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Measuring and modelling the rainfall interception loss by hedgerows in southern England

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Abstract

Gross rainfall (P_G), net rainfall and stemflow were measured for nearly 3 years in two hedgerows in southern England. The width of the zone where net rainfall was affected by the hedgerows was equivalent to about two hedgerow heights. Rainfall interception was calculated as the difference between the volume of water, from gross rainfall, that would have reached the ground of the sampling area (which also included areas outside the canopy) without the presence of a hedgerow and the actual amount of net rainfall plus stemflow. Averaged over both hedgerows the interception loss during the period of full leaf cover was 57% of P_G if related to the ground area covered by the hedgerow canopies or 24% of P_G if related to the total ground area affected by the presence of the hedgerows. For the leafless period, the respective values were 49 and 19%. Stemflow constituted a small part in the water balance of the hedgerows and equalled 0.2% of P_G in the summer and 0.5% of P_G in the winter. Interception storage capacity, if related to projected canopy area, was 2.6 mm during the growing season and 1.2 mm in the leafless hedgerows. During many small rainstorms, which were often associated with high windspeeds, the hedgerows intercepted more rainwater than the amount that would have fallen on the ground covered by them without their presence. This caused the coefficient of free throughfall, when calculated per unit projected canopy area, to be negative. The original Gash [Gash, J.H.C., 1979. An analytical model of rainfall interception by forests. Quart. J. R. Meteorol. Soc. 105, 43–55] analytical model of rainfall interception was parameterised for the hedgerows and tested using data that had not been included in the parameterisation process. The Gash model predicted the interception loss of hedgerows from daily rainfall data with reasonable accuracy.

Keywords: Hedgerow; Rainfall interception; Rainfall inclination angle; Canopy water storage capacity; Aerodynamic resistance; Gash model

1. Introduction

The rainfall interception loss from woodlands is an important component in the water balance of a catchment and has been subject of many studies. A wide range of forest types has been covered by previous measurement campaigns, for example tropical rainforest (Lloyd et al., 1988; Asdak et al., 1998), coniferous forest (Gash and Stewart, 1977; Loustau et al., 1992; Link et al., 2004) and temperate deciduous forest (Dolman, 1987; Hörmann et al., 1996). To predict the interception loss from these woodland types, numerical (Rutter et al., 1975; Mulder, 1985), analytical (Gash, 1979) and stochastic (Calder, 1986) simulation models have been developed. As well as extensive, homogeneous forests, also sparse forest canopies (Teklehaimanot et al., 1991; Gash et al., 1999) and even isolated trees (King and Harrison, 1998; David

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et al., 2006) and shrubs (Návar and Bryan, 1990) have been subject to rainfall interception studies. Little is known, however, about the interception loss from linear vegetation structures such as hedgerows, windbreaks and narrow strips of woodland. This is a significant shortcoming in our knowledge given that fragmented woodlands form an important part of rural landscapes in many regions. In Britain, for example, the overall length of all hedges in 1998 was 468,000 km (Petit et al., 2003). It is well known, on the other hand, how hedgerows affect the hydrology and thus the yield of adjacent fields (Pollard et al., 1974; Cleugh, 1998) and there is an awareness of the benefits of establishing hedgerows for managing runoff and protecting landscapes against erosion (Burel, 1996).

The intrinsic, structural features, as opposed to external environmental variables, of linear woodlands and hedgerows probably contribute predominantly to their influence on the evaporative loss of intercepted rainfall. These structural features are likely to be determined by hedgerow dimensions and configuration and are therefore amenable to management. A more fundamental knowledge of the interaction of hedgerows with incident rainfall is therefore timely and justified.

There is as yet an unquantified impact of woodlands (especially through woodland edges, copses and hedgerows) in promoting the deposition of aerosols associated with agricultural activities (Velthorst and van Breemen, 1989). For woodland edges, at least, the efficiency of aerosol deposition has been shown to be strongly linked to aerodynamic properties (Draaijers, 1993). These same aerodynamic properties are likely to play a large part in determining the evaporation loss of intercepted rainfall of hedgerows. Therefore there is a further benefit to be had from the parameterization of the aerodynamic properties of hedgerows.

The aims of this study were to quantify the interception loss of hedgerows per unit ground area, to determine the horizontal extension of the zone which is being influenced by the presence of a hedgerow and to evaluate and parameterise a well-established analytical model of rainfall interception for hedgerows.

2. Materials and methods

2.1. Site description

The study was carried out at Roves Farm near Swindon, U.K. (51°36′N, 1°42′W). The two hedgerows investigated are located in nearly flat terrain between 100 and 105 m a.s.l. and surrounded by large arable fields and grassland. One of the hedgerows runs in a north–south direction (NS-hedgerow) and the other runs east–west (EW-hedgerow). The climate is cool-temperate, with annual rainfall ranging between 600 and 700 mm and the prevailing wind-direction being southwest. Hawthorn (*Crataegus monogyna* L.) is the dominant tree species in both hedgerows and accounts for 85% of the stems in the NS-hedgerow and 75% of the stems in the EW-hedgerow. The second-most abundant species in both hedgerows is field maple (*Acer campestre* L.). Details on both hedgerows are summarised in Table 1. A 'LAI 2000 Plant Canopy Analyzer' (Li-Cor, Lincoln, NE, USA) was used to determine the projected canopy surface area in different seasons. Thirty readings per hedgerow were taken twice a month. The difference between the readings taken in the summer and in the winter equalled the leaf area index which was also measured directly by leaf litter collection (Herbst et al., 2007). For simplicity, in further references, the period from mid April to mid-November is referred to as the leafed period and the rest of the year as the leafless period. The EW-hedgerow was trimmed in February 2005 for the first time in 3 years which altered its dimensions and structure considerably.

2.2. Meteorological data

An automatic weather station (AWS) (Didcot Instrument Co., Abingdon, UK) was installed on a large (24 ha)

Table 1
Some structural characteristics of the two hedgerows at Roves Farm

Parameter	North–south-hedge 2004	East–west-hedge 2004	East–west-hedge 2005
Year of planting	1987	1990	
Trimming interval (years)	1	3	
Width (m)	3.2	4.0	2.75
Height (m)	3.8	4.0	3.3
Leaf area index ('LAI-2000')	5.2	4.2	n.d.
Leaf area index (litter)	4.8	3.7	n.d.
Projected branch area index	2.9	2.9	n.d.

field 200 m west of the NS-hedgerow and 50 m south of the EW-hedgerow. The AWS comprised sensors measuring the incoming solar radiation, net radiation, wet and dry bulb aspirated temperature, wind speed, wind direction and rainfall. Data were measured at 10 s intervals and recorded as hourly averages onto a solid state data logger (CR10, Campbell Scientific Ltd., Shepshed, UK). The tipping bucket raingauge of the AWS had a resolution of 0.50 mm per tip. A second tipping bucket gauge with a calibration factor of 0.24 mm per tip was installed close to the AWS. Data from this gauge were recorded on a micro-datalogger ('Tinytag', Gemini Data Loggers Ltd., Chichester, UK) at 5 min intervals. Rainfall totals obtained from the two gauges differed by 8%, over the investigation period, and it was decided to use the data from the more sensitive raingauge as gross rainfall (P_G). From P_G and horizontal windspeed the rainfall inclination angle was calculated according to the formulae given by David et al. (2006).

2.3. Net rainfall

An array of 45 simple storage raingauges, with a funnel diameter of 146 mm, was used to examine the spatial variability of net rainfall both inside and outside the hedgerows. The manual gauges were arranged to cover the complete area of influence of the hedgerows. On each side of both hedgerows four collectors were placed in a row pointing orthogonally away from the hedgerow (Fig. 1). Additional collectors were arranged inside the hedgerows in parallel, longitudinal rows, in order to account for the heterogeneity of the throughfall. Three rows each of 5 gauges were placed in the NS-hedgerow and two rows of 7 gauges placed in the EW-hedgerow. The 29 collectors inside the hedgerows were installed in April 2003 and the others were added on 21 June 2004. All gauges were emptied at least weekly until 12 April 2005.

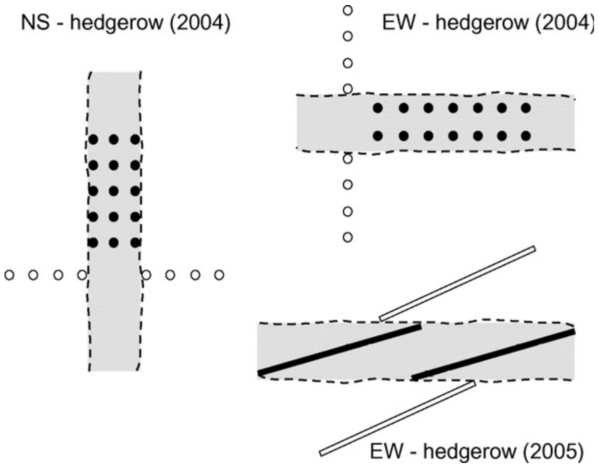

Fig. 1. A plan view of the array of 45 manual raingauges (circles) used in 2004/2005 and four tipping gauges connected to gutter constructions (rectangles) used in 2005/2006. The perimeters of the hedgerow canopies are indicated as dashed lines and the areas covered by the canopies are shaded. Rainfall collectors under the canopy are shown as black symbols and collectors accounting for the rainfall shadow areas as white symbols. The raingauges are not drawn to scale.

In the second part of the measurement campaign, four automatic tipping bucket raingauges were attached to rainfall collectors made from 110 mm wide and 4.12 m long plastic guttering and arranged in such a way as to measure the total net rainfall both in and around the EW-hedgerow (Fig. 1). In this design the calibration factors for the four gauges ranged between 0.034 and 0.037 mm per tip. The data were recorded onto 'Tinytag' data loggers (Gemini Data Loggers Ltd., Chichester, UK) at 5 min intervals from 1 June 2005 to 1 February 2006.

2.4. Stemflow

Stemflow was collected from the base of nine bushes in the NS-hedgerow from waterproof collars made of 150 mm wide self-adhesive tape (''flashing tape'', FEB Ltd., Manchester, UK) and connected to outlet pipes that were sealed with silicone rubber. The water was collected in plastic bottles which were emptied bi-weekly from September 2003 to April 2005. A survey of the diameters of 338 stems found in a 63 m long section of this hedgerow enabled the stemflow volumes to be related to projected canopy surface area.

2.5. Interception loss

Interception loss was calculated, on a volume basis, as the difference between the amount of rainfall that would have fallen on the ground in the absence of a hedgerow and the amount that was actually measured by the net rainfall gauges. This procedure was based on the assumption that the net rainfall collectors covered all possible rain-shadow areas both up- and downwind of the hedgerows.

The amount of rainfall that would have fallen on the ground in the absence of a hedgerow was calculated as the product of gross rainfall and the area covered by the throughfall gauges. The actual amount of rainfall reaching the ground in and around the hedgerows was calculated assuming that each gauge (or each mean value produced by the rows of gauges inside the hedgerows, respectively) represented a strip parallel to the hedgerow, extending from half the distance to the adjacent bottle on one side to the respective point on the other side. The interception loss as the difference between these two volumes was finally related to the projected surface area of the hedgerows and expressed in mm. This procedure is equivalent to that described by David et al. (2006) in a study of the interception loss of an isolated tree.

2.6. Evaporation from the wet canopy

The rate of evaporation, E, from the wet canopies of the hedgerows was calculated using the Penman–Monteith–equation for saturated canopy conditions (see Monteith and Unsworth, 1990) and

$$E = \frac{sA + \rho c_p D g_A}{\lambda(s+\gamma)} \tag{1}$$

where s is the slope of the curve relating saturated vapour pressure to temperature, A the available energy (in W m^{-2}), ρ the density of dry air (in g m^{-3}), c_p the specific heat of air (in J g^{-1} °C^{-1}), D the saturation deficit of the air (in Pa) at a reference point outside the hedge, g_A the bulk aerodynamic conductance between the leaf surfaces and that reference point (in m s^{-1}), λ the latent heat of vaporisation of water (in J g^{-1}), and γ is the psychrometric constant (in Pa °C^{-1}). The evaporation rate was converted from g m^{-2} s^{-1} to mm h^{-1} through multiplication by 3.6.

Bulk aerodynamic conductance was scaled up from measurements of boundary-layer conductance (g_A) of leaves and twigs (in m s^{-1}) which was determined from the weight loss of wetted leaf replicas made of blotting paper, and detached twigs wrapped in blotting paper, using the formula:

$$g_a = \frac{E}{\chi_1 - \chi} \tag{2}$$

where E is the water loss (in g m^{-2} s^{-1}), χ_1 the specific humidity of air saturated at leaf temperature (in g m^{-3}) and χ is the specific humidity of the ambient air (in g m^{-3}). The leaf replicas were cut around actual hawthorn and field maple leaves of various sizes. Two identical replicas, in the case of the leaves being supported on fine wire and thread platforms, were placed in situ in the hedgerow and saturated with water. One of the replicas was weighed at 120 s intervals and the temperature of the other one was monitored with a fine thermocouple (Model EMQSS-IM025E, Omega Engineering Ltd., Manchester, UK). Absolute humidity in the vicinity of the replica was calculated from wet and dry bulb temperature measured with a ventilated psychrometer (Herbst et al., 2007).

Bulk aerodynamic conductance was finally calculated from wind speed, branch area index and leaf area index using regression lines derived from the replica experiments which, for the leaves, were weighted according to the fractions of leaf area represented by the different groups of leaf types shown. The leaf area fractions were obtained from leaf litter collection (Herbst et al., 2007). Half of the total leaf area of hawthorn was made up of leaves larger than 10 cm^2, and half of the leaf area of field maple of leaves larger than 30 cm^2. These sizes were used as thresholds to distinguish "small" from "big" leaves (and replicas) which were averaged when the response lines were calculated. There was no significant difference in g_A between replicas placed in different heights in the canopy. The wind speed at the canopy surface on the lee side of the hedgerow was on average 40% of that on the opposite side, and g_A was calculated for an average windspeed of 70% of the speed measured with the AWS.

2.7. Gash's model of rainfall interception

Gash's analytical model (Gash et al., 1999) predicts the interception loss of a canopy on the basis of daily rainfall data. For a canopy cover of 100% the 'state-of-the-art' version of the model is identical to its basic version (Gash, 1979) which was used in this study. It requires estimates of the storage capacity of the canopy, S, and the trunks, S_t, as well as the fraction of free throughfall, p, and the fraction of rain which is diverted to the trunks, p_t. In terms of meteorological conditions, the average rainfall and evaporation rates during canopy saturation $(\bar{R}, \bar{E})$ are needed as further empirical, site-specific parameters. The model is storm-based and if it is run with daily rainfall data this implies the assumption that there is one rainfall event per day. It is further assumed that rainstorms are separated by periods in which the canopy dries completely, and further, that the deviations of the actual rainfall and evaporation rates from their mean values $(\bar{R}, \bar{E})$ can be neglected. On the basis of these assumptions the interception loss is calculated separately for m days with small storms insufficient to saturate the canopy and for n days with large storms sufficient to saturate the canopy. In large storms, the interception loss comprises of three components. These are the evaporation during the wetting-up of the canopy, the evaporation whilst the canopy remains saturated and the evaporation after the rainfall has ceased. Evaporation from the trunks adds to the total interception loss and is calculated separately for q days in which the trunks were saturated and $n+m-q$ days in which they were not. The amount of rain necessary to saturate the canopy is given by

$$P'_{\mathrm{G}} = -\frac{\bar{R}}{\bar{E}} S \ln\left(1 - \frac{\bar{E}}{\bar{R}} \frac{1}{1-p-p_{\mathrm{t}}}\right) \tag{3}$$

and the amount necessary to saturate the trunks by

$$P'_{\mathrm{t}} = \frac{S_{\mathrm{t}}}{p_{\mathrm{t}}} \tag{4}$$

The total interception loss, I_j, for j rain days is then calculated as

$$\sum_{j=1}^{n+m} I_j = n(1-p-p_{\mathrm{t}})P'_{\mathrm{G}} + \left(\frac{\bar{E}}{\bar{R}}\right)\sum_{j=1}^{n}(P_{\mathrm{G}j} - P'_{\mathrm{G}}) + (1-p-p_{\mathrm{t}})\sum_{j=1}^{m} P_{\mathrm{G}j} + qS_{\mathrm{t}} + p_{\mathrm{t}}\sum_{j=1}^{m+n-q} P_{\mathrm{G}j} \tag{5}$$

2.8. Derivation of the model parameters

The canopy structure parameters, S and p, were derived from an event based analysis of the gross and net rainfall data measured automatically at 5 min time intervals from June 2005 to January 2006. The storage capacity can be approximated by the recorded interception loss for those large storms in which the evaporation during wetting-up and saturation was negligible (David et al., 2006). Only storms preceded by a dry period of at least 8 h of daylight were considered for this purpose (Gash and Morton, 1978). The end of a storm was defined following the procedure of Pearce and Rowe (1981). This meant that within a storm consecutive hours of rainfall were permitted to be interrupted by one hour without rain if the storm duration was 4 h or less and two intermittent hours if the storm duration was longer. From a total of 22 storms with $P_{\mathrm{G}} > 3$ mm during the leafed period and 10 storms with $P_{\mathrm{G}} > 1.5$ mm during the leafless period matching these criteria, the three events with the lowest interception loss were selected from each period and S was calculated as the average interception loss of those three events. The free throughfall coefficient (p) was derived from a regression of interception loss versus gross rainfall for small rainstorms insufficient to saturate the canopy (Gash and Morton, 1978). The slope of the regression line equals $(1-p-p_{\mathrm{t}})$. Forty rain events from the leafed period with $P_{\mathrm{G}} < 2$ mm and 24 from the leafless period with $P_{\mathrm{G}} < 1$ mm were isolated from the data to derive p accordingly.

The rainfall fraction diverted to the trunks and the trunk storage capacity was estimated as the negative intercept and the slope from a regression of stemflow versus gross rainfall (Gash and Morton, 1978). Since stemflow was recorded only bi-weekly, 11 intervals for the leafed period and 8 for the leafless period were selected for this purpose, which were dominated by a single rainfall event.

All hourly AWS data with $P_{\mathrm{G}} > 0.5$ mm from 2004 and 2005 were used to calculate the average meteorological conditions during canopy saturation in terms of $\bar{E}$ and $\bar{R}$ (Gash, 1979). The evaporation rate as calculated from the Penman–Monteith equation and the rainfall rate were averaged over all those hours which occurred during the leafed and leafless periods, respectively.

2.9. Validation of model results

The canopy structure parameters, S and p, were derived from the interception measurements by the tipping bucket gauges attached to the throughfall troughs in the EW-hedgerow in 2005 after it had been robustly trimmed. Using these parameters, the Gash model was then run with daily rainfall data recorded from June 2004 to April 2005 and compared to the manual interception measurements in both hedgerows (the EW-hedgerow still having a different shape then) which were made over this period. Since these data were independent of the derivation of the canopy structure parameters, the procedure represents an independent validation.

3. Results

3.1. Meteorological conditions during rainfall

The rainfall pattern at the research site differed between the seasons. A wide range of rainfall intensities was observed during the summer when about half of the total rainfall fell at rates below 2 mm h^{-1} and more then 10% fell at rates greater than 6 mm h^{-1}. Rates as high as this never occurred during the winter when instead almost three quarters of total rainfall occurred at rates of less than 2 mm h^{-1} (Fig. 2a). The difference in windspeed during rainfall between the seasons was even more striking. Rainfall events with low windspeeds of up to 2 m s^{-1} accounted for nearly half of the rainfall amount recorded in summer, but for just 10% in winter. Typical windspeeds during rainfall events in winter ranged from 2 to 5 m s^{-1} and almost 20% of the total

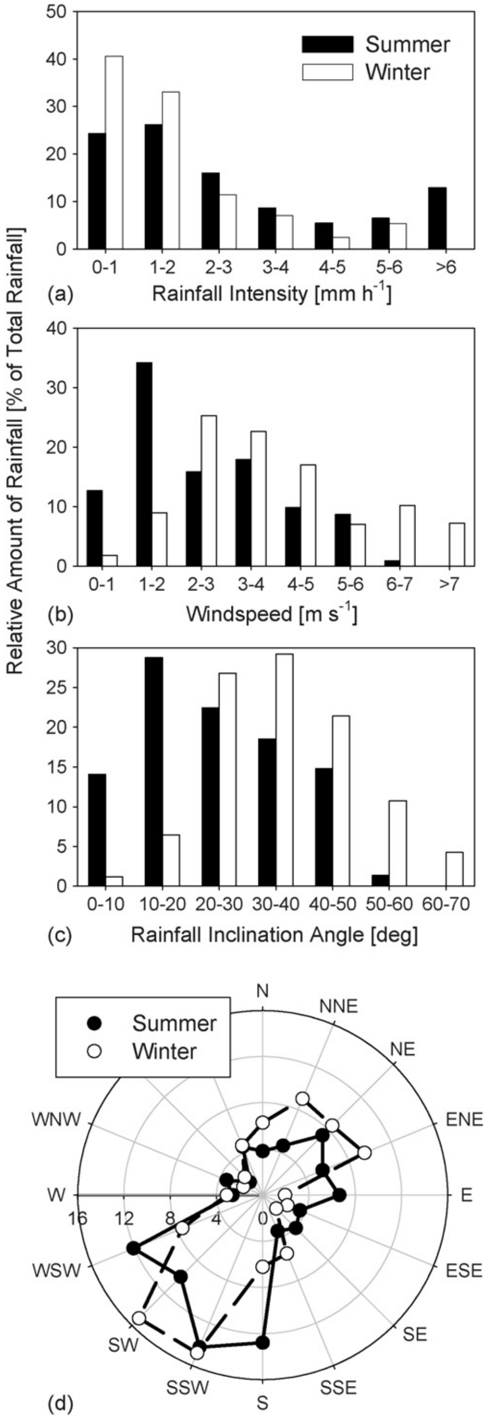

Fig. 2. Meteorological conditions during rainfall at the research site in 2004 and 2005. ‘Summer’ refers to the fully leafed period (June to September), and ‘winter’ to the leafless period (December to March).

rainfall in winter was accompanied by windspeeds exceeding 6 m s^{-1}, speeds which rarely occurred in summer (Fig. 2b). Together the seasonal differences in rainfall intensity and windspeed caused even larger differences in the typical rainfall inclination angle between summer and winter. Almost two thirds of the summer rain fell at angles below 30°, which is about the same fraction of the rain that fell in the winter at angles above 30° (Fig. 2c). This shows that wind-driven rainfall played a much larger role in controlling the interception loss in the winter than in the summer. Most of the rain fell when the wind came from the south–west (Fig. 2d).

3.2. *Spatial variability of net rainfall*

The collection of rainfall below the hedgerow canopies over 2 years revealed a high spatial variability across the ground areas covered by the hedgerows. Near the typical downwind edges of the hedgerows (north side of the EW-hedgerow and east side of the NS-hedgerow) the lowest throughfall totals were recorded, which when averaged over both years were less than a third of the gross rainfall in the summer and slightly more than half of the gross rainfall in winter (Table 2). Much higher fractions of rain penetrated the canopies close to the typical windward edges. It is therefore important to represent the complete area covered by the hedgerows in measurements of net rainfall.

For the fully leafed period of 2004 and the leafless period of 2004/2005 this observation is illustrated in Fig. 3. This shows that the area where net rainfall was influenced by the presence of the hedgerows was not restricted to their projected canopy surface areas but spanned over a width of at least 8 m. This rainfall shadow was most pronounced on the typical lee sides (east, north) of the hedgerows where the turbulence was affected most strongly by the presence of the hedgerows. Throughfall sums exceeding P_G and indicating areas of rainfall concentration were observed mainly at the western edge of the NS-hedge (where water often dripped from the twigs and leaves) but also a few metres ‘behind’ that same hedge, on the mostly wind-sheltered east side. The overall width of the zones where rainfall shadows were observed did not differ between the seasons.

3.3. *Stemflow*

Stemflow plays a minor role in the water balance of the NS-hedgerow. Over an observation period of eighteen months, less than half a percent of gross rainfall reached the ground as stemflow. A linear regression between these two quantities was performed and resulted in a slope of $p_t = 0.0015$ and a negative intercept of $S_t = 0.0118$ in the summer ($R^2 = 0.95$).

Table 2
Spatial distribution of throughfall inside the hedgerows over 2 years

Measurement Period	Rain (mm)	Throughfall									
		North–south-hedge						East–west-hedge			
		West		Middle		East		South		North	
		mm	%	mm	%	mm	%	mm	%	mm	%
3 April 2003–25 November 2003	321	164	51.1	167	52.0	81	25.2	106	33.0	88	27.4
26 November 2003–4 April 2004	314	233	74.2	215	68.5	151	48.1	223	71.0	168	53.5
5 April 2004–24 November 2004	521	322	61.8	288	55.3	174	33.4	236	45.3	187	35.9
25 November 2004–12 April 2005	194	154	79.4	119	61.3	125	64.4	124	63.9	107	55.2
Total summer	842	486	57.7	455	54.0	255	30.3	342	40.6	275	32.7
Total winter	508	387	76.2	334	65.7	276	54.3	347	68.3	275	54.1

Data are averages of $n = 5$ (north–south-hedge) or $n = 7$ (east–west-hedge) throughfall collectors per location which were placed in rows in line with the hedgerows.

Maintaining this value for S_t in the analysis of the (more scattered) data for the leafless period resulted in a slope of $p_t = 0.0049$ ($R^2 = 0.37$). These findings indicate that stemflow can be regarded as negligible in the water balance of hedgerows.

3.4. Interception loss

The total interception loss, which was calculated from the manual net rainfall (and stemflow) measurements on a volume basis, was related both to unit projected canopy area and to unit ground area of the total affected zone of 8.4 m width (Table 3). Over the course of the year the fractional interception loss for the hedgerows, including rainshadow zones, decreased from summer to winter as the leaves were shed and the hedgerows were trimmed. Related to projected canopy area, however, the fractional interception loss in the winter after trimming was almost as high as in the summer. This is because trimming the hedgerows reduced the projected canopy area and left only the most densely structured parts of the canopy. Summarised over nearly 10 months of measurements, the interception loss by the two hedgerows was on average 52% of P_G if related to projected canopy area or 23% of P_G if related to total affected area. In other words, more than half of the amount of rainfall that would have fallen onto the ground which is now covered by the hedgerows if they had not been there was intercepted.

3.5. Model parameterisation

The calculation of the average evaporation rate from the saturated canopy using the Penman–Monteith

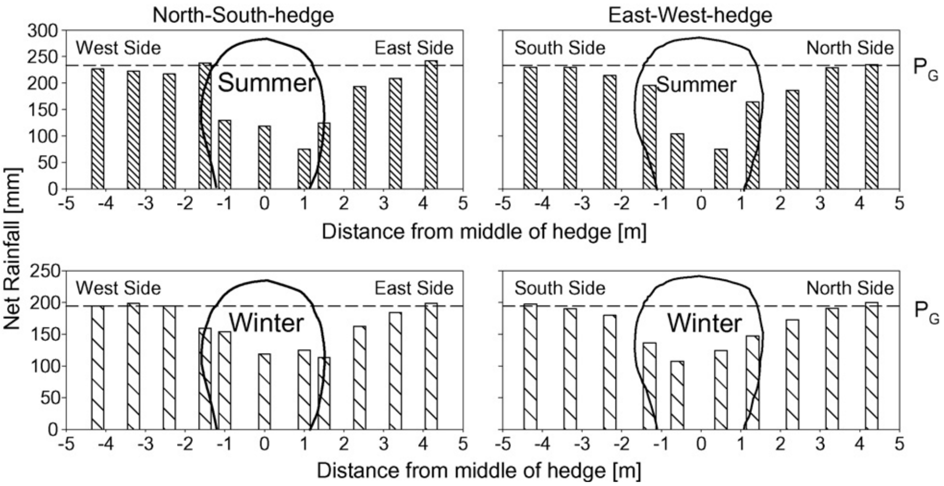

Fig. 3. Spatial distribution of net rainfall in two transects across the hedgerows under fully leafed and leafless conditions (21 June 2004–30 September 2004 and 25 November 2004–12 April 2005, respectively). The line drawings indicate the dimension of the hedgerows.

Table 3
Total rainfall interception by two hedgerows during different seasons

Measurement period	Rain (mm)	Total rainfall interception							
		North–south-hedge				East–west-hedge			
		Per projected canopy area		Per total affected area		Per projected canopy area		Per total affected area	
		mm	%	mm	%	mm	%	mm	%
21 June 2004–30 September 2004 (fully leafed)	233.5	148.5	63.6	63.4	27.2	116.2	49.8	61.2	26.2
1 October 2004–24 November 2004 (transition)	163.1	81.6	50.0	34.8	21.3	79.5	48.7	41.9	25.7
25 November 2004–9 February 2005 (leafless)	99.5	48.4	48.6	20.6	20.7	39.9	40.1	21.0	21.1
10 February 2005–12 April 2005 (leafless, cut)	94.9	53.9	56.8	15.8	16.6	46.7	49.2	16.6	17.5
Total	591.0	332.4	56.2	134.6	22.8	282.3	47.8	140.7	23.8

Projected canopy area changed on 9 February 2005 when both hedgerows were trimmed.

equation required knowledge of the actual g_A. This was scaled-up from aerodynamic conductances for the water vapour transfer between leaf and twig surfaces and a reference point above the hedgerow as measured using the replica technique and related to horizontal windspeed (Fig. 4). A linear relationship was observed between the aerodynamic conductance of leaf replicas and windspeed, but a different response function was found for the conductance of twig replicas. For all rainy hours with $P_G > 0.5$ mm Penman–Monteith evaporation was calculated using AWS data and g_A values derived from windspeed using the response functions shown in Fig. 4 which were multiplied by the surface area of leaves and branches in the hedgerow. The mean evaporation rate from the saturated canopy calculated using this procedure was 0.367 mm h^{-1} for all hours from the leafed periods of 2004 and 2005 and 0.096 mm h^{-1} for all hours from the leafless period in between (Table 4). Mean rainfall rates for the same hours were 1.84 mm h^{-1} in the summer and 1.40 mm h^{-1} in the winter. This means that the ratio of $\bar{E}/\bar{R}$ was almost three times as high in the summer than in the winter.

The canopy storage capacity which was calculated as the average interception loss during those large rainstorms which had the lowest evaporation was found to be 2.56 (±0.14) mm for the leafed hedgerow and 1.22 (±0.18) mm for the leafless hedgerow. The regression of interception loss versus gross rainfall for small rainstorms produced slopes bigger than one for both seasons which means that more rain was intercepted under these circumstances than the amount that would

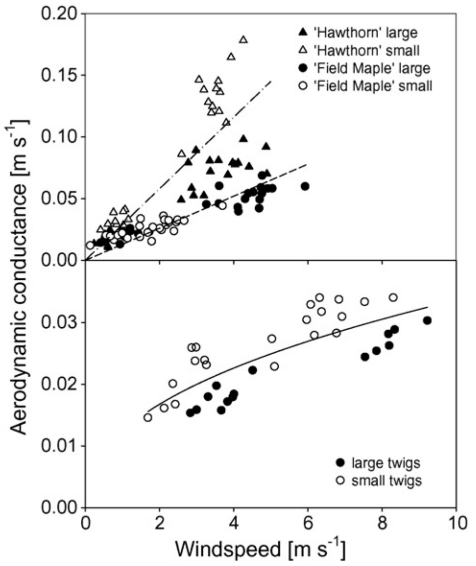

Fig. 4. Aerodynamic conductance for the evaporation of intercepted rainfall from leaves and twigs as determined by the replica technique in relation to windspeed. Regression lines (±S.E.) representing the mean responses of different sizes of replicas are $y = 0.0275\ (\pm 0.0014) \times x (R^2 = 0.62)$ for hawthorn leaves, $y = 0.0124\ (\pm 0.0004) \times x (R^2 = 0.74)$ 0.74) for field maple leaves, and $y = 0.0124\ (\pm 0.0014) \times x^{0.433\ (\pm 0.063)} (R^2 = 0.61)$ for twigs.

Table 4
Parameters used in the Gash-model in its new application for hedgerows

Parameter	Leafed hedgerow	Leafless hedgerow
Canopy storage capacity, S (mm)	2.56	1.22
Trunk storage capacity, S_t (mm)	0.012	0.012
Free throughfall coefficient, p	−0.16	−0.47
Proportion of rain diverted to the trunks, p_t	0.002	0.005
Amount of rain to saturate the canopy, P'_G (mm)	2.42	0.85
Amount of rain to saturate the trunks, S_t/p_t (mm)	7.87	2.41
Mean rainfall rate, $\bar{R}$ (mm h^{-1})	1.84	1.40
Mean evaporation rate, $\bar{E}$ (mm h^{-1})	0.37	0.10

Data refer to projected canopy area.

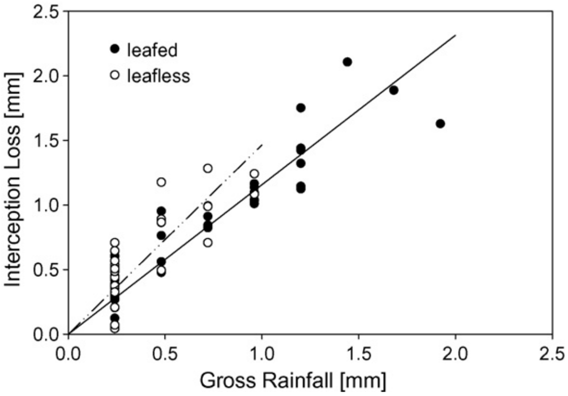

Fig. 5. Interception loss plotted against gross rainfall for 'small' rainstorms which did not saturate the canopy. The slope of the regression lines through the origin represents $(1 - p - p_t)$ and was determined as 1.157 ($R^2 = 0.81$) for the leafed hedgerow and 1.465 ($R^2 = 0.51$) for the leafless hedgerow, resulting in free throughfall coefficients of $p = -0.159$ and -0.470, respectively.

have fallen onto the ground in the absence of a hedgerow. Consequently, the free throughfall coefficients derived from the slopes of the regression lines were negative and were found to be even lower in the winter, when rainfall was often accompanied by high windspeeds, than in the summer (Fig. 5). This means that not only an amount of water equivalent to all rainfall that would have fallen onto the projected canopy area is prevented from reaching the ground directly, but also an additional amount that would have fallen onto the area downwind of the hedgerow which actually has no canopy above it. This phenomenon demonstrates the role of wind-driven rainfall in the process of interception loss from hedgerows and has the further implication that the rainfall amount necessary to saturate the canopy as calculated from Eq. (3) is lower than the canopy storage if both are given in mm (Table 4).

The parameters derived for the interception loss from the trunks indicate that the trunk water balance hardly influences hedgerow rainfall interception. Nevertheless, the parameters were included in Table 4 and in the model run.

3.6. Model results and validation

The results from Gash's model, which was run using daily rainfall data collected during the period when the independent manual throughfall measurements were made, agreed with the observed interception loss from both hedgerows within about 12% during the summer and about 25% during the winter (Table 5), although the size and shape of the EW-hedgerow had changed significantly between the manual recordings and the automatic measurements from which S and p were derived. The model output was slightly lower than the measurements from both hedgerows during the winter but ranged between them during the summer. Evaporation from the canopy when rainfall has ceased following large storms was the largest component of interception loss, accounting for about 50% of the loss in the summer and 70% in the winter. Evaporation during canopy saturation with rainfall still continuing was much more important in the summer because of the higher $\bar{E}/\bar{R}$ ratio. Small storms that did not saturate the canopy accounted for one fifth of the interception loss in the summer and one sixth in the winter. The model results are plausible and the extent to which they deviate from the manually measured throughfall totals is similar to the observed variation between the two hedgerows and only slightly higher than the differences between the two gross rainfall gauges.

Table 5
Components of interception loss by a hedgerow according to the Gash model which was parameterised on the basis of throughfall data measured continuously at 5 min intervals between June 2005 and January 2006 (see Table 4)

Component of interception loss	Leafed hedgerow	Leafless hedgerow
Small storms	44.1	15.1
Wetting-up the canopy	10.7	1.4
Evaporation from saturation until rainfall ceases	45.0	11.8
Evaporation after rainfall ceases	109.9	57.5
Evaporation from trunks	0.4	0.5
Total interception loss according to Gash model	210.2	86.4
Measured interception loss EW-hedgerow	188.9	93.4
Measured interception loss NS-hedgerow	222.7	109.6
Gross rainfall	367.9	223.1

Totals modelled for the leafed and leafless periods between 21 June 2004 and 12 April 2005 using rainfall data from an automatic weather station are compared against independent throughfall data collected in two hedgerows. All data are given in mm

4. Discussion

4.1. Spatial variability of net rainfall

Net rainfall in and around the hedgerows showed a high spatial variability in terms of (1) a systematic variation dependent on the distance of a sampling point from the upwind edge of the hedgerow and (2) a random variation along the hedgerow. It had to be ensured that the sampling design accounted for this variability and that errors due to poor sampling density were avoided, especially since a fixed grid was used for the placement of the net rainfall gauges which in other studies has been regarded as less than ideal (Lloyd and Marques, 1988). Rodrigo and Àvila (2001) found that under a dense, coppiced holm oak canopy (which, in terms of density and structure, can to some extent be compared to a hawthorn hedge) 10 gauges of 10 cm diameter were sufficient to ensure that net rainfall was measured with less than 10% error and pointed out that obviously an increase in funnel size would reduce this number. The spacing of the net rainfall gauges when a regular grid is used plays only a minor role for the accuracy of the measurements (Czarnowski and Olszewski, 1970). The array and size of raingauges used in the present study (Fig. 1) can therefore be considered as suitable to account for random spatial variability of throughfall. This applies even more so for the 2005/2006 observations since the area per throughfall trough was about 27 times the area of one funnel of the manual gauges used in the preceding year. The sampling area was hence equivalent to having 54 gauges inside and 54 gauges outside the hedgerow. The use of rainfall collectors covering a large area and thereby accounting for the spatial variation of net rainfall in order to improve the representativeness of measurements was also recommended by Calder and Rosier (1976).

For our research site there was a large impact of wind-driven rainfall on rainfall interception, as evident from the net rainfall distribution shown in Fig. 3 and the analysis of small rainstorms (Fig. 5). An influence of wind on rainfall interception loss has been noticed by Rowe (1983) and Hörmann et al. (1996) who mentioned that wind shakes intercepted water off the canopy and thereby *reduces* S and hence I. The opposite effect was described by Herwitz and Slye (1995) who observed that the wind can *increase* I through an extra input of inclined gross rainfall to tree canopies which stand out from the surrounding vegetation. The latter effect was the dominating one in our study and caused the interception loss to be even higher than the gross rainfall during rainstorms which did not saturate the canopies. During large storms it caused a partial redistribution of rainfall (Gómez et al., 2002) in terms of rainfall concentration near the windward canopy edge and rainfall depletion near (and beyond) the downwind edge. These two processes, however, did not balance each other out. Rainfall with high inclination angles is often accompanied by high windspeeds, which in turn are often associated with high evaporation rates (through a high aerodynamic conductance). Therefore the rainfall concentration on the windward edge of a hedgerow will always be lower than the rainfall depletion on the lee side.

4.2. Comparison with other woody vegetation

A dense and linear canopy, as formed by a regularly trimmed hedgerow dominated by hawthorn, provides a vegetation structure which has few similarities with other types of woody vegetation. Amongst all studies about interception losses from woodlands, only one deals with the special situation of thorny shrubs (Návar and Bryan, 1990). These authors reported an interception loss of 27% of P_G for shrubs in a semi-arid climate and stemflow coefficients ranging between 0.007 and 0.048 dependent on the species. However, those observations refer to climatic conditions very different from those at our research site and are therefore hardly comparable.

To validate the role of the interception process in the hydrology of a hedgerow it is nevertheless useful to compare the results of this study with findings from other woodland types. The magnitude of the average interception loss from broadleaved forests depends on both rainfall regime and canopy structure and varies from 9% in Amazonian rainforest (Lloyd et al., 1988) to 36% in temperate deciduous forests (Rutter et al., 1975). Coniferous forests in low rainfall areas can lose between 40 and 50% of P_G by interception (Rutter et al., 1975; Gash et al., 1980). The storage capacity in coniferous forests ranges from 0.5 mm in a pine stand (Loustau et al., 1992) to 3 mm in an old-growth Douglas fir forest (Link et al., 2004). In temperate deciduous forests such as oak woodlands the observations of S vary between 0.8 in the summer and 0.3 in the winter (Dolman, 1987) and 2.3 in the summer and 1.5 in the winter (Halldin et al., 1984). For beech forests Elling et al. (1990) reported a storage capacity of 2.6 during the summer. However, this was confirmed by Hörmann et al. (1996) but only for rainfall events that had low windspeeds, whilst the average S over the entire leafed period, observed in the same forest, was only half as high.

Thus the storage capacity of the hedgerows ranks amongst the highest observed for broadleafed tree stands and in the summer it is not much lower than the highest S reported for coniferous woods. The magnitude of the seasonal variation in S is in accordance with that found in other broadleafed woodlands and the same holds for the seasonal variation in p_t which tends to be higher in the winter than in the summer (Brown and Barker, 1970; Herbst and Thamm, 1994). However, overall p_t in the hedgerows was about one order of magnitude lower than in many forests, which is not surprising given the fact that hedgerow bushes comprise mainly of 'crowns' rather than 'stems'. The most striking difference between hedgerows and most other types of woodland is the behaviour of the coefficient of free throughfall. Not only do the exposed sides of a hedgerow receive an additional input of inclined rain which when being intercepted and producing a rainfall shadow results in a negative *p* (which is impossible and meaningless for any extensive stand of vegetation), but *p* is even lower (i.e. more negative) under leafless conditions than in a fully leafed hedgerow. This at first seems somewhat contradictory since there should be more gaps for raindrops directly reaching the surface below the canopy when no leaves are in the way. The reason for this observation is that under the climate of the research site the rainfall patterns are very different between different seasons and *p* is influenced by rainfall intensity and inclination much more strongly than by the canopy structure.

4.3. Applicability of Gash's model

Gash's analytical interception model aims to provide a method to predict the interception loss on the basis of readily available climate data, such as daily rainfall, without neglecting the physical processes which determine the different components of the interception loss in specific ways. This requires not only the empirical derivation of some site-specific, meteorological and structural parameters, but also some simplifying assumptions in terms of the temporal rainfall pattern. The most critical of these assumptions is the approximation that one rainday is equivalent to one rainfall event. Under climates where this does not apply, the model when used with daily data fails to predict the interception loss correctly (Pearce and Rowe, 1981; Link et al., 2004). In many cases, however, the Gash model has proven to be robust and reliable (also for forests which were very different from the pine stand of the original application) and often superior to other models in practical applications (Dolman, 1987; Lloyd et al., 1988; Aboal et al., 1999).

Another simplifying assumption we had to make was to distinguish between two seasons only without taking gradual changes in canopy structure or $\bar{E}/\bar{R}$ into account. This was necessary to assemble a database large enough to apply the parameter estimation procedures. The relatively low model output for April 2005 if compared with the measured interception loss (Fig. 6), for example, could be explained by a gradual start of leaf unfolding that took place over this period. Assuming a constant wet canopy evaporation might cause another uncertainty if modelled and measured results are compared over short time periods, since Gash's model was found to be very sensitive to $\bar{E}$ (Lankreijer et al., 1993) and, thus, to the way g_A is parameterised. In this study g_A was scaled up from leaf and twig aerodynamic conductance data measured in situ and empirically related to windspeed. For a hedgerow this was not only the only possible way but it was also based on experimental verification rather than literature data. Realistic values for g_A were therefore achieved without making too many theoretical assumptions. In general, the Penman–Monteith equation has proven to be a reliable method to calculate evaporation from a wet canopy (Klaassen, 2001), and our average evaporation values calculated from it fit in a plausible range. The statistical uncertainty in the response functions of g_A versus u (Fig. 4) corresponds to an uncertainty in $\bar{E}$, through Eq. (1), of $\pm 0.03\ \mathrm{mm\ h^{-1}}$ in the summer and $\pm 0.02\ \mathrm{mm\ h^{-1}}$ in the winter. The resulting error margin for the modelled interception loss would be $\pm 2\%$ in the summer and $\pm 3\%$ in the winter.

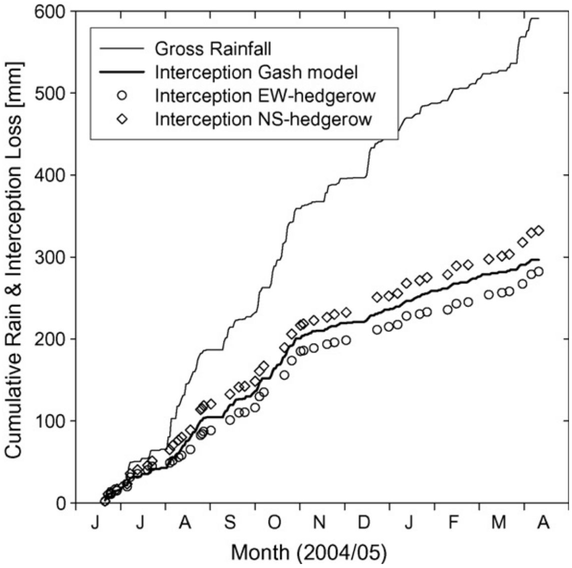

Fig. 6. Cumulative interception loss over a 10 months period as predicted by Gash's model and recorded by the manual raingauges in two hedgerows. Daily gross rainfall was the input for the model and is shown for comparison.

The tendency of the model to underestimate the interception loss during the winter was probably caused by the specific rainfall patterns that occurred at the research site. On some of the rainy days several small or very small rain events (such as drizzle) were recorded per day. This means that in fact there may have been more wetting and drying cycles than is assumed by the model on the basis of the daily rainfall totals. This would cause an underestimation of the actual interception loss, being complementary to the observation that the model overestimates I in the reversed situation when one rainstorm lasts several days (Link et al., 2004). The sensitivity of the tipping bucket rainfall gauge that recorded P_G during periods with very low rainfall intensities may well have added to some inaccuracy in the modelled values for the winter.

The model has never been applied before using negative numbers for the free throughfall coefficient. It was discussed in Section 4.2. how these numbers are interpreted in practical terms and they do not violate the consistency or the reliability of the model. They have the consequence that $P'_G < S$ (Table 4) which correctly accounts for the situation when inclined rainfall is intercepted. This way of representing the additional rainfall input at a canopy edge is complementary to the formulation used by Herwitz and Slye (1995) who introduced an ‘effective intercepting crown area’ for trees intercepting wind-driven rainfall. Had we neglected this effect and simply used $p = 0$, referring to the complete canopy cover of the hedgerows, the modelled interception loss would have been 202 mm instead of 210 mm in the summer and 80 mm instead of 86 mm in the winter.

The overall performance of the model was satisfying and the deviations from the measured data were in the same range as the natural variation in the interception loss between the two hedgerows. Measurements of P_G also include uncertainties with magnitudes often similar to the model accuracy achieved in this study, especially during storms with high windspeeds and low rainfall intensities (Pypker et al., 2005).

It should be pointed out that it was the original, most basic model version that was used in this study and its performance was good. It was not necessary for us to develop any site-specific adaptations which have been found to be necessary in other applications: vis-á-vis an event-based model run (Pearce and Rowe, 1981), a wind-dependent storage capacity (Hörmann et al., 1996) and a new formulation to calculate interception evaporation from sparse canopies (Gash et al., 1999). It seems likely that the performance of the model benefited from the similarity of the climates and rainfall patterns between the research site and the forest for which the model was originally developed. Future studies will have to investigate if the parameterisation given in this study is applicable to a wider range of hedgerows of different extensions and structures. Perhaps a generalisation will be possible on a theoretical basis which uses the hedgerow dimensions to predict the sizes and intensities of rainfall shadows (David et al., 2006) and which takes information about turbulence patterns across hedgerows (Cleugh, 1998) into account.

5. Conclusions

Hedgerows can intercept a substantial fraction of the rainfall that would have fallen onto their projected ground area without their presence. The interception loss in two hedgerows in southern England was found to be 50–60% of gross rainfall in the summer and 40–50% of P_G in the winter if related to projected ground area. In regions with climates characterised by high windspeeds, wind-driven rainfall plays a major role in the hydrology of hedgerows. A rainfall shadow of a width similar to the height of the hedgerows is found downwind of them and some rainfall concentration can occur near their upwind edge. The analytical model of rainfall interception (Gash, 1979), which was previously used for extensive forests, can be parameterised for hedgerows and reliably predicts their interception loss on the basis of daily rainfall data.

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