch flow

Estimates of branch flow from the centre of the structural unit determined based on selected 15-min sub-periods were positive, indicating outgoing fluxes of water from the centre towards the periphery of the unit at canopy saturation. Average proportions of incident rainfall deviated as branch flow are presented in Fig. 5. For a given species composition, it was significantly higher for the high density than for the low density units, except for oak during the leafed season where no significant difference appeared. Regarding the seasonal effect, branch flow proportions in the low density unit tended to be higher during the leafed period by comparison with the leafless period, and conversely for the high density situations; nevertheless, the seasonal effect was only significant for the dense oak and mixture units.

Comparison of branch flow from the unit centre with estimates of stemflow volume at canopy saturation is presented in Fig. 6. A good agreement between both quantities was observed for the high density units for the leafless season while estimations of branch flow were systematically higher than stemflow volumes for the low density zones for the same period (Fig. 6a). For the leafed period, branch flow estimates systematically overvalued stemflow volumes, whatever canopy density; however, the discrepancy was larger for the low density zones than for the high density situations (Fig. 6b).

3.3. Numerical model

Measured and predicted throughfall amounts in the centre of the sampling zones are compared in Fig. 7 for each canopy situation and each season, considering the time course of cumulated throughfall volumes during specific rain events (26th July 2003–27th July 2003 for the leafed period; 8th January 2004 for the leafless period) (Fig. 7a and c) and total throughfall volumes for all rain events for which real-time data were available (Fig. 7b and d). In all cases, good agreement was observed with differences between measurements and model predictions generally lower than 15%.

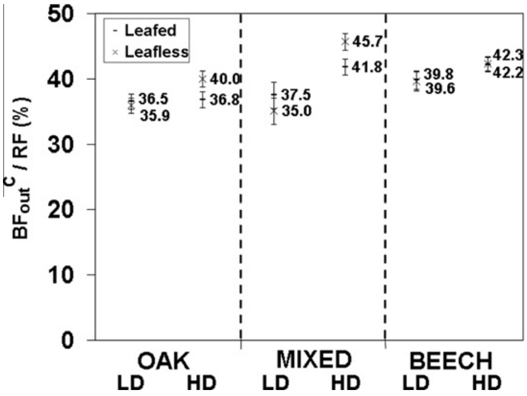

Fig. 5. Mean proportions of incident precipitation transferred laterally out of the central zone at canopy saturation. Error bars are confidence intervals at level $\alpha = 0.05$. LD = low density; HD = high density.

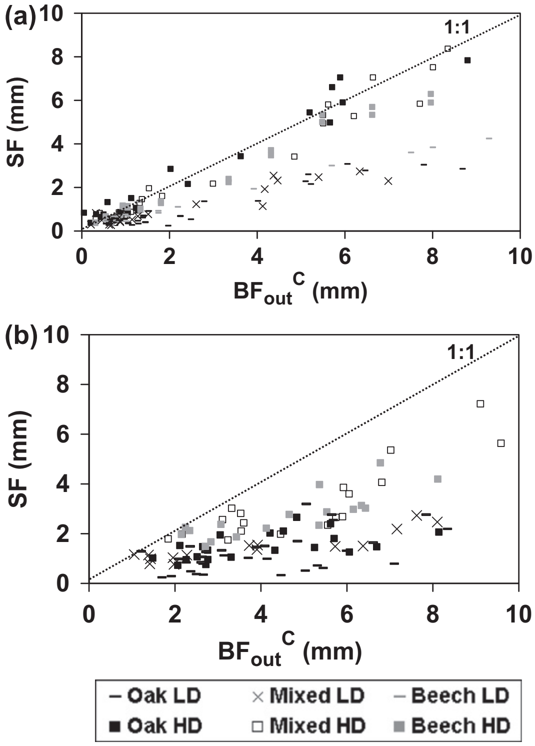

Fig. 6. Comparison between stemflow volume and lateral transfer estimated at the sampling zone level during rain event sub-periods of low evaporation and at canopy saturation for (a) the leafless season and (b) the leafed season. Differences of numbers of observations amongst situations result from tipping bucket dysfunctioning.

4. Discussion

4.1. Effect of rainfall volume

For the leafed season, the increase of throughfall proportions with increasing rainfall volume and the subsequent stabilisation (Fig. 3a and b) has been reported by several authors for deciduous forests during the growing season as well as for evergreen species throughout the year (e.g., Aussenac, 1968; Link et al., 2004; Price and Carlyle-Moses, 2003; Staelens et al., 2008).

The sharp increase in throughfall proportion with rainfall volume may partly arise from the parallel decrease in evaporation for rain events lower than 5 mm precipitation volume (André et al., 2008d), which is probably due to an increase in relative humidity (Klaassen et al., 1998). However, this evolution of the potential evaporation percentage with rainfall volume is found to occur for both the leafed and leafless periods (André et al., 2008d) while, during the leafless period, throughfall is not significantly affected by precipitation volume (Fig. 3c). These observations underline the major role of foliage in rain interception at the beginning of the rain events during the growing season. For the smallest events, throughfall corresponds almost exclusively to the part of rain passing through canopy gaps; the other part hits canopy organs and

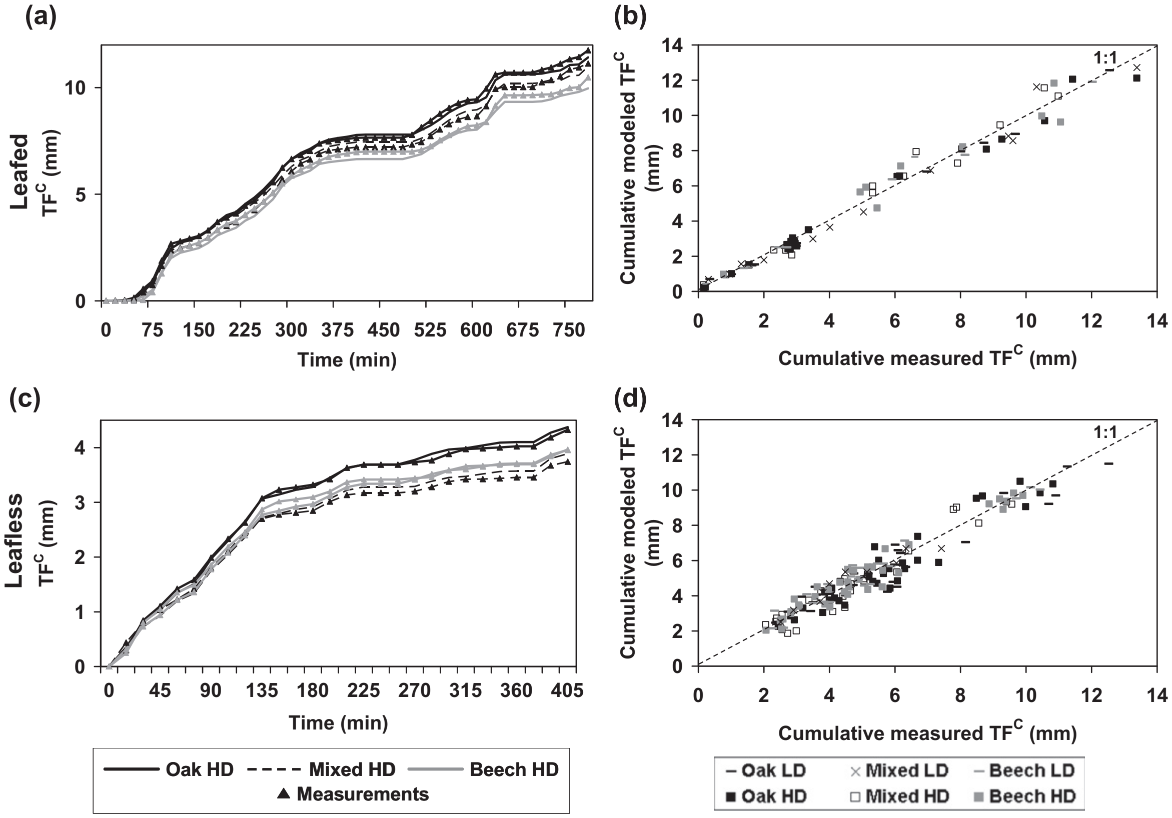

Fig. 7. Measurements and model predictions (a and c) of time course throughfall volumes for specific rain events and (b and d) of total cumulated throughfall volumes in the centre of the sampling zones. TF^C: throughfall volume at the centre of the sampling zones (i.e., collected on the roof). For the sake of legibility of the graphs, only repetition 1 of the high density modality of each species composition level is represented for time course throughfall volumes.

will either stay on them or evaporate. As rainfall volume increases, canopy organs catch increasing cumulated amounts of water on their surface filling progressively canopy storage capacity and a part of this water will drip onto the ground, increasing gradually the proportion of rain contributing to throughfall.

Stabilisation of throughfall proportions for rain events larger than 5 mm arise for two reasons. First, beyond 5 mm rainfall volume, the proportion of potential evaporation relative to the rain event volume also tends to stabilise to values lower than 5% (André et al., 2008d). Second, stabilisation of throughfall proportions corresponds to canopy saturation, with the water amount on the canopy remaining more or less constant and the dripping rate being mainly fixed by rain intensity, so that the proportion of rain converted to throughfall tends to stabilise to a maximum value. The value of around 5 mm rainfall to observe canopy saturation agrees with those found by Price and Carlyle-Moses (2003) and Link et al. (2004).

Regarding the leafless period, the nonsignificant effect of rainfall volume on throughfall proportion (Fig. 3c) results from the absence of foliage. Indeed, branches alone constitute a much lower area for rain interception and evaporation, and the effects of these processes are less significant during this season, even for the smallest events (Link et al., 2004; Rutter et al., 1975). In addition, evaporation rate from wet woody surfaces tends to be lower than that from wet leaves as a result of differences in boundary layer thickness (Rutter et al., 1975) and the adsorption of water in porous bark tissues (Herwitz and Levia, 1997). Yet, our observations contrast with results reported by Staelens et al. (2008) who found an increase of throughfall proportions with increasing incident precipitation volume for the smallest rainfalls even during the leafless season, though this trend was less pronounced than for the leafed period. These differences with our results may arise from the fact that Staelens et al. (2008) focused on throughfall measurements beneath a single beech tree, and their collectors were then placed closer to the trunk than our roofs placed in the centre of the structural units. Therefore, the branch cover over some of their collectors was high and amounted up to 72% (Staelens et al., 2006), implying the occurrence of an unsaturated phase at the early stages of rain events during which throughfall proportions increase progressively with branch wetting. Unfortunately, no throughfall measurements were performed at the periphery of the sampling zones during the leafless season, which would have allowed to check for similar observations at our study site.

Throughfall proportions measured in this study tend to be at the lower end of the range of values reported in literature for the same species, commonly ranging from 66% to 95% (Augusto et al., 2002; Peck, 2004; Staelens et al., 2006), while other authors found throughfall percentages similar to ours (Chang and Matzner, 2000; Dalsgaard, 2008; Krämer and Hölscher, 2009; Nordén, 1991). These latter authors attributed these observations to the relatively low precipitation conditions characterising the respective study areas.

4.2. Effects of local stand characteristics (density and species composition)

Systematic higher throughfall proportions under oak than under beech as well as for the low density mixed units compared to the dense mixture (Fig. 3) are in agreement with observations of Nordén (1991) and may be explained by contrasted canopy characteristics.

4.2.1. Leafed season

For the smallest events of the leafed season, i.e., before canopy saturation, these differences amongst structural units probably result from contrasted foliage storage capacities. Indeed, estimating foliage storage capacities for the structural units, André et al. (2008c) found that storage on foliage tended to increase with increasing percentage of beech, especially for the high density units. Moreover, higher branch cover in the dense units and in the units containing beech trees (Table 1) is likely to increase rain interception, which could partly explain the differences in throughfall proportions amongst structural units. Finally, these differences could partly be ascribed to contrasted crown architecture which might affect rainfall partitioning when passing through the canopy (Crockford and Richardson, 2000; Levia and Frost, 2003; Pypker et al., 2005).

At saturation, no accumulation of water occurs on the canopy and differences of throughfall proportions amongst units result only from the effect of crown architecture. This effect may also be highlighted by comparing the central branch flow of the different structural units. Indeed, for sub-periods with low evaporation rate and at canopy saturation, the branch flow proportion is the complementary of the throughfall proportion (Eq. (2)). The higher branch flow proportions observed under beech compared with oak may partly be ascribed to the highly ramified and the vertical shape of the beech branches, which facilitates water flow along them while the bended and more horizontal branches of oak are more favourable to dripping (Aboal et al., 1999; Crockford and Richardson, 2000; Herwitz, 1987; Levia and Frost, 2003).

4.2.2. Leafless season

Similarly to us, Bittner et al. (2010) found a high value (c.a. 30%) for the proportion of rainfall intercepted by a mixed temperate broad-leaved canopy during the leafless period, despite the low canopy cover for this season. They attributed these observations to the fact that rain drops are smaller in winter (due to lower rainfall intensities) compared to summer, which increases their probability to be intercepted.

The higher branch flow proportions in the oak and mixed units of high density compared with the corresponding low density units for the leafless period (Fig. 5) results possibly from the greater branch cover (Table 1) and to the higher verticality of oak branches in high density units due to stronger competition between neighbouring crowns (Fig. 1). The density effect is less pronounced for beech, probably due to the lower effect of competition on crown architecture for this species; beech branches form a rather narrow angle with the vertical even in the low density units. Furthermore, the higher branch flow proportions observed in winter for the high density mixed units by comparison with the oak and beech units of high density could arise from crown superposition of both species as a result of stand history, which is typical for mixed forests (Kelty, 1992; Menalled et al., 1998); this is not observed for the low density zones because of larger tree spacing (Fig. 1).

In contrast to beech plots, the density effect on branch flow for the oak and the mixed units is more marked for the leafless season than for the leafed period, the high density units exhibiting higher branch flow. These observations suggest that the effect of foliage, sheltering branches from rainfall or deviating rainfall from branches (Noirfalise, 1959; Herbst et al., 2008), is more effective for oak than for beech.

4.3. Highlight of indirect throughfall

The comparison of ‘central’ throughfall proportions with ‘peripheral’ throughfall proportions for the low density units (Fig. 4) reveals the existence of lateral transfers of water along the branches that fall as indirect throughfall before reaching the trunk.

For low throughfall proportions, i.e., for the smallest events (see Fig. 3), higher values at the centre compared with the periphery probably results from larger storage capacities near the trunk, possibly due to higher dimension and superposition of branches. Differences of storage capacities could also explain the higher rainfall volume needed to observe the inflexion of throughfall proportion at the periphery (c.a. 15 mm, see Fig. 3b) compared with the centre (c.a. 5 mm, see Fig. 3a). The value around 15 mm rainfall for stabilisation of throughfall proportions at the periphery during the leafed period corresponds to that observed by Staelens et al. (2008) for the same season from throughfall collectors placed under the canopy of a single beech tree.

The reduction of the difference between ‘central’ and ‘peripheral’ throughfall proportions with increasing values (Fig. 4b), namely as rainfall volume increase (see Fig 3a and b), results from progressive saturation of the canopy until reaching values around 55–65% which correspond to canopy saturation in the centre. Beyond this point, ‘peripheral’ throughfall proportions increased by comparison with ‘central’ throughfall proportions (Fig. 4b). This can be explained by the fact that branches near the trunk must not only directly receive a portion of the incident rainfall but also the additional branch flow from the centre of the unit, which is not the case for branches at the centre of the unit. This argument can be demonstrated based on Eqs. (2) and (3). In this respect, neither for coniferous nor for broadleaved species, no general consensus is found in available literature regarding the variation of throughfall volume as a function of distance to tree trunks. Indeed, some authors reported greater throughfall amounts either near the trunk (Ford and Deans, 1978; Herwitz, 1987; Robson et al., 1994), at crown periphery (Beier et al., 1993; Stout and McMahon, 1961; Whelan et al., 1998) or at intermediate distance (Carleton and Kavanagh, 1990) while others (Keim et al., 2005; Loustau et al., 1992) found distance to the trunk to be a poor predictor for throughfall volume. According to our results, throughfall volumes would be greater at crown periphery than close to the trunks at the early stages of rain events (c.a. <5 mm rainfall) and inversely for larger rainfall volumes, which agrees with observations of Kittredge et al. (1941).

The comparison of branch flow estimates for the centre of the unit during sub-periods of low evaporation and at canopy saturation with stemflow volumes (Fig. 6) corroborates the occurrence of indirect throughfall at the periphery of the low density units at canopy saturation.

The fact that stemflow are systematically lower than branch flow from the centre of the low density units (Fig. 6) suggests that a part of water flowing along the branches from the crown extremities drips when coming closer to the trunk and forms indirect throughfall. Regarding the high density zones, the good agreement between branch flow estimates and stemflow volume observed for the leafless period (Fig. 6a) indicates that the major part of incident rainfall diverted laterally along the branches is converted as stemflow. In contrast, systematic lower stemflow volume compared with branch flow during the leafed season (Fig. 6b) suggests occurrence of indirect throughfall near the trunk, as for the low density units.

Finally, the good agreement observed between real-time throughfall volume measurements and model predictions (Fig. 7) corroborates the reliability in the values of the canopy rainfall partitioning parameters derived in this study.

5. Conclusions and perspectives

This study revealed significant effects of rainfall volume, canopy density, species composition as well as of season on the rainfall partitioning when passing through the canopy of a mixed oak–beech stand.

Contrasted throughfall volumes between species, lower under beech than under oak, were related to crown characteristics of beech favouring flow of water along branches towards the trunks. Throughfall were slightly lower in dense units compared with low density units, probably due to a more intimate overlapping of crowns; the more pronounced effect of canopy density in mixed units, could be explain by crown superposition of both species in the dense units.

Concerning the spatial pattern within structural units, measurements during the leafed season in low density zones showed that throughfall volumes were higher under crown extremities than near the trees before canopy saturation, presumably because of storage capacity differences; the opposite was observed after saturation at least partly because of lateral transfers of water within canopy. Moreover, comparison between estimates of the volumes of rain transferred laterally within the canopy and stemflow volumes at saturation also suggested that indirect throughfall increase when coming closer of the trunk.

The seasonal effect on rainfall partitioning was particularly pronounced for the smallest rain events, with throughfall volumes much lower during the leafed season by comparison with the leafless period as consequence of rain interception by foliage. Differences between seasons attenuated strongly as rainfall volume increased but remained significant at canopy saturation for the dense oak and the dense mixed units, suggesting an effect of foliage on rain partitioning between throughfall and water flow along tree skeleton.

A physically based numerical model was implemented using canopy rainfall partitioning parameters determined in this study and allowed to successfully describe real-time throughfall measurements for both the leafed and the leafless periods.

Finally, the approach adopted in this study is also interesting as it enables to upscale the results at the stand level provided that all the structural units of the stand are characterised. This could allow comparing rainfall partitioning in stands of different types.

Acknowledgements

This research was co-funded by a FRIA (Fonds pour la Recherche dans l'Industrie et l'Agriculture) grant and the "Accord cadre – Recherche et Vulgarisation forestières" project. We wish to thank Ir. A. Barjasse and the local forester A. Laboureix for giving us access to the site. We are grateful to E. Dambrine for his advices as well as to C. Nys and his technical team and to J. Morren for technical and material assistance. Field measurements and maintenance were carried out by C. Tilquin, M. Pierard, F. Plume, and F. Hardy. We also gratefully thank the two anonymous reviewers for their constructive comments and suggestions on an earlier version of the manuscript.

References

Aboal, J.R., Jiménez, M.S., Morales, D., Hernández, J.M., 1999. Rainfall interception in laurel forest in the Canary Islands. Agric. Forest Meteorol. 97 (2), 73–86.

André, F., Jonard, M., Ponette, Q., 2008a. Effects of biological and meteorological factors on stemflow chemistry within a temperate mixed oak–beech stand. Sci. Total Environ. 393, 72–83.

André, F., Jonard, M., Ponette, Q., 2008b. Spatial and temporal patterns of throughfall chemistry within a temperate mixed oak–beech stand. Sci. Total Environ. 397, 215–228.

André, F., Jonard, M., Ponette, Q., 2008c. Precipitation water storage capacity in a temperate mixed oak–beech canopy. Hydrol. Process. 22, 4130–4141.

André, F., Jonard, M., Ponette, Q., 2008d. Influence of species and rain event characteristics on stemflow volume in a temperate mixed oak–beech stand. Hydrol. Process. 22, 4455–4466.

Augusto, L., Ranger, J., Binkley, D., Rothe, A., 2002. Impact of several common tree species of European temperate forests on soil fertility. Ann. Forest Sci. 59, 233–253.

Aussenac, G., 1968. Interception des précipitations par le couvert forestier. Ann. Forest Sci. 25 (3), 135–156.

Aussenac, G., 1970. Action du couvert forestier sur la distribution au sol des précipitations. Ann. Forest Sci. 27 (4), 383–399.

Beier, C., Hansen, K., Gundersen, P., 1993. Spatial variability of throughfall fluxes in a spruce forest. Environ. Pollut. 81, 257–267.

Bittner, S., Talkner, U., Krämer, I., Beese, F., Hölscher, D., Priesack, E., 2010. Modeling stand water budgets of mixed temperate broad-leaved forest stands by considering variations in species specific drought response. Agric. Forest Meteorol. 150, 1347–1357.

Böttcher, J., Lauer, S., Strebel, O., Puhlmann, M., 1997. Spatial variability of canopy throughfall and groundwater sulfate concentrations under a pine stand. J. Environ. Qual. 26, 503–510.

Bouten, W., Heimovaara, T.J., Tiktak, A., 1992. Spatial patterns of throughfall and soil water dynamics in a Douglas fir stand. Water Resour. Res. 28, 3227–3233.

Calder, I.R., 1986. A stochastic model of rainfall interception. J. Hydrol. 89, 65–71.

Carleton, T.J., Kavanagh, T., 1990. Influence of stand age and spatial location on throughfall chemistry beneath black spruce. Can. J. Forest Res. 20, 1917–1925.

Chang, S.C., Matzner, E., 2000. The effect of beech stemflow on spatial patterns of soil solution chemistry and seepage fluxes in a mixed beech/oak stand. Hydrol. Process. 14, 135–144.

Cortez, J., 1998. Field decomposition of leaf litters: relationships between decomposition rates and soil moisture, soil temperature and earthworm activity. Soil Biol. Biochem. 30, 783–793.

Crockford, R.H., Richardson, D.P., 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrol. Process. 14, 2903–2920.

Dalsgaard, L., 2008. Transpiration and Water Budgets of European Beech (*Fagus sylvatica* L.) Dominated Stands in Relation to Canopy Structure. PhD Thesis, University of Copenhagen, Forest and Landscape Research, vol. 39, Frederiksberg, Denmark.

Davie, T.J.A., Durocher, M.G., 1997a. A model to consider the spatial variability of rainfall partitioning within deciduous canopy. I. Model description. Hydrol. Process. 11, 1509–1523.

Davie, T.J.A., Durocher, M.G., 1997b. A model to consider the spatial variability of rainfall partitioning within deciduous canopy. II. Model parametrization and testing. Hydrol. Process. 11, 1525–1540.

Devlaeminck, R., De Schrijver, A., Hermy, M., 2005. Variation in throughfall deposition across a deciduous beech (*Fagus syvatica* L.) forest edge in Flanders. Sci. Total Environ. 337, 241–252.

Dolman, A.J., 1987. Summer and winter rainfall interception in an oak forest. Predictions with an analytical and a numerical simulation model. J. Hydrol. 90, 1–9.

Eschner, A.R., 1967. Interception and soil moisture distribution. In: Sopper, W.E., Lull, H.W. (Eds.), Proceedings of the International Symposium on Forest Hydrology, August 29–September 10. Pergamon Press, New York, pp. 191–200.

Falkengren-Grerup, U., 1989. Effect of stemflow on beech forest soils and vegetation in Southern Sweden. J. Appl. Ecol. 26, 341–352.

Ford, E.D., Deans, J.D., 1978. The effects of canopy structure on stemflow, throughfall and interception loss in a young Sitka Spruce plantation. J. Appl. Ecol. 15, 905–917.

Forrester, D.I., Bauhus, J., Cowie, A., 2005. Nutrient cycling in a mixed-species plantation of *Eucalyptus globulus* and *Acacia mearnsii*. Can. J. Forest Res. 35, 2942–2950.

Gash, J.H.C., 1979. An analytical model of rainfall interception by forests. Quart. J. Roy. Meteorol. Soc. 105, 43–55.

Gash, J.H.C., Lloyd, C.R., Lachaud, G., 1995. Estimating sparse forest rainfall interception with an analytical model. J. Hydrol. 170 (1–4), 79–86.

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, 3011–3025.

Gesper, P.L., Holowaychuck, N., 1970. Effects of stemflow water on a Miami soil under a beech tree. I. Morphological and physical properties. Soil Sci. Soc. Am. J. 34, 779–786.

Hall, R.L., 2003. Interception loss as a function of rainfall and forest types: stochastic modelling for tropical canopies revisited. J. Hydrol. 280 (1–4), 1–12.

Herbst, M., Roberts, J.M., Rosier, P.T.W., Taylor, M.E., Gowing, D.J., 2007. Edge effects and forest water use: a field study in a mixed deciduous woodland. Forest Ecol. Manage. 250 (3), 176–186.

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. Forest Meteorol. 148, 1655–1667.

Herwitz, S.R., 1987. Raindrop impact and water flow on the vegetative surfaces of trees and the effects on stemflow and throughfall generation. Earth Surf. Process. Land. 12, 425–432.

Herwitz, S.R., Levia, D.F., 1997. Mid-winter stemflow drainage from big-tooth aspen (*Populus grandidentata* Michx.) in central Massachusetts. Hydrol. Process. 11, 169–175.

Horton, R.E., 1919. Rainfall interception. Mon. Weather Rev. 47, 603–623.

Huber, A., Iroumé, A., 2001. Variability of annual rainfall partitioning for different sites and forest cover in Chile. J. Hydrol. 248, 78–92.

Jonard, M., André, F., Ponette, Q., 2006. Modeling leaf dispersal in mixed hardwood forests using a ballistic approach. Ecology 87 (9), 2306–2318.

Jonard, M., André, F., Jonard, F., Mouton, N., Procès, P., Ponette, Q., 2007. Soil carbon dioxide efflux in pure and mixed stands of oak and beech. Ann. Forest Sci. 64, 141–150.

Jonard, M., André, F., Ponette, Q., 2008. Tree species mediated effects on leaf litter dynamics in pure and mixed stands of oak and beech. Can. J. Forest Res. 38, 528–538.

Keim, R.F., Skaugset, A.E., Weiler, M., 2005. Temporal persistence of spatial patterns in throughfall. J. Hydrol. 314, 263–274.

Kelty, M.J., 1992. Comparative productivity of monocultures and mixed-species stands. In: David, M.S., Kelty, M.J., Larson, B.C., Oliver, C.D. (Eds.), The Ecology and Silviculture of Mixed-Species Forests. Kluwer, Dordrecht, pp. 125–141.

Kelty, M.J., 2006. The role of species mixtures in plantation forestry. Forest Ecol. Manage. 233, 195–204.

Killham, K., 1990. Nitrification in forest soils. Plant Soil 128, 31–44.

Kittredge, J., Loughead, H.J., Mazurak, A., 1941. Interception and stemflow in a pine plantation. J. Forest. 39, 505–522.

Klaasen, W., Lankreijer, H.J.M., Veen, A.W.L., 1996. Rainfall interception near a forest edge. J. Hydrol. 185, 349–361.

Klaassen, W., Bosveld, F., de Water, E., 1998. Water storage and evaporation as constituents of rainfall interception. J. Hydrol. 212–213, 36–50.

Krämer, I., Hölscher, D., 2009. Rainfall partitioning along a tree diversity gradient in a deciduous old-growth forest in Central Germany. Ecohydrology 2, 102–114.

Kukla, J., 2002. Variability of solutions percolated through cambisol in a beech ecosystem. Ekologia Bratislava 21, 13–25.

Levia, D.F., Frost, E.E., 2003. A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. J. Hydrol. 274, 1–29.

Levia, D.F., Frost, E.E., 2006. Variability of throughfall volume and solute inputs in wooded ecosystems. Prog. Phys. Geogr. 30 (5), 605–632.

Levine, J.M., D'Antonio, C.M., 1999. Elton revisited: a review of evidence linking diversity and invisibility. Oikos 87, 15–26.

Lilieholm, R.J., 1991. Financial risk and desired species composition in mixed species stands. Southern J. Appl. Forest. 15 (4), 185–187.

Link, T.E., Unsworth, M., Marks, D., 2004. The dynamics of rainfall interception by a seasonal temperate rainforest. Agric. Forest Meteorol. 124, 171–191.

Llorens, P., Oliveras, I., Poyatos, R., 2003. Temporal variability of water fluxes in a *Pinus sylvestris* forest patch in Mediterranean mountain conditions. In: Servat, E., Najem, W., Leduc, C., Shakeel, A. (Eds.), Hydrology in Mediterranean and Semi-Arid Regions, IAHS Publications No. 278, Wallingford, pp. 101–105.

Loescher, H.W., Powers, J.S., Oberbauer, S.F., 2002. Spatial variation of throughfall volume in an old-growth tropical wet forest. J. Trop. Ecol. 18, 397–407.

Loustau, D., Berbigier, P., Granier, A., El-Hadj Moussa, F., 1992. Interception loss, througfall and stemflow in a maritime pine stand. I. Variability of throughfall and stemflow beneath the pine canopy. J. Hydrol. 138, 449–467.

Mahendrappa, M.K., 1990. Partitioning of rainwater and chemicals into throughfall and stemflow in different forest stands. Forest Ecol. Manage. 30 (1–4), 65–72.

Massman, W.J., 1983. The derivation and validation of a new model for interception of rainfall by forests. Agric. Meteorol. 28, 261–286.

Menalled, F.D., Kelty, M.J., Ewel, J.J., 1998. Canopy development in tropical tree plantations: a comparison of species mixtures and monocultures. Forest Ecol. Manage. 104, 249–263.

Morris, D.M., Gordon, A.G., Gordon, A.M., 2003. Patterns of canopy interception and throughfall along a topographic sequence for black spruce dominated forest ecosystems in northwestern Ontario. Can. J. Forest Res. 33, 1046–1060.

Návar, J., 1993. The causes of stemflow variation in three semi-arid growing species of northeastern Mexico. J. Hydrol. 115, 51–63.

Noirfalise, A., 1959. Sur l'interception de la pluie par le couvert dans quelques forêts belges. Bull. Soc. Roy. For. Belgique 66, 433–439.

Nordén, U., 1991. Acid deposition and throughfall fluxes of elements as related to tree species in deciduous forests of South Sweden. Water Air Soil Pollut. 60, 209–230.

Peck, A.K., 2004. Hydrometeorologische und mikroklimatische Kennzeichen von Buchenwäldern. PhD Thesis, Berichte des Meteorologischen Intitutes der Universität Freiburg, vol. 10, University of Freiburg.

Price, A.G., Carlyle-Moses, D.E., 2003. Measurement and modelling of growing-season canopy water fluxes in a mature mixed deciduous forest stand, southern Ontario, Canada. Agric. Forest Meteorol. 119, 69–85.

Pypker, T.G., Bond, B.J., Link, T.E., Marks, D., Unsworth, M.H., 2005. The importance of canopy structure in controlling the interception loss of rainfall: examples from a young and an old-growth Douglas-fir forest. Agric. Forest Meteorol. 130, 113–129.

Robson, A.J., Neal, C., Ryland, G.P., Harrow, M., 1994. Spatial variations in throughfall chemistry at the small plot scale. J. Hydrol. 158, 107–122.

Rutter, A.J., Kershaw, K.A., Robins, P.C., Morton, A.J., 1972. A predictive model of rainfall interception in forests. I. Derivation of the model from observations in a plantation of Corsican Pine. Agric. Meteorol. 9 (5–6), 367–384.

Rutter, A.J., Morton, A.J., Robins, P.C., 1975. A predictive model of rainfall interception in forests. II. Generalisation of the model and comparison with observations in some coniferous and hardwood stands. J. Appl. Ecol. 12, 367–380.

Staelens, J., De Schrijver, A., Verheyen, K., Verhoest, N.E.C., 2006. Spatial variability and temporal stability of throughfall water under a dominant beech (*Fagus sylvatica* L.) tree in relationship to canopy cover. J. Hydrol. 330, 651–662.

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, 33–45.

Stout, B.B., McMahon, R.J., 1961. Throughfall variation under tree crowns. J. Geophys. Res. 66, 1839–1843.

Teklehaimanot, Z., Jarvis, P.G., 1991. Direct measurements of evaporation of intercepted water from forest canopies. J. Appl. Ecol. 28 (2), 603–618.

Vrugt, J.A., Dekker, S.C., Bouten, W., 2003. Identification of rainfall interception model parameters from measurements of throughfall and forest canopy storage. Water Resour. Res. 39 (9), 1251.

Whelan, M.J., Anderson, J.M., 1996. Modelling spatial patterns of throughfall and interception loss in a Norway spruce (*Picea abies*) plantation at the plot scale. J. Hydrol. 186, 335–354.

Whelan, M.J., Sanger, L.J., Baker, M., Anderson, J.M., 1998. Spatial patterns of throughfall and mineral ion deposition in a lowland Norway spruce (*Picea abies*) plantation at the plot scale. Atmos. Environ. 32, 3493–3501.

Zirlewagen, D., von Wilpert, K., 2001. Modeling water and ion fluxes in a highly structured, mixed-species stand. Forest Ecol. Manage. 143, 27–37.