Journal of Hydrology 512 (2014) 254–262

Contents lists available at ScienceDirect

Journal of Hydrology

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

Canopy wetness patterns in a Mediterranean deciduous stand

P. Llorens [a,*], F. Domingo [b], P. Garcia-Estringana [a], A. Muzylo [a], F. Gallart [a]

[a] *Institute of Environmental Assessment and Water Research (IDAEA), CSIC, Jordi Girona 18-26, 08034 Barcelona, Spain*
[b] *Department of Desertification and Geoecology, Arid Zones Research Station (EEZA), CSIC, General Segura 1, 04001 Almería, Spain*

ARTICLE INFO

Article history:
Received 27 December 2013
Received in revised form 20 February 2014
Accepted 1 March 2014
Available online 11 March 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Ellen Wohl, Associate Editor

Keywords:
Canopy wetness
Canopy drying duration
Inter-event time
Rainfall interception
Deciduous forest
Seasonal

SUMMARY

This study provides detailed information on the canopy drying process subsequent to rainfall events in a Mediterranean deciduous stand. Since this is a study of a deciduous forest (*Quercus pubescens* Willd.), it has been possible to assess the differences in canopy structure as well as in meteorological conditions between seasons. Results show clear seasonal differences in wetness duration during the drying phase after rainfall, with longer wetness duration in the leafed period (8 h) than in the leafless one (4 h). There is better canopy ventilation in the leafless season, increasing canopy boundary layer conductance. However, there is a wind shelter effect in the leafed season, which entails low turbulence transfer within the canopy. Likewise, canopies remain wet longer at night in both seasons, but the differences in wetness duration between day and night are greater in the leafless season. Finally, the results indicate that the methods commonly used to separate rainfall events give an erroneous indication of the real canopy drying duration. This leads to inaccuracy in the number and duration of rainfall events and, thus, in their properties (such as rainfall depth and intensity) and represents a challenge to rainfall interception models.

1. Introduction

Rainfall interception loss is the volume of rainfall that is retained by the vegetation canopy and subsequently evaporates without reaching the ground. It is controlled by several factors. Abiotic factors are related to rainfall characteristics and the meteorological conditions controlling the evaporative demand, while biotic factors are related to the structural characteristics of the vegetation cover, such as vegetation roughness and the storage capacity of vegetation elements (canopy, branches, trunks etc.). Storage capacity is the volume of water stored in the vegetation (Leyton et al., 1967; Rutter et al., 1972) and vegetation roughness controls the aerodynamic conductance of the evaporation of stored water (Monteith, 1965).

In deciduous forest, the seasonal changes in canopy structure, which affect both the characteristics of the vegetation elements and the microclimate within the canopy, add complexity to the rainfall partitioning process. This complexity is greater in Mediterranean areas due to the variability of the rainfall-interception loss relationship, caused by the characteristic Mediterranean precipitation regime (David et al., 2005; Llorens et al., 2011).

There are no clear conclusions about seasonal differences in rainfall interception loss and wet evaporation rates in deciduous forest. Some studies show significant seasonal throughfall and stemflow differences, whereas others do not. In forests where oaks are dominant, or one of the dominant tree species, in the leafed season throughfall represents about 80–85% of bulk rainfall, whereas in the leafless season it varies widely, from 67% to 94% (Deguchi et al., 2006; Dolman, 1987; Muzylo et al., 2012a; Price and Carlyle-Moses, 2003; Šraj et al., 2008). Similarly, the factors determining the wet evaporation rate in deciduous forest and the role of seasonal changes are open to debate. While some authors found higher wet evaporation rates during the leafed season (e.g. Dolman, 1987; Deguchi et al., 2006) and explain these differences by the combined role of the meteorological variables, other authors reported higher wet evaporation rates during the leafless season (e.g. Herbst et al., 2008; Staelens et al., 2008). The latter attributed this to the increased wind speed in the leafless season. Moreover, the role of available radiation should not be ignored, especially during the leafed season (e.g. Šraj et al., 2008).

Despite the importance of canopy wetness duration for wet canopy evaporation, few studies of rainfall partitioning have measured canopy wetness duration. Leaf wetness measurements are important in agriculture and ecology, because the frequency and duration of water on leaves have important consequences for plant growth and photosynthetic gas exchange, as well as for plant

* Corresponding author. Tel.: +34 93 400 61 00.
E-mail address: pilar.llorens@idaea.csic.es (P. Llorens).

http://dx.doi.org/10.1016/j.jhydrol.2014.03.007
0022-1694/

disease through pathogen infection forecasting (Brewer and Smith, 1997; Dietz et al., 2007; Huber and Gillespie, 1992) and for atmospheric pollutant deposition, especially in foggy regions (Burkhardt and Eiden, 1994; Klemm et al., 2002). Even though several physical or empirical models have been worked out to predict leaf wetness from meteorological variables for crop protection (Sentelhas et al., 2008), leaf wetness under natural field conditions cannot be easily predicted from meteorological variables or rainfall. In fact, many other factors are involved that clearly influence wetness duration, such as type of vegetation, boundary layer conditions and leaf characteristics (hydrophobicity, particle load, etc).

In this context, little is known about the duration of leaf wetness under natural field conditions, its variability within the canopy or its relationship with the microclimate inside the stand. Only the studies by Klemm et al. (2002) in temperate forest and Dietz et al. (2007) and Chu et al. (2012) in tropical montane forests provided information on this issue. Some of the main findings of these studies highlight the greater leaf surface wetness decrease after rainfall events in forested sites than at grassy ones, due to a major atmospheric exchange of the forest surface with the boundary layer (Klemm et al., 2002). In addition, it has been emphasized that differences in wetness duration depend on the position in the canopy and on the time of day (Dietz et al., 2007; Chu et al., 2012). The importance of wetness duration for rainfall interception and transpiration modelling was also mentioned. On the one hand, the results of Chu et al. (2012) indicated that transpiration occurs from a partially wet canopy. On the other hand, the long drying time observed by Dietz et al. (2007) questions the viability of the assumption of some rainfall interception models that the canopy dries completely between rainfall events.

A review of rainfall interception modelling (Muzylo et al., 2009) indicated that the original and sparse Gash models (Gash, 1979; Gash et al., 1995) are used more frequently than the other rainfall interception models. Gash (1979) provided an analytical solution to the original Rutter et al. (1972, 1975) model that assumes the separation of rainfall events by intervals sufficiently long for the canopy and stems to dry completely. This assumption is maintained in the majority of analytical models, as well as in Calder's models (1986, 1996). This approach assumes that canopy storage compartments are empty at the beginning of each storm and, in consequence, each rainfall event has a closed water balance. In practice, a fixed number of hours is used to separate storms, either for data treatment or modelling (see Dunkerley (2008) review).

The application of different inter-event times substantially change both the number of rainfall events and their properties, such as mean rainfall duration, depth or rate (Dunkerley, 2008), and in consequence affect the simulated interception loss (Wallace and McJannet, 2006). Suspecting the constraints of defining a set number of hours to separate storms, some authors used more elaborate methods to break up events, for example by determining the inter-event period as a function of the duration of each storm (Herbst et al., 2006; Pearce and Rowe, 1981).

The main objective of this study was to analyse whether the common use of a fixed number of hours to separate rain events is consistent with the observations of canopy wetness duration, in particular for stands with seasonal changes in both canopy and rainfall characteristics. The secondary aim of this study is to evaluate whether the assumption of the use of set inter-event duration means that canopy storage compartments are empty at the beginning of each storm.

To attain these objectives, this study aims to answer the following questions: (i) What differences are observed in canopy wetness duration between events? (ii) Are there differences in canopy wetness duration between seasons? (iii) Are there differences in canopy wetness duration between day and night conditions? (iv) What driving forces explain wetness variability? and finally (v) Is the use of a set number of hours, after precipitation ending, adequate for separating events?

We attempted to answer these questions by analysing the patterns of deciduous canopy drying in a number of rainfall events in different seasons, which in turn entailed distinct canopy structures and meteorological conditions.

2. Materials and methods

2.1. Site description

The study plot is located in the Vallcebre research catchments (Gallart et al., 2005; Latron et al., 2010a) in the eastern Pyrenees at 1100 m a.s.l. The climate is Sub-Mediterranean, with a mean annual temperature of 9.1 °C. Mean annual reference evapotranspiration is 823 ± 26 mm and mean annual precipitation is 862 mm ± 206 mm (Latron et al., 2010a). Precipitation is seasonal, with autumn and spring usually the wet seasons, whereas summer and winter are dry. Summer rainfall is characterised by intense convective events, whereas in winter precipitation is caused by frontal systems (Latron et al., 2010b).

The forest canopy consists mainly of downy oaks (*Quercus pubescens* Willd.), mixed with a few other deciduous species. The forest understorey is mostly composed of *Buxus sempervirens* patches of varying density and height. The mean tree height at the study site was 11.2 m (±2 m) and tree density is 828 stems per hectare (Poyatos et al., 2005). Leaves appear in the first half of May and autumn leaf-fall is progressive, with 90% of leaves falling between October and December. The main traits of the canopy structure in the plot studied are presented in Table 1 (Muzylo et al., 2012b).

2.2. Precipitation and meteorological variable measurements

Precipitation was recorded in a nearby clearing with a standard 0.2 mm-resolution tipping bucket rain gauge (AW-P, Institut Analític, Spain) and collected data was stored on a data logger (DT500, DataTaker, Australia) every five minutes.

Net radiation (NR-Lite, Kipp&Zonen, The Netherlands), air temperature and relative humidity (HMP35C, Vaisala, Finland), wind speed (A100R, Vector Instruments, UK) and wind direction (6504, Unidata, Australia) were measured above the canopy at 13.5 m. These meteorological data were completed with measurements of air temperature, relative humidity and wind speed at the maximum crown volume level (8.0 m) and below crowns (2.5 m). Measurements were taken every minute and five-minute averages were stored on the data logger.

2.3. Leaf-wetness measurement

Twenty leaf-wetness sensors (237F, Campbell Scientific, UK) were installed on a mast in pairs at 1-m intervals throughout the canopy, from 3 to 12 m above the ground. The sensors were glued to rigid supports, which were mounted on flexible poles. This

Table 1
Stand and canopy characteristics of the *Quercus pubescens* plot.

	Leafed	Leafless
DBH (cm)	22.3	
Basal area (cm^2)	411.8	
LAI ($m^2\ m^{-2}$)	3.35 (±0.5)	
Canopy cover	0.64	0.35
Canopy storage capacity (mm)	0.49	0.17
Trunks storage capacity (mm)	0.03	0.07

Adapted from: Muzylo et al. (2012b).

arrangement enabled them to oscillate with twig-like movements within the canopy.

The 237F sensor consists of a flexible polyimide film circuit (14 × 90 mm) with interlacing gold-plated 0.25 mm-spaced copper fingers. Sensors' electric current (mA) and applied potential (mV) were measured every minute and five-minute averages were recorded on a data logger (DT85, DataTaker, Australia).

These measurements were complemented with descriptions of changes in canopy characteristics between leafed and leafless seasons, as follows: canopy cover by hemispherical photographs and LAI by means of litterfall collection (Bréda, 2003). In addition, canopy storage capacity was calculated as proposed in Valente et al. (1997) (Muzylo et al., 2012b).

2.4. Data analysis

The data collected during the years 2008 and 2009 were divided into two periods: the leafed season, including events from mid-May to mid-October, and the leafless season, including events from the beginning of January to the first week of May. The period between mid-October and beginning of January, when leaf fall occurs, as well as the period of leaf burst, were not included in the analysis.

40 Rainfall events, 20 during the leafed and 20 during the leafless season, with more than 1 mm rainfall and without any instrument malfunction, were used in this study.

Measured electric current and applied potential were used to calculate the electric conductance of each sensor. These data were averaged for each level (means of 2 sensors per level). Then, the relative wetness of each level was calculated as the quotient between the 5-min mean conductance and the maximum conductance calculated for the whole event, under the assumption that the maximum conductance is representative of a completely wet surface. This information then determined, for each time-step, whether the measuring level was wet or dry. To avoid uncertainties, when relative wetness was lower than 5%, the sensor was considered dry. Canopy drying phase duration was defined as the period from the first 5 min without rainfall until all the sensors were considered dry.

Day drying phases were those in which rainfall ended between sunrise and sunset, whereas night drying phases were those in which rainfall ended between sunset and sunrise the following day.

The temporal stability analysis methodology (Vachaud et al., 1985) was used to compare, over time, the wetness duration measured at each level with the mean wetness duration of the whole profile.

The Shapiro–Wilk test, with a threshold probability of $\alpha = 0.05$, was used for testing the normality of the distributions, unless stated otherwise. For testing differences between samples the Student's *t*-test was used when samples were normally distributed and the Mann–Whitney Rank Sum test when they were not, in both cases with a threshold probability of $\alpha = 0.05$.

2.5. Event separation

The results of two different methods currently used for separating different precipitation events for rainfall interception modelling were compared with the events separated using the measurements of wetness duration. The first method takes fixed rainless periods between events and was named Minimum Inter-event time (MIT) by Dunkerley (2008). In the second one, the inter-event periods are estimated, following Pearce and Rowe (1981), as a function of the duration of each storm. This method considers inter-event periods of 1 h for rainfall events up to 4 h, 2 h for events between 4 and 8 h and 3 h for events longer than 8 h.

3. Results

3.1. Rainfall characteristics of the studied events

The mean rainfall amount of the events studied was slightly higher in the leafed season than in the leafless one, 8 and 7 mm respectively. Moreover, there was less variability between event depths during the leafed season than during the leafless one, as indicated by the respective coefficients of variation (51% and 99%). However, there were noticeable differences in rainfall intensity and duration. The events studied were shorter and more intense during the leafed season, with mean duration of less than 3 h and mean rainfall intensity of about 5 mm h^{-1}, than during the leafless season, when mean duration was 7 h and rainfall intensity less than 2 mm h^{-1} (Table 2).

There was no statistically significant relationship between event rainfall amount or rainfall intensity and wetness duration in the leafless season. However, the correlation between wetness duration and rainfall amount was significant at the 0.05 level for the leafed events (data not shown).

Another difference between the leafed and leafless seasons was the timing of rainfall events; during the leafless season, rainfall events occurred nearly uniformly throughout the day with 40% of rainfall events ending before noon, whereas during the leafed season only 10% of events ended before noon.

3.2. Canopy wetness duration during the drying phase

The results indicated differences in wetness duration during the drying phase between the leafed and the leafless events. The mean wetness duration of the leafed season was 7.6 h and the median 8.5 h, whereas in the leafless season the mean was 4.2 h and the median only 1.7 h (Fig. 1). In the leafed season, wetness duration data were not far from normally distributed ($p = 0.047$). However, in the leafless season wetness duration was not normally distributed, but rather followed bimodal distribution (Fig. 1a). For this reason, events with short and long canopy wetness duration data were taken separately (Fig. 1b). Both resulting groups were normally distributed ($p > 0.05$), with the long events having the same distribution (mean and standard deviation) as the leafed events.

Relative differences, respect to the mean, in wetness duration were similar in both seasons (Fig. 2), with wetness duration near the mean for the main part of the crown volume, the shortest wetness duration at the top of the canopy (above 10–11 m) and the longest wetness duration below the crown (below 5 m) and, in particular, near the ground. These results indicate that both profiles showed a temporal persistence of within canopy wetness duration patterns.

3.3. Temperature, vapour pressure deficit and wind speed profiles during the drying of the canopy

Air temperature profiles showed the expected differences between the leafed season encompassing spring and summer (mean temperature of 13 °C) and the leafless season during the winter

Table 2
Characteristics of the studied rainfall events.

	N	Duration (h)	Rainfall amount (mm)	Rainfall intensity	
				I (mm/h)	I5' (mm/h)
Leafed	20	2.8 (±0.5)	8.4 (±1.0)	4.7 (±4.2)	26.2 (±16.7)
Leafless	20	7.3 (±1.4)	6.9 (±1.5)	1.9 (±2.6)	8.6 (±7.2)

I = mean rainfall intensity and I5′ = 5 min rainfall intensity.

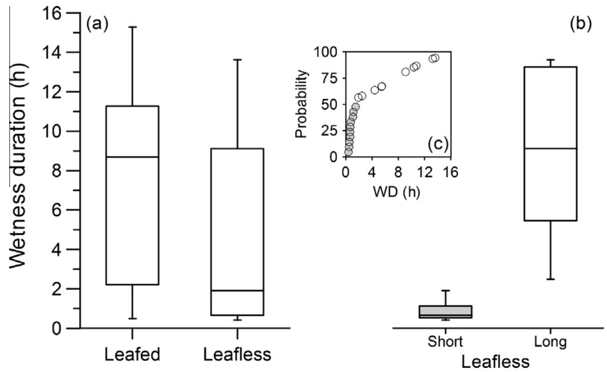

Fig. 1. Box-whisker plots of canopy wetness duration for the leafed and leafless seasons (a). Canopy wetness duration for the leafless season when long and short events were separated (b). These two groups were divided because leafless data followed a bimodal distribution (c), WD = Wetness duration.

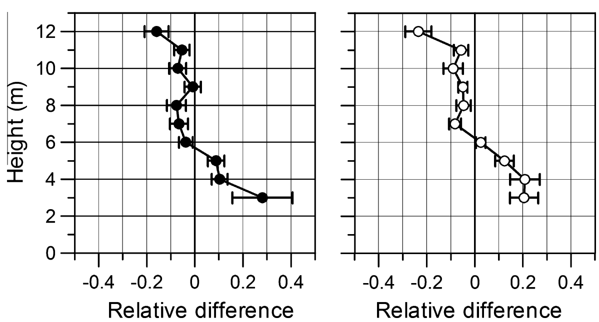

Fig. 2. Time-stability plot of wetness duration profiles in the leafed (left) and leafless seasons (right). Dots represent means and bars standard errors.

(mean temperature 6 °C). Moreover, slight variations in mean air temperature profile were observed in both seasons (Fig. 3a).

Vapour pressure deficit (VPD) distributions were further away from normality at the lower levels within the canopy during the leafed season ($p = 0.147$ at 13 m and $p < 0.001$ at the other levels) and at all levels during the leafless one ($p < 0.001$). Wind speed distributions were also further away from normality during both seasons ($p < 0.001$). For this reason, the median instead of the mean will be used from now on to compare the profiles of VPD and wind speed.

VPD profiles (Fig. 3b) showed the wettest conditions below the canopy in both seasons, but the differences between levels were more marked during the leafed season. Even though the air below the lowest green branches (2.5 m) was almost always saturated in both seasons, the air at the top of the canopy, as well as the air at the maximum crown volume, was drier in the leafed season (medians of 0.24 and 0.15 kPa at the top and of 0.10 and 0.05 kPa at 8 m, respectively).

Higher median wind speeds were observed during the leafless season, in particular within the canopy (Fig. 3f). At the maximum crown volume, median wind speed during the leafless season was more than 3 times greater than during the leafed season (medians of 0.47 and 0.12 ms^{-1}, respectively), whereas below the lowest green branches it was 5 times greater, indicating high ventilation and a better mixing of air at this level when trees had no leaves (medians of 0.26 and 0.05 ms^{-1}, respectively).

Wind speed profiles in both seasons were statistically different ($p < 0.001$), whereas VPD profiles were not ($p = 0.510$) (Fig. 4). On comparing profiles level by level, it could be seen that VPD was statistically different between seasons only at the top of the canopy ($p = 0.014$). In contrast, wind speed was similar in both seasons at the top of the canopy ($p = 0.156$) and different at the maximum crown volume and at the bottom of the profile ($p < 0.001$). Moreover, there were no significant differences in wind direction (measured above the canopy) during the drying phase of both seasons. The dominant wind direction was W-NW in both cases (70% and 60% of events in the leafed and leafless seasons, respectively).

Wetness duration decreased markedly as wind speed and VPD measured above the canopy (13 m) increased (Fig. 5). The relationship between wetness duration and wind speed followed the same negative exponential trend in both seasons (Fig. 5a), with wetness durations under 2 h when wind speed was higher than 1.5 ms^{-1}. The relationship between wetness duration and VPD followed the same negative exponential trend, but the relationship was different for the two seasons. During the leafless season when VPD was higher than 0.2 kPa, wetness durations were shorter than 2 h, while in the leafed season wetness durations shorter than 2 h were observed for VPD higher than 0.4 kPa (Fig. 5b).

3.4. Day and night-time wetness duration

Results indicated considerable differences in wetness duration between day and night in both seasons, with the sensors remaining wet for longer at night (Fig. 6). Mean wetness duration at night was 11.5 and 7 h in the leafed and leafless seasons, respectively, whereas during the day duration was 5 and 2 h. Moreover, wetness duration at night was more similar between events, especially in the leafed season (coefficients of variation of 17% and of 67% in leafed and leafless seasons, respectively), than during the day (98% and 170%). In the leafless season, the very short wetness durations during the day, compared with the wide range of durations at night, explain the bimodal distribution shown in Fig. 1. In addition, during the day, in both seasons the wetness duration was more uniform throughout the profile than at night. Maximum differences of one level respect to the mean of the whole profile were less than 8% during the day, while at night they were up to 18%. Finally, the stratification of wetness duration was more marked at night than during the day in the leafless season (mean difference of 2 h between 12 and 3 m), while the opposite occurred in the leafed season (mean difference of 1.5 h) (Fig. 7).

The shapes of VPD profiles were similar by day and by night, with the highest VPD at the top of the canopy. However, mean VPD was about double during the day than at night in both seasons and for each measured height (Fig. 7). During the leafless season the shape of the wind speed profiles was similar during the day and at night, while in the leafed season there were differences, especially at the maximum crown volume (Fig. 7). However, both varied greatly within the canopy (with coefficients of variation up to 170% for both variables at the bottom of the profile).

3.5. Inter-event time

A series of three rainfall events in June shows important differences in wetness duration depending on the meteorological conditions (Fig. 8). Wetness lasted longer with low wind speed and VPD measured above the canopy (Fig. 8a). Moreover, differences depending on the measurement height, 12 or 3 m, were also seen. The drying started earlier at the top of the canopy and took longer at the bottom (Fig. 8d).

The comparison of three examples of fixed rainless periods or MITs of 2, 6 and 12 h, as well as the measured event duration using the wetness sensors for the three events indicates low correspondence between the two, whatever the MIT used (Fig. 8c). As there is no correspondence in the number of events for MIT equal to 12 h, more than one rainfall burst is considered in the same single event. The use of a shorter MIT (2 h) allows rainfall events to be separated

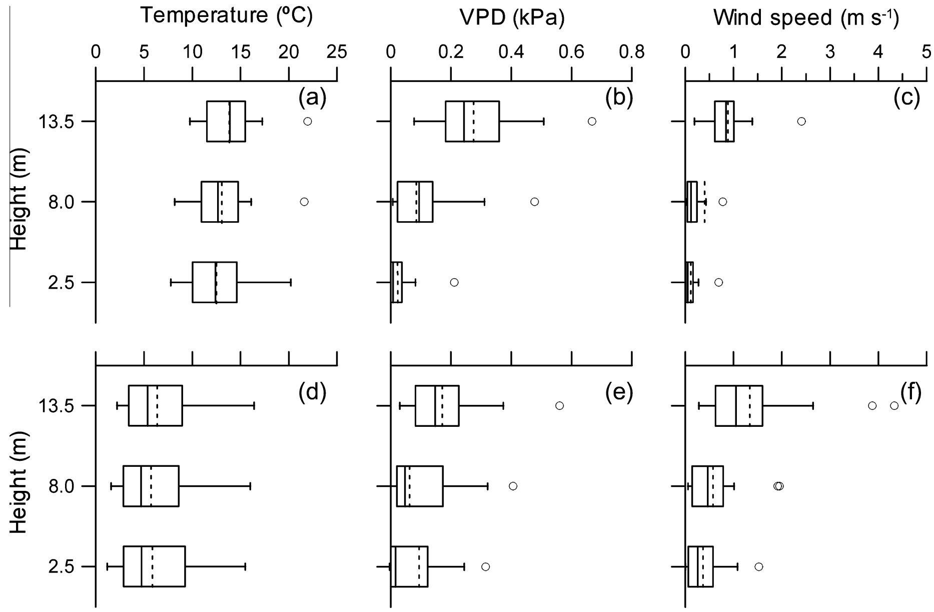

Fig. 3. Box-whisker profiles of temperature, relative humidity and wind speed during the drying phase, for the leafed (a–c) and leafless seasons (d–f). The dotted lines represent the means, the continuous lines the medians and the dots the outliers.

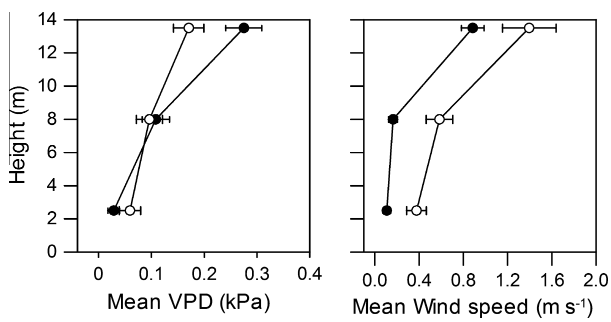

Fig. 4. Intra-canopy mean (±1 SE) vapour pressure deficit and wind speed profiles for the leafed and leafless seasons (black dots and white dots, respectively).

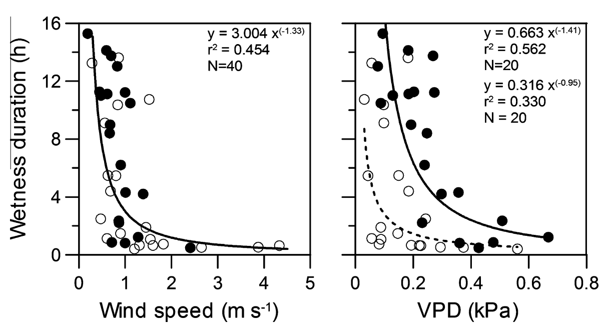

Fig. 5. Relationship between event canopy wetness duration and wind speed and vapour pressure deficit in the leafed and leafless seasons (black and white dots, respectively).

better. However, none of the MIT gave any indication of the real canopy drying duration.

The relationship between event rainfall duration and wetness duration after rainfall ends, for all the events studied, indicates that if a set number of hours is used to separate events (fixed MIT), a large number of events had longer durations than the selected MIT (Fig. 9). For example, a MIT of 12 h is acceptable for 80% and 90% of the events during the leafed and leafless seasons,

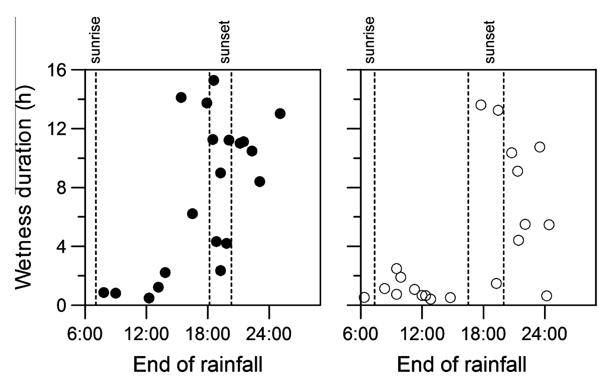

Fig. 6. Relationship between time-end of rainfall (24-h clock time) and canopy wetness duration for the leafed (left) and leafless (right). seasons.

respectively, but these values drop to 40% and 75% if the selected MIT is 6 h. However, the risk of choosing longer MIT durations is that different rainfall bursts may be taken as the same event. For example, a MIT of 12 h considers events 1 and 2 in Fig. 8 as only one event.

Using the separation of events proposed by Pearce and Rowe (1981), we saw that their assumptions were better met during the leafless season than during the leafed one. In the leafless season, half the observed events had wetness durations shorter than the proposed ones. However, there were only 3 events in the leafed season meeting the proposed conditions, inducing an over-estimation of the intercepted depth.

4. Discussion

4.1. What about the method used for measuring the duration of canopy wetness?

This paper compares the drying time of a profile of electric grid sensors designed to allow the wind to move the sensors just as it moves twigs. This monitoring design, with a replicate number of sensors, at 10 levels with two sensors on each level, characterises

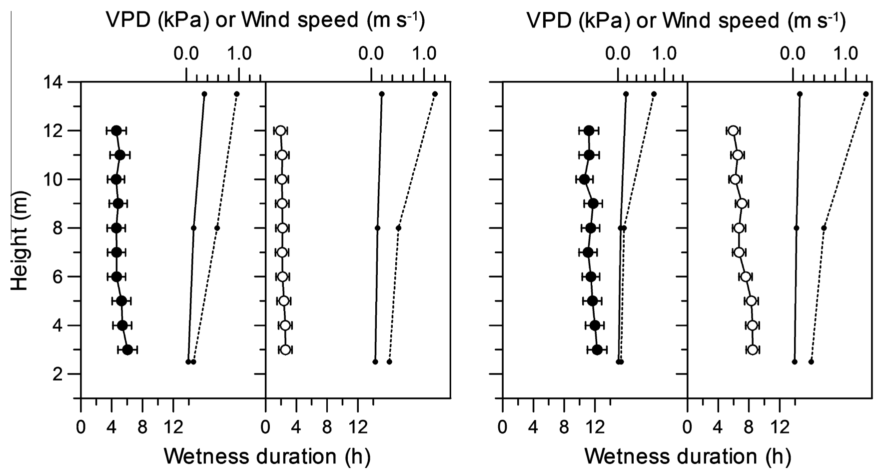

Fig. 7. Profiles of wetness duration, wind speed and VPD during day (left) and night (right). Black dots and white dots represent wetness duration in the leafed and leafless seasons (±1 SE), respectively. Continuous lines represent VPD and discontinuous wind speed.

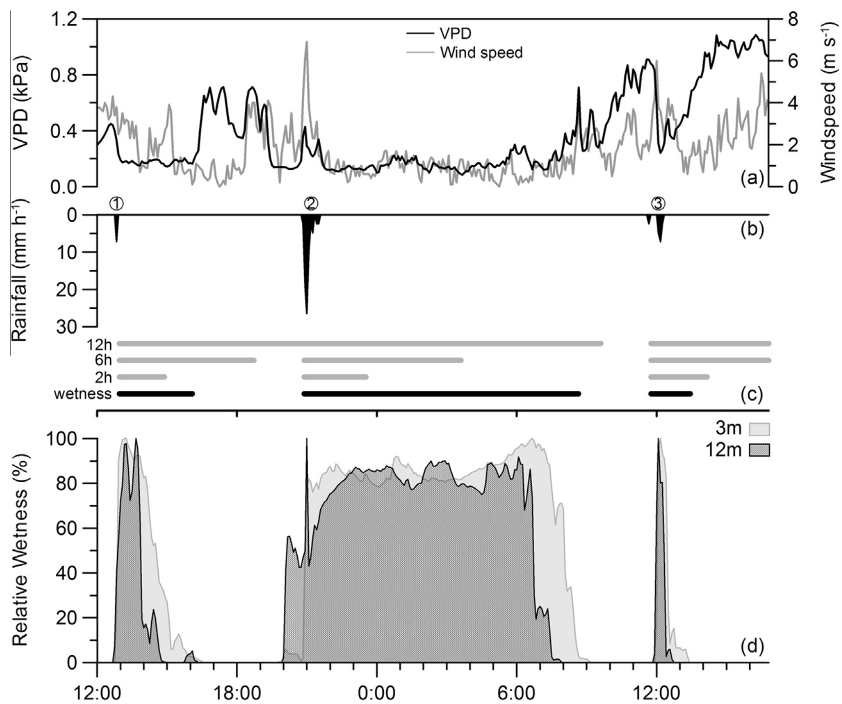

Fig. 8. Series of three rainfall events in June. Wind speed and VPD above the canopy (a), rainfall intensity (b), inter-event times of 2, 6 and 12 h (see text) (c) and wetness duration at 3 and 12 m (d).

the wetness profile adequately, as suggested by Chu et al. (2012). However, we are aware that future research is needed to improve canopy wetness monitoring, especially to interpret better the degree of leaf wetness by artificial sensors (Klemm et al., 2002). The grid sensors used in this study (237F, Campbell Scientific), as well as the other wetness sensors measuring electric resistances or dielectric constants (both grid and clip sensors), still do not allow the volume of water intercepted to be measured, even though they are useful for calculating the duration of canopy wetness (Chu et al., 2012; Klemm et al., 2002).

Miranda et al. (2000) indicated that grid sensors correlated better with the weight loss of water than clip sensors did, but that the water accumulation observed in the sensor structure gave grid-sensor wetness durations longer than those given by direct observations of wetness duration on natural leaves. For this reason, the studies of differences in wettability of natural surfaces and the factors influencing them (e.g. Garcia-Estringana et al., 2010; Holder, 2012, 2013) should be considered, in order to adapt wetness sensors to natural behaviour. Even if the measured wetness durations do not exactly match the real behaviour of leaves and twigs, they provided a standardized way to analyse the seasonal changes in drying processes due to weather and canopy variations.

4.2. What are the seasonal differences observed in canopy wetness duration? And which drivers explain these differences?

There were clear seasonal differences in wetness duration between seasons: wetness duration was longer in the leafed season, with median duration 4 times greater than during the leafless season. The drivers explaining these differences could be related to the characteristics of rainfall events, differences in canopy wetting and differences in wet canopy evaporation between seasons.

The seasonal differences in the magnitude, duration and frequency of rainfall events could contribute to seasonal variations

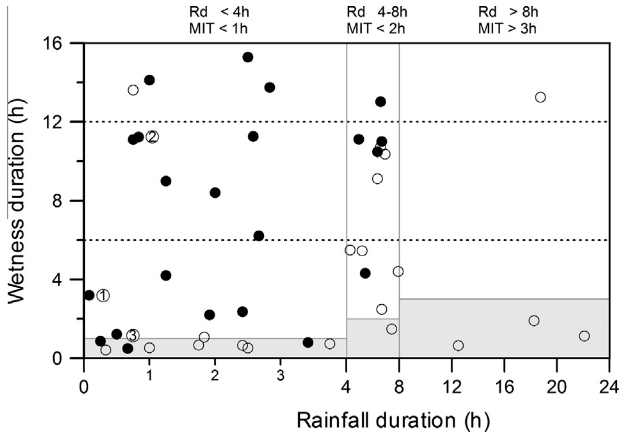

Fig. 9. Relationship between rainfall duration and wetness duration for the leafed and leafless events studied (black dots and white dots, respectively). The dotted line indicates fixed 6 and 12 h values for separating events. The grey boxes indicate the hours proposed by Pearce and Rowe (1981) for separating events, Rd = rainfall duration and MIT = Minimum Inter-event time (see text). Numbers refer to the three events of Fig. 8.

in intercepted water (e.g. David et al., 2005; Llorens et al., 1997) and therefore in canopy wetness duration. However, in the present study, there was no clear influence of rainfall characteristics on canopy wetness duration. The shorter and the more intense rainfall events occurring during the leafed season had the longer drying durations.

Leaf area, increasing the canopy storage capacity, is the main canopy factor determining rainfall interception (e.g. Deguchi et al., 2006; Llorens and Domingo, 2007). In canopies with seasonal changes, the differences in S are larger between seasons (Table 1) and the absence of leaves reduces canopy storage and increases free throughfall, i.e. helps the drops fall through the canopy. Differences in canopy storage capacity, as calculated by Muzylo et al. (2012b) for the forest studied, are responsible for a higher volume of water intercepted when there are leaves, which will result in longer wetness duration for the same evaporative demand. Moreover, the greater frequency of rainfall events ending during the afternoon in the leafed season, observed in this study, increases the time the canopy remains wet and the number of drying periods that last till the following morning, because of the lower evaporative demand during the night, as described elsewhere (Chu et al., 2012; Dietz et al., 2007).

Moreover, micrometeorological conditions differ between seasons due to seasonal changes in the canopy structure. For both seasons, mean wetness lasted much less when wind speed at the top of the canopy was higher than 1.5 ms^{-1}, indicating the marked influence of wind speed on the canopy drying rate. However, higher wind speeds were observed in the leafless season at the top and also within the canopy, indicating good wind penetration through the leafless canopy. On the other hand differences in VPD between seasons were observed only at the top of the canopy, related to higher temperatures in summer, but longer wetness durations were observed for the same VPD during the leafed season.

Differences in canopy wetness duration (as well as the wet evaporation rate) should be primarily related to differences in wind speed profiles between seasons, particularly to higher canopy boundary layer conductance in the leafless season. Although high VPD in the leafed season could enhance wet evaporation at the top of the canopy, the foliage produces a denser canopy and shelter that decreases wind speed and favours lower canopy boundary layer conductance (Domingo et al., 1996) and, in consequence, low turbulence transfer within the forest in this season (Baldocchi, 1989). Unfortunately, the possible role of radiation penetration in wetness duration could not be analysed because radiation was not measured along the profile.

4.3. Are there any differences in wetness duration between day and night conditions?

The analysis of the differences between day and night wetness duration has not, to our knowledge, been documented for seasonal, temperate or Mediterranean, forests. However, there is some information for tropical montane cloud forests, where the role of fog and rain has been analysed (Chu et al., 2012; Dietz et al., 2007).

Our results indicated that canopies remain wet longer at night in both seasons. However, in the leafed season night durations were twice as long as day-time ones, whereas in the leafless season night durations were 3.5 times longer. Long wetness durations following afternoon fog or rainfall were also observed by Chu et al. (2012) and Dietz et al. (2007), as well as enhanced midday canopy conductance during the days following afternoon fog or rain events, compared with days with prevalent dry conditions (Chu et al., 2012).

The stratification of wetness duration after rainfall events was formerly described (e.g. Dietz et al., 2007). However, differences in profiles of wetness duration between seasons, as described here, have not been documented elsewhere. For this reason, the findings reported here are highly relevant to the understanding of seasonal differences in canopy wetness duration.

In the forest studied, the wetness stratification was more marked during nights in the leafless season, while the opposite occurred during the leafed season. This could be the result of stronger stable thermal stratification during winter nights, whereas during the day turbulence was effectively promoting transport through the canopy. However, the stratification of day-time wetness duration in the leafed season should be related to higher air saturation and slow air motion in the lowermost part of the profile, along with dryer and hotter air at the top of the canopy (e.g. Baldocchi, 1989).

4.4. Is the use of a set number of hours sufficient for separating events?

The differences observed in wetness duration between seasons, and especially between days and nights in the same season, raise questions about the use, in both data treatment and modelling, of a set number of hours to separate rainfall events.

Our results indicate that the comparison of event separation when using wetness duration data with either set MITs or with MIT changes depending on the rainfall duration (Herbst et al., 2006; Pearce and Rowe, 1981), gave poor results, especially during the leafed season.

If any of the set MITs tested gives an erroneous indication of the real canopy drying duration, this will result in an incorrect determination of the number of rainfall events and, in consequence, of their properties. Moreover, as indicated by Wallace and McJannet (2006), the total simulated interception loss decreases as the MIT increases, when using a model that considers that the canopy dries completely between events, such as the Gash (1979) model or its derivatives. This effect is due to both the decrease in the term of the model associated with the evaporation of small events, which are included in larger events, and the decrease of evaporation after rainfall, since there are fewer rainfall events able to saturate the canopy.

Furthermore, results indicating transpiration (sapflow-based) prior to the end of the drying phase show that transpiration occurs even when the canopy is still partially wet in a tropical montane forest (Chu et al., 2012), which is an additional challenge to water balance models.

5. Conclusions

The canopy wetness patterns in a Mediterranean deciduous stand show clear seasonal differences in wetness duration, with longer wetness duration in the leafed season. While rainfall characteristics seem to have no influence on canopy wetness duration, differences in canopy storage capacity between seasons, as well as the time of day when the rainfall ends, have a determining effect on wetness duration. Differences in canopy structure, besides entailing differences in canopy storage capacity between seasons, will promote higher canopy boundary layer conductance in the leafless season, due to better canopy ventilation. However, there is a wind shelter effect in the leafed season, which entails low turbulent transfer within the canopy.

Another important behaviour of deciduous stands is that canopies remain wet longer at night in both seasons, but differences between day and night were larger in the leafless season. There is greater wetness stratification at night than during the day in the leafless season, whereas the opposite occurs during the leafed season. This is explained by stronger stable thermal stratification during winter nights, as well as higher saturation and slow air motion in the lowermost part of the profile during summer days. The findings on the differences in wetness duration stratification reported here, and not documented elsewhere, are highly relevant to the understanding of seasonal differences in canopy wetness duration in canopies with seasonal changes.

Finally, all the tested methods for separating rainfall events give an erroneous view of real canopy drying duration, which will lead to incorrect determination of the number of rainfall events and, in consequence, of their properties. Moreover, these findings raise a challenge to the rainfall interception models that assume that the canopy dries completely between events.

Acknowledgments

This study was supported by the MONTES (CSD2008-00040) and the RespHiMed (CGL2010-18374) projects, funded by the Spanish Ministry of Economy and Competitiveness (MINECO). The Vallcebre Research Catchments operate with the support of RESEL, belonging to the Spanish Ministry of Agriculture, Food and Environment (MAGRAMA). We sincerely thank J. Gash for fruitful discussions. We are also grateful to J. Latron, G. Nord, X. Huguet, O. Avila and M.A. González for their support during field work and data collection and to M. Eaude for English style revision. We are also indebted to two anonymous reviewers whose comments significantly improved this paper.

References

Baldocchi, D.D., 1989. Turbulent transfer in a deciduous forest. Tree Physiol. 5 (3), 357–377.

Bréda, N.J., 2003. Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. J. Exp. Bot. 54 (392), 2403–2417.

Brewer, C., Smith, W., 1997. Patterns of leaf surface wetness for montane and subalpine plants. Plant, Cell Environ. 20 (1), 1–11.

Burkhardt, J., Eiden, R., 1994. Thin water films on coniferous needles: a new device for the study of water vapour condensation and gaseous deposition to plant surfaces and particle samples. Atmos. Environ. 28 (12), 2001–2011.

Calder, I.R., 1986. A stochastic model of rainfall interception. J. Hydrol. 89 (1), 65–71.

Calder, I.R., 1996. Dependence of rainfall interception on drop size: 1. Development of the two-layer stochastic model. J. Hydrol. 185 (1), 363–378.

Chu, H.-S., Chang, S.C., Klemm, O., Lai, C.-W., Lin, Y.Z., Wu, C.C., Lin, J.Y., Jiang, J.Y., Chen, J., Gottgens, J. F. and Hsia, Y.-J., 2012. Does canopy wetness matter? Evapotranspiration from a subtropical montane cloud forest in Taiwan. Hydrological Processes. (doi:10.1002/hyp.9662).

David, J.S., Gash, J.H.C., Valente, F., 2005. Evaporation of intercepted rainfall. In: Anderson, M. (Ed.), Encyclopedia of Hydrological Sciences. John Wiley, Chichester, pp. 627–634.

Deguchi, A., Hattori, S., Park, H.T., 2006. The influence of seasonal changes in canopy structure on interception loss: application of the revised Gash model. J. Hydrol. 318 (1–4), 80–102.

Dietz, J., Leuschner, C., Hölscher, D., Kreilein, H., 2007. Vertical patterns and duration of surface wetness in an old-growth tropical montane forest, Indonesia. Flora – Morphol. Distrib. Funct. Ecol. Plants 202 (2), 111–117.

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 (1–2), 1–9.

Domingo, F., Van Gardingen, P., Brenner, A., 1996. Leaf boundary layer conductance of two native species in southeast Spain. Agric. For. Meteorol. 81 (3), 179–199.

Dunkerley, D., 2008. Identifying individual rain events from pluviograph records: a review with analysis of data from an Australian dryland site. Hydrol. Process. 22 (26), 5024–5036.

Gallart, F., Latron, J., Llorens, P., 2005. Catchment dynamics in a Mediterranean mountain environment. The Vallcebre research basins (south eastern Pyrenees) I: hydrology. In: Garcia, C., Batalla, R.J. (Eds.), Catchment Dynamics and River Processes: Mediterranean and Other Climate Regions. Elsevier, pp. 1–16.

Garcia-Estringana, P., Alonso-Blázquez, N., Alegre, J., 2010. Water storage capacity, stemflow and water funneling in Mediterranean shrubs. J. Hydrol. 389 (3), 363–372.

Gash, J.H.C., 1979. An analytical model of rainfall interception by forests. Quart. J. Roy. Meteorol. Soc. 105 (443), 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.

Herbst, M., Roberts, J.M., Rosier, P.T.W., Gowing, D.J., 2006. Measuring and modelling the rainfall interception loss by hedgerows in southern England. Agric. For. Meteorol. 141 (2–4), 244–256.

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.

Holder, C.D., 2012. The relationship between leaf hydrophobicity, water droplet retention, and leaf angle of common species in a semi-arid region of the western United States. Agric. For. Meteorol. 152 (1), 11–16.

Holder, C.D., 2013. Effects of leaf hydrophobicity and water droplet retention on canopy storage capacity. Ecohydrology 6, 483–490.

Huber, L., Gillespie, T., 1992. Modeling leaf wetness in relation to plant disease epidemiology. Annu. Rev. Phytopathol. 30 (1), 553–577.

Klemm, O., Milford, C., Sutton, M.A., Spindler, G., van Putten, E., 2002. A climatology of leaf surface wetness. Theoret. Appl. Climatol. 71 (1–2), 107–117.

Latron, J., Llorens, P., Soler, M., Poyatos, R., Rubio, C.M., Muzylo, A., Martinez-Carreras, N., Delgado, J., Regüés, D., Catari, G., 2010a. Hydrology in a Mediterranean mountain environment-the Vallcebre research basins (northeastern Spain). I. 20 years of investigation of hydrological dynamics. IAHS Publication 336, 38–43.

Latron, J., Soler, M., Llorens, P., Nord, G., Gallart, F., 2010b. Hydrology in a Mediterranean mountain environment-the Vallcebre research basins (northeastern Spain). II Rainfall runoff relationships and runoff processes. IAHS Publication 336, 151–156.

Leyton, L., Reynolds, E., Thompson, F., 1967. Rainfall interception in forest and moorland, International Symposium on forest hydrology. Pergamon Press, New York, USA, pp. 168.

Llorens, P., Domingo, F., 2007. Rainfall partitioning by vegetation under Mediterranean conditions. A review of studies in Europe. J. Hydrol. 335 (1–2), 37–54.

Llorens, P., Latron, J., Álvarez-Cobelas, M., Martínez-Vilalta, J., Moreno, G., 2011. Hydrology and biogeochemistry of mediterranean forest. In: Levia, D.F., Carlyle-Moses, D.E., Tanaka, T. (Eds.), Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions. Springer-Verlag, Heidelberg, Germany, pp. 301–319 (invited).

Llorens, P., Poch, R., Latron, J., Gallart, F., 1997. Rainfall interception by a Pinus sylvestris forest patch overgrown in a Mediterranean mountainous abandoned area I. Monitoring design and results down to the event scale. J. Hydrol. 199, 331–345.

Miranda, R.A., Davies, T.D., Cornell, S.E., 2000. A laboratory assessment of wetness sensors for leaf, fruit and trunk surfaces. Agric. For. Meteorol. 102 (4), 263–274.

Monteith, J., 1965. Evaporation and environment. Symp. Soc. Exp. Biol. 19, 205–234.

Muzylo, A., Llorens, P., Valente, F., Keizer, J., Domingo, F., Gash, J., 2009. A review of rainfall interception modelling. J. Hydrol. 370, 191–206.

Muzylo, A., Llorens, P., Domingo, F., 2012a. Rainfall partitioning in a deciduous forest plot in leafed and leafless periods. Ecohydrology 5 (6), 759–767.

Muzylo, A., Valente, F., Domingo, F., Llorens, P., 2012b. Modelling rainfall partitioning with sparse Gash and Rutter models in a downy oak stand in leafed and leafless periods. Hydrol. Process. 26 (21), 3161–3173.

Pearce, A.J., Rowe, L.K., 1981. Rainfall interception in a multi-storied, evergreen mixed forest: estimates using gash's analytical model. J. Hydrol. 49 (3–4), 341–353.

Poyatos, R., Llorens, P., Gallart, F., 2005. Transpiration of montane *Pinus sylvestris* L. and *Quercus pubescens* Willd. forest stands measured with sap flow sensors in NE Spain. Hydrol. Earth Syst. Sci. 9 (5), 493–505.

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. For. Meteorol. 119 (1–2), 69–85.

Rutter, A., Kershaw, K., Robins, P., Morton, A., 1972. A predictive model of rainfall interception in forests, 1. Derivation of the model from observations in a plantation of Corsican pine. Agric. Meteorol. 9, 367–384.

Rutter, A., Morton, A., Robins, P., 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., 367–380.

Sentelhas, P.C., Dalla Marta, A., Orlandini, S., Santos, E.A., Gillespie, T.J., Gleason, M.L., 2008. Suitability of relative humidity as an estimator of leaf wetness duration. Agric. For. Meteorol. 148, 392–400.

Šraj, M., Brilly, M., Mikoš, M., 2008. Rainfall interception by two deciduous Mediterranean forests of contrasting stature in Slovenia. Agric. For. Meteorol. 148 (1), 121–134.

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.

Vachaud, G., Passerat de Silans, A., Balabanis, P., Vauclin, M., 1985. Temporal stability of spatially measured soil water probability density function. Soil Sci. Soc. Am. J. 49 (4), 822–828.

Valente, F., David, J.S., Gash, J.H.C., 1997. Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models. J. Hydrol. 190 (1–2), 141–162.

Wallace, J., McJannet, D., 2006. On interception modelling of a lowland coastal rainforest in northern Queensland. Australia. J. Hydrol. 329 (3–4), 477–488.