Measurement and modelling of rainfall interception by three semi-arid canopies

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Abstract

The main aims of this study were, firstly, to adapt the rainfall interception model of Rutter et al. (Agric. Meteorology, 1971, 9, 367–384) to individual plants of two semiarid shrubs (\textit{Anthyllis cytisoides} L. and \textit{Retama sphaerocarpa} (L.) Boiss.) and a tussock grass (\textit{Stipa tenacissima} L.) and secondly, to understand how the different canopy structures influence rainfall partitioning by individual plants. The selected species represent contrasting canopy types typical of vegetation of semiarid areas. Free throughfall coefficients were estimated from field measurements of low volume rainfall events and vertical photographs taken beneath the plant canopy. Canopy drainage curves were measured by continuous weighing of wetted plants. Canopy boundary layer conductances were calculated by measuring the evaporation of water from wet canopies. Field measurements of gross rainfall, throughfall and stemflow were taken for each rainfall event for \textit{A. cytisoides} and \textit{R. sphaerocarpa}. The Rutter type model of rainfall interception was adapted for individual shrubs and tested with measured rainfall events showing a good agreement between observed and predicted values for \textit{R. sphaerocarpa} and for \textit{A. cytisoides}.

The interception model was then run to simulate interception loss during actual rainfall events, using atmospheric conditions measured every 5 s. The results from this simulation showed significant differences in interception loss between species, which can be explained by differences in canopy drainage and boundary layer conductance, and are caused primarily by the structural differences in their canopies. \textit{R. sphaerocarpa} gave lower interception than the other two species, \textit{S. tenacissima} gave higher interception, while \textit{A. cytisoides} had an intermediate value. The low interception loss by \textit{R. sphaerocarpa} can be explained by its low total area index, thus, high free throughfall and high canopy drainage rate per unit projected canopy area. On the other hand, \textit{S. tenacissima} and \textit{A. cytisoides} show a low free throughfall and drainage rate per unit projected canopy area because of their higher aerial biomass density. The ecological implications of these adaptations are discussed. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Rainfall interception model; Rainfall partitioning; Canopy drainage; Canopy boundary layer conductance; Semi-arid canopy

1. Introduction

Semi-arid environments are frequently characterised by a sparse spatial pattern where individual shrubs or perennial grasses form conspicuous

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vegetated patches that sharply contrast with open areas of bare soil or ephemeral plants. Substantial evidence supports the idea that knowledge of hydrological processes operating at plant-scale can be crucial to understand the functioning of these heterogeneous landscapes. From a hydrological point of view, individual canopies exert a significant control by modifying both evaporation and the redistribution of incident rainfall. Morphological and structural traits of canopies influencing canopy water storage capacity and boundary layer conductances along with micrometeorological conditions during the rainfall events are key factors influencing rainfall partitioning.

The main aims of this study are, firstly, to adapt the rainfall interception model of Rutter et al. (1971) (which we will call the Rutter type model) to individual plants of two shrub species (*Anthyllis cytisoides* L. and *Retama sphaerocarpa* (L.) Boiss.) and a tussock grass (*Stipa tenacissima* L.), the main perennial species found in the Rambla Honda field site (Almería, southeast Spain). Secondly, to understand how canopy structure and micrometeorological variables influence rainfall partitioning by individual plants. The species chosen represent contrasting plant canopy types which are typical of vegetation found in semi-arid zones.

In order to apply the Rutter type model to individual plants, canopy boundary layer conductance and canopy storage capacity had to be estimated on an individual plant basis. Boundary layer conductances are generally calculated using the momentum transfer equation (Monteith, 1965) and canopy storage capacities by plotting throughfall against gross rainfall following the method of Leyton et al. (1967), for closed forest canopies. These relationships cannot, however, be used for widely spaced vegetation since estimates of the roughness parameters required for application of the momentum transfer equation, including zero plane displacement $d$, and roughness length $z_0$, are not sufficiently understood under these conditions to make generalised equations. Teklehaimanot and Jarvis (1991a) used calculated boundary layer conductance for widely spaced stands of Sitka Spruce derived from measurements of evaporation rates of intercepted water for individual trees. This method was considered in the present study the most appropriate for working on individual plants. A variation of this method was also used for measuring the canopy water storage capacity.

The accurate quantification of net radiation absorbed by individual plants is difficult using conventional microclimate equipment. Therefore, the rate of evaporation from the wet canopy was obtained in the present study from the Teklehaimanot and Jarvis (1991a) approximation of the Penman equation which neglects the net radiation term. The non-inclusion of the net radiation term in the Penman equation has been based on results of other authors (Stewart, 1977; McNaughton and Jarvis, 1983; Teklehaimanot and Jarvis, 1991a, b) assuming that during the course of a rainfall event, evaporation is driven by the saturation deficit and boundary layer conductance and hence, there is only a small dependence of evaporation on the net radiation term of the Penman equation.

The present work is included as part of an investigation of the processes controlling use of water by vegetation in sparse canopies in semi-arid environments (Brenner and Incoll, 1997; Domingo et al., 1991 and Domingo et al., 1996; Puigdefàbregas et al., 1996, Haase et al. 1996; Pugnaire and Haase, 1996; Sánchez and Puigdefàbregas, 1994).

2. Theory

The most significant advances to the understanding of the physical processes of interception loss were developed by Rutter in his series of papers (Rutter et al., 1971, 1975; Rutter and Morton, 1977). In these models, a running water balance is calculated for the canopy and tree stems using hourly data inputs of rainfall and meteorological variables controlling evaporation, i.e. net radiation, wind speed, air temperature and water vapour pressure. Gash (1979) developed a semi-empirical simplification of the Rutter model, while acknowledging some of the assumptions implicit in the use of regression models. The Gash model assumed that there is only one storm per day and consequently daily records can be used to provide the inputs to the model. The Gash model has been recently reformulated (Gash et al., 1995) and adapted for estimating rainfall interception in sparse forests. Numerical models by Mulder (1985) and Whitehead and Kelliher (1991), and to a lesser extent a stochastic model by Calder (1986) have been derived from the Rutter model.
Interception loss in closed canopy vegetation usually uses parameters that are derived from wind profiles measured over that vegetation (Jarvis et al., 1976; Gash et al., 1980). However, these relationships cannot be used for widely spaced canopies that are often encountered in semi-arid areas. Lankreijer et al. (1993) presented a comparison of some of these models concluding that the approximation of calculating the aerodynamic resistance for scalar fluxes from momentum transport leads to an overestimation of interception loss, and they introduced an improvement recognising that the roughness length for heat (both sensible and latent) deviates from that for momentum. Using an equation that related to tree density Teklehaimanot and Jarvis (1991b) successfully applied a modified form of the Rutter and Gash models to widely spaced trees in agroforestry situations.

In all models of rainfall interception loss by forest canopies mentioned, the most important variables are boundary layer conductance and canopy storage capacity. In our study, in order to apply the Rutter type model to individual shrubs these variables have to be estimated accurately. As mentioned above, boundary layer conductance was measured by the method of Teklehaimanot and Jarvis (1991a) derived from measurements of evaporation rates of intercepted water and a variation of this method was used for measuring the canopy water storage capacity.

3. Materials and methods

3.1. Site description

The field site is located in the Rambla Honda, a dry valley on the southern slope of the Sierra de los Filabres, ca. 40 km north of Almería, Spain (37°8’ N, 2°22’ W, 630 m altitude). A detailed description of the field site has been given by Puigdefábregas et al. (1996). The location of the field site is in the lower sector of the basin from 630 m altitude at the valley bottom to 800 m. In the upper sector, soils are on mica schist bedrock and the vegetation is dominated by Stipa tenacissima L. The upper part of the alluvial fans are sedimentary deposits with vegetation dominated by the shrub Anthyllis cytisoides L. The lower part of the fans and drainage channels are dominated by the shrub Retama sphaerocarpa (L.) Boiss. A large part of the valley bottom is covered with a steppe extended by man, dominated by the grass S. tenacissima with variable proportions of A. cytisoides. This vegetation is also typical for large areas of semi-arid eastern Spain (Peinado et al., 1992).

The climate is semi-arid and there are no long-term climatic data available for the Rambla Honda site. Estimates of mean annual rainfall of 300 mm and mean screen air temperature of 17°C were previously derived for more than thirty years using geographic and topographic interpretation from 166 meteorological stations installed in the Almería province (Lázaro and Rey, 1991). There is a pronounced dry season from May to September, often with practically no rainfall from June to August, and a high variation both in the pattern and total amounts of rainfall from year to year.

3.2. Description of the studied species

The three species studied, Stipa tenacissima L., Anthyllis cytisoides L. and Retama sphaerocarpa (L.) Boiss. have different canopy characteristics. S. tenacissima is a perennial tussock grass (Fig. 8), that grows to 1.5 m in height and 3 m in diameter. The tussock structure is described in Sánchez and Puigdefábregas (1994) and Sánchez (1995). Leaves are long, narrow, cylindrical, evergreen and usually live more than a year. After dying, leaves accumulate between tillers at the base of the plant which get tangled forming a persistent, rigid mat with individual leaves taking years to decompose. The long, hard sheaths and tillers remain upstanding for some time after the leaves have died forming a clump. Clumps with a common origin and joined by the same branching system form a module. Tussocks are usually formed by several physiologically independent modules physically interconnected by dead leaves. S. tenacissima has a dense superficial rooting system which provides rapid access to water from even small rain events. In mature tussocks much of the mass is the standing dead leaf litter, which produces a very high plant mass per unit area.

A. cytisoides is a drought-deciduous leguminous shrub (Fig. 9), it grows to a height of 1.5 m and a diameter of 1 m, and has mesophyllous leaves. It has a moderately deep root system that reaches down to 5 m in softened rock joints or in alluvium (Domingo et al.,...
1991). Shrubs are highly branched and dense. Their shape changes with age with young bushes forming an inverted funnel, while old ones tend to be hemispherical. The density of aerial biomass (the majority being branches) although high, is smaller than that of *S. tenacissima*. *R. sphaerocarpa* is a woody leguminous shrub with ephemeral leaves, it grows to 4 m in height and 6 m in diameter, with cylindrical photosynthetic stems (cladodes) (Fig. 3). The shrub has an open canopy structure and a deep root system which can extract water from depths below 25 m (Haase et al., 1996). Woody branches represent the majority of its aerial biomass and its proportion of dead standing biomass is very small relative to *S. tenacissima* and *A. cytisoides*.

3.3. Field measurements

3.3.1. Field measurements of rainfall partitioning on Retama sphaerocarpa and Anthyllis cytisoides

Net rainfall (throughfall and stemflow) was measured in the field on *R. sphaerocarpa* and *A. cytisoides*. Plots were selected based on the occurrence of the shrub type, at the bottom of the valley for *R. sphaerocarpa* and on the middle part of the alluvial fan for *A. cytisoides*. For each plant, height of the plant, mean diameter of canopy, projected canopy area and basal diameter of the trunk and branches were measured.

Stemflow and throughfall were measured on five shrubs of *A. cytisoides* and eight shrubs of *R. sphaerocarpa* representing the range of size classes. Accordingly, we selected plants with projected canopy areas that ranged between 4.88 m² to 25 m² for *R. sphaerocarpa* and 0.24 m² to 1.76 m² for *A. cytisoides*. Stemflow was collected with channel rings of PV-isocyanate attached at the bottom of the trunk (*A. cytisoides*) and at the base of representative branches (*R. sphaerocarpa*). Throughfall volume in each individual of *A. cytisoides* was collected with three 0.18 m diameter funnels placed halfway between the centre and the edge of the shrub canopy at three fixed orientations. Owing to the small distance between the soil and the lower branches in *A. cytisoides* both, rings of stemflow and throughfall funnels in this species were connected by a plastic tube to conventional polyethylene containers outside the canopy. Throughfall in *R. sphaerocarpa* was measured with eight funnels 0.25 m diameter attached directly to six litre polyethylene collectors. Two sets of four collectors were placed beneath each canopy, one set of collectors being placed at each vertex of a square layout and the other set placed on the diagonals midway between the vertices of the square and the centre of the crown. Stemflow and throughfall volumes were measured immediately after each rainfall event.

For *A. cytisoides* stemflow volume of each shrub was expressed in mm on a projected canopy area basis. For *R. sphaerocarpa* a regression between volume of stemflow and branch diameter was obtained for all branches for each rainfall event. This regression equation was applied to all branches of a shrub obtaining the total stemflow volume expressed in mm on a projected canopy area basis. Interception was calculated as rainfall minus the sum of stemflow and throughfall.

A nearby meteorological station located halfway between *R. sphaerocarpa* and *A. cytisoides* stands gave meteorological information for the rainfall events used for the comparison with the model interception predictions (Table 1). The rainfalls presented in Table 1 are only a part of the rainfall that fell during the study period for which meteorological information for the whole rainfall event was available. The meteorological station measured wind direction (potentiometric wind vane, W200P, Vector Instruments, Rhyl, UK), wind speed (A100, Vector Instruments, Rhyl, UK), air temperature (LM35CZ, National Semicond.), solar radiation (CM6B, Kipp and Zonen, Delft, Holland) and relative humidity (EE Electronik HC500). Measurements were taken every second and averaged every 5 min. Rainfall volumes were measured by rainfall gauges installed separately in each species plot. The meteorological station provided data during two periods: 15 April–31 May 1994 and 28 February–30 June 1995.

3.3.2. Field measurements and parametrization of canopy drainage rate and boundary layer conductance

In Rambla Honda field site, 10 tussocks of *S. tenacissima*, 11 shrubs of *A. cytisoides* and 10 of *R. sphaerocarpa* were selected to perform measurements of canopy drainage and boundary layer conductance. The chosen individuals of each species represent the range of canopy sizes and ages present in the study area. Before cutting, the following descriptive measurements were made: height of plants,
mean diameter of crown, projected canopy area and cover of standing dead biomass. After finishing the two experiments described below, plants were transported to the laboratory where total dry mass, dry mass density (total dry mass per volume of canopy) and total area index based on canopy projected area (branch and leaf area indices) were calculated. Table 2 contains the average values (± one standard error) of these variables for each species.

Canopy drainage rates were measured for individual plants by cutting the plant at ground level and suspending it from a load cell (20 kg ± 20 g, RS Components Ltd., Corby, UK) a few centimetres above the ground and near to its original position. Plants were wetted using a hand-held spray nozzle (0.02 m³, Kima-12, Matabi, Denmark). The load cell was connected to a data-logger (CR10, Campbell Scientific Ltd, Loughborough, UK) that recorded the plant mass every 0.125 s and averaged every 10 s. Cut plants were sprayed until the mass stopped increasing and remained constant for several seconds. The plant was then allowed to drain and its change of weight was recorded. Plants were covered by plastic to minimise water loss by evaporation and to ensure that the loss of weight from the plant resulted entirely from drainage.

The water drainage from the canopy \(D\), measured as the decrease in mass of wetted plants between time \(t\) and time \(t - 10\) minutes, was calculated using the formula:

\[
D = \frac{m_t - m_{t-10}}{10} \times \frac{1}{A}
\]

where \(m_t\) is the mass of the plant at time \(t\), and \(A\) is the canopy area. The canopy area was calculated using the projected canopy area basis.

Table 1
Average environmental data (±1 standard error) recorded during the rainfall events in the Rambla Honda (SE Spain) used for comparing the interception measured and calculated by the model, i.e. rainfalls events for which there was meteorological information for the whole event. Rainfall volume were measured by rainfall gauges installed separately in each species plot. The meteorological station was not operative all the time, having information only for two periods: 15 April–31 May 1994 and 28 February–30 June 1995.

<table>
<thead>
<tr>
<th>Event date</th>
<th>Temperature (°C)</th>
<th>Humidity (%)</th>
<th>Wind speed (m s⁻¹)</th>
<th>Total rainfall (mm)</th>
<th>Max Intensity in 10 min (mm h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. cytisoides</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>10.1±3.6</td>
<td>70.5±16.4</td>
<td>1.0±0.8</td>
<td>4.0</td>
<td>14.1</td>
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<tr>
<td>24-04-94</td>
<td>12.8±2.8</td>
<td>48.2±11.6</td>
<td>2.0±1.2</td>
<td>1.5</td>
<td>11.6</td>
</tr>
<tr>
<td>17-05-94</td>
<td>15.6±3.6</td>
<td>43.2±10.3</td>
<td>2.1±1.4</td>
<td>9.4</td>
<td>135.8</td>
</tr>
<tr>
<td>28-02-95</td>
<td>7.7±2.6</td>
<td>78.2±9.8</td>
<td>3.7±1.3</td>
<td>50.1</td>
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</tr>
<tr>
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<td>1.4±0.8</td>
<td>3.9</td>
<td>18.1</td>
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<td>68.1±10.1</td>
<td>1.3±0.9</td>
<td>10.2</td>
<td>12.3</td>
</tr>
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<td>R. sphaerocarpa</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>1.0±0.8</td>
<td>4.0</td>
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<td>14.8</td>
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Table 2
Characteristics of shrubs and tussocks used for canopy drainage and boundary layer conductance measurements. Average values (±1 standard error)

<table>
<thead>
<tr>
<th>Species</th>
<th>n</th>
<th>Height(m)</th>
<th>Projected canopy area (m²)</th>
<th>Total dry mass (kg m⁻²)</th>
<th>Dry mass density (kg m⁻³)</th>
<th>Total area indexᵃ</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. tenacissima</td>
<td>10</td>
<td>0.60±0.05</td>
<td>0.34±0.06</td>
<td>5.76±0.58</td>
<td>9.84±0.81</td>
<td>6.63±1.29</td>
</tr>
<tr>
<td>A. cytisoides</td>
<td>11</td>
<td>0.71±0.06</td>
<td>0.50±0.13</td>
<td>3.12±0.32</td>
<td>4.76±0.58</td>
<td>3.90±0.62</td>
</tr>
<tr>
<td>R. sphaerocarpa</td>
<td>10</td>
<td>1.68±0.16</td>
<td>2.60±0.57</td>
<td>1.67±0.12</td>
<td>1.14±0.21</td>
<td>0.73±0.11</td>
</tr>
</tbody>
</table>

ᵃ Projected canopy area basis.
and \( t + dt \), was related to the quantity of water stored on the canopy \((C)\) (Eq. (1)) by fitting field data to a power equation using non-linear regression analysis (SPSS, 1992)

\[
\frac{D}{dt} = aC^b
\]

(1)

where \( a \) and \( b \) are constants for a particular plant. Values of the parameters \( a \) and \( b \) were obtained for each shrub and tussock measured.

Boundary layer conductance per plant was measured as a function of wind speed with the Teklehai-manot and Jarvis (1991a) method on the same plants used for the canopy drainage study. Cut plants were sprayed again until the mass stopped increasing and remained constant for several seconds. The plastic covering used to minimise evaporation when the rate of drainage was measured was not used for this part of the experiment. The plant was then allowed to dry and its change of weight was recorded. Times when wetting started and stopped, and when canopy drip became negligible were noted.

For boundary layer conductance calculations, micrometerological variables were recorded simultaneously with the change of mass a few centimetres above each measured plant. Variables measured were wet and dry bulb temperatures with a ventilated psychrometer (Allen et al., 1994), wind speed (A100G, Vector Instrument, Rhyl, UK), average canopy surface temperature \((0.3\ mm\ copper-constantan\ thermocouples,\ type\ T,\ Omega\ Engineering,\ Leicestershire,\ UK)\). Canopy temperature was calculated from two sets of four replicate thermocouples in the centre and edge of the canopy. Variables were measured every 0.125 s and averaged every 10 s by a CR10 datalogger. Each plant went through three wetting and drying cycles.

Mass transfer is proportional to a concentration difference, so that for evaporation from a moist surface \((E)\) (Jones, 1992)

\[
E = g_w\Delta C_w
\]

(2)

where \( g_w \) is the total conductance of the pathway between evaporating sites and the bulk air (stomatal and boundary layer conductances) and \( \Delta C_w \) is the water vapour concentration difference between the surface and the bulk air. Rewriting Eq. (2) expressing water vapour concentration as vapour pressure, the canopy boundary layer conductance of a wet canopy (stomatal resistance assumed equal to zero) can be written as

\[
g_a = \frac{PE}{M\rho_a(e_g^* - e_a)} \tag{3}
\]

where \( g_a \) is boundary layer conductance per shrub, \( P \) is atmospheric pressure, \( M \) is the ratio of molecular weights of water and air \((=0.622)\), \( E \) is the rate of evaporation per unit area from the wet crown, \( \rho_a \) is density of air, \( e_g^* \) is the saturated water vapour pressure at the temperature of the surface of the canopy and \( e_a \) is water vapour pressure of the air. Expressing \( P \) in kPa, \( E \) in kg m\(^{-1}\)s\(^{-1}\), \( \rho_a \) in kg m\(^{-3}\) and \( e_a \) in kPa, boundary layer conductance per plant will be given in m\(^3\)s\(^{-1}\).

Table 4 contains values \((\pm 1\ standard\ error)\) of boundary layer conductance \((g_a)\) per shrub \((m^3\ s^{-1})\), on a total surface area basis \((m^3\ s^{-1})\), on a projected canopy area basis \((m^3\ s^{-1})\) and on a total ground area basis \((m^3\ s^{-1})\) (calculated taking into account the fractional cover for each species (0.34 for \(R.\ sphaerocarpa\), 0.38 for \(A.\ cytisoides\) and 0.60 for \(S.\ tenacissima\)).

Following the method of Teklehai-manot and Jarvis (1991a), \(E\) was obtained directly from the change in weight of the wetted plant while the surface temperature remained approximately equal to the wet-bulb temperature after drainage became visually negligible.

### 3.4. Rainfall interception model

The Rutter type model shown schematically in Fig. 1 assumes that the water stored on the canopy \((C_t)\) at time \(t\) changes to \(C_{t+dt}\) at time \(t+dt\) by the following equation:

\[
C_{t+dt} = C_t + Q_t - D_t - E_t \tag{4}
\]

where, \(E_t\) is evaporation between time \(t\) and \(t+dt\) controlled by environmental variables at time \(t\), \(D_t\) the water draining to the soil between time \(t\) and \(t+dt\), \(Q_t\) the rainfall reaching the canopy between the time \(t\) and \(t+dt\) and is calculated by the equation

\[
Q_t = R_t(1-p) \tag{5}
\]

where \(R_t\) is the rainfall between time \(t\) and \(t+dt\), and \(p\) is the proportion of free throughfall.

The drainage of the water from the canopy \((D_t)\) (6) between time \(t\) and \(t+dt\) is derived from (1):

\[
D_t = aC_t^b dt \tag{6}
\]
Interception or evaporation of water from the canopy \( (E_t) \) between time \( t \) and \( t+\Delta t \) is given by

\[
\text{If } C_t < s \text{ then } E_t = \frac{E_{p,t}C_t}{S} \Delta t \tag{7}
\]

\[
\text{and if } C_t \geq s \text{ then } E_t = E_{p,t} \Delta t \tag{8}
\]

where \( s \) is the minimum amount of water required to wet all the canopy surfaces and \( E_{p,t} \) is the rate of evaporation from the wet canopy in time \( t \) and can be obtained from the Teklehaimanot and Jarvis (1991a) approximation of the Penman equation (see Campbell, 1977; McNaughton and Jarvis, 1983), which neglects the net radiation term

\[
E_{p,t} = \frac{M \rho L (\varepsilon + 1)D}{(\varepsilon + 1)P} \tag{9}
\]

where \( D \) is water vapour pressure saturation deficit of the air and \( \varepsilon \) is the ratio of change of latent heat to sensible heat in saturated air. The non-inclusion of the net radiation term in the Penman equation has been based on results of other authors (Stewart, 1977; McNaughton and Jarvis, 1983; Teklehaimanot et al., 1991), arriving at the conclusion that during the course of a rainfall event, evaporation is driven by the saturation deficit and boundary layer conductance and hence, there is only a small dependence of evaporation on the net radiation term of the Penman equation.

Effective rainfall \( (R_{e,t}) \) (or throughfall plus stemflow) between time \( t \) and \( t + \Delta t \) was estimated by

\[
R_{e,t} = R_tP + D_t \tag{10}
\]

To summarise, each species is defined by the following parameters: \( p \) (percentage of free throughfall), \( a \) and \( b \) (canopy drainage parameters), \( g_a \) (boundary layer conductance per plant) and \( s \) (the quantity of water on canopy when all surfaces are wet). Parameter \( p \) was estimated by the Rutter method, measuring the rainfall partitioning for actual rainfall events, for \( A. \ cytisoides \) and \( R. \ sphaerocarpa \). When the total volume of the rainfall event was lower than the minimum amount of water required to wet all the canopy surfaces \( (\sum R < s) \) then effective rainfall came from gaps in canopy \( (\sum R_c = p \sum R) \).

No field throughfall data were available for \( S. \ tenacissima \), thus the free throughfall coefficient \( p \) was estimated by image analysis of vertical photographs taken beneath the crown of four tussocks when they were suspended from the load cell during the canopy drainage and boundary layer conductance experiment described above. The photographs were scanned (300 pixels inch\(^{-1}\), Scanjet II C, Hewlett Packard) and \( p \) was estimated as the fraction of gaps in the canopy.

The model works as follows: After the ‘parameter input’, the model runs an iterative loop. Each iteration starts with the input of environmental variables (rainfall since last iteration, temperature, humidity and wind speed), then calculates \( E \) and \( Q \) with environmental variables and then \( D \). Finally, \( C \) is estimated and \( R_c \) is calculated. Each iteration represents a 10 s interval \( (\Delta t = 10 \text{ s}) \) with actual or simulated meteorological data of each rainfall event. Rainfall interception is calculated as the sum of water evaporated over all intervals from the start of the rain event to 24 h after the event ends, when it is assumed that the canopy is completely dry.
4. Results

4.1. Rainfall partitioning and free throughfall coefficients

In *A. cytisoides* canopies, 40% of the gross rainfall was throughfall, 20% was stemflow and 40% was interception loss (Fig. 2a). In *R. sphaerocarpa* corresponding percentages were: throughfall 72%; stemflow 7% and interception 21% (Fig. 2b).

Interception loss showed a linear relationship with rainfall volume for both species. The slope of that regression was higher for *A. cytisoides* (Fig. 3a) than for *R. sphaerocarpa* (Fig. 3b). The points represented in Fig. 3 are referred to the storms for which the throughfall and stemflow were measured by the volumetric method in the field for the two species (period 19 April 1994 to 21 June 1995).

The Rutter et al., 1971 method for estimating free throughfall coefficients (*p*) was applied to the data of throughfall collected in the field. *R. sphaerocarpa* had the highest value of *p* (Table 3) resulting from its particular open canopy structure which allows a high proportion of rainfall to reach the soil through the gaps. In contrast, dense canopies of *A. cytisoides* individuals yield a lower free throughfall coefficient (Table 3). *S. tenacissima*’s canopy is also dense because of the accumulation of litterfall and dead material. Gap fraction of a *S. tenacissima* tussock calculated by image analysis was around 0.1±0.02 (Table 3).

4.2. Canopy drainage rate and boundary layer conductance

Field data of water drainage rates from the canopy (*D*) and the amount of water stored on the canopy (*C*)

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Table 3

Average values of the empirically derived parameters used to run the rainfall interception model (±1 standard error)

<table>
<thead>
<tr>
<th></th>
<th><em>S. tenacissima</em></th>
<th><em>A. cytisoides</em></th>
<th><em>R. sphaerocarpa</em></th>
</tr>
</thead>
<tbody>
<tr>
<td><em>p</em></td>
<td>0.1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>ln <em>a</em> (<em>D/dt</em> in mm h&lt;sup&gt;-1&lt;/sup&gt; and <em>C</em> in mm)</td>
<td>−6.25±1.05</td>
<td>−0.62±0.05</td>
<td>3.48±0.36</td>
</tr>
<tr>
<td><em>b</em> (<em>D/dt</em> in mm h&lt;sup&gt;-1&lt;/sup&gt; and <em>C</em> in mm)</td>
<td>7.71±0.61</td>
<td>4.30±0.34</td>
<td>3.12±0.46</td>
</tr>
<tr>
<td><em>g</em>&lt;sub&gt;a&lt;/sub&gt; (m s&lt;sup&gt;-1&lt;/sup&gt;, wind speed: 1–2 m s&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>1.36±0.42</td>
<td>0.65±0.32</td>
<td>0.52±0.29</td>
</tr>
<tr>
<td><em>s</em> (mm)</td>
<td>2.44±0.27</td>
<td>1.80±0.21</td>
<td>0.29±0.02</td>
</tr>
</tbody>
</table>

<sup>a</sup>Estimated from image analysis.
were fitted to a power Eq. (1) (Fig. 4, solid line). The power relationship between $D$ and $C$ in Eq. (1) has been successfully used by Pitman (1989). An excellent approximation is the Gash and Morton (1978) and Gash (1979) exponential drainage model in which drainage stops when $C < s$ where $s$ is canopy storage capacity. Both equations, power and exponential, are equally valid for relating $D$ and $C$. In our study the power relationship (1) had similar $r^2$ to the exponential relationship used by the Rutter exponential drainage model when fitted to the same data (Fig. 4, dashed line). Eq. (1) has the computational advantage in the fact that it does not produce a non-zero drainage when water on canopy is zero, and it simplifies the operation of the model since it is possible to use the same equation for the whole range of $C$ values. On the other hand, Eq. (1) has the disadvantage that it implies that drainage fully stops only when the canopy is dry which would reduce the modelled interception loss, however, this fact would not produce any sensitive errors. Rutter and Morton (1977) pointed out that the model is very insensitive to low errors in drainage.

The different relationships between $D$ and $C$ for each species indicates a difference in canopy structure. $R. sphaerocarpa$ (Fig. 4c) showed the highest drainage rates when calculated on a projected canopy area basis (Fig. 4a–c), due to its low dry mass and low canopy surface per unit of projected canopy area (total area index, Table 2). Comparing $D$ calculated on a total canopy surface area basis (Fig. 4d–f), $S. tenacissima$ (Fig. 4d) had the highest values of drainage when the amount of water stored on the canopy is high. For instance, when the amount of water on the canopy is 0.5 mm (see line $a$ on Fig. 4d–f), the drainage rate for $S. tenacissima$ has a much higher (logarithmic scale) value than the other two species (see line $b$). This fact can be explained by the short pathway of water going to the soil in $S. tenacissima$ and because its green leaves appears to be partially hydrophobic.

The regression between $D$ and $C$ (power equation) was calculated for all $R. sphaerocarpa$ plants giving an average $r^2=0.597\pm0.047$, for all $A. cytisoides$ plants giving an average $r^2=0.889\pm0.022$, and for all $S. tenacissima$ plants giving an average $r^2=0.902\pm0.018$. Canopy boundary layer conductances calculated by measuring the evaporation of water from the canopy (Teklehaimanot and Jarvis, 1991a), expressed per plant (m$^3$s$^{-1}$), are significantly higher in the case of $R. sphaerocarpa$ than in the other two species (Table 4). The same results are obtained when the

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**Table 4**

<table>
<thead>
<tr>
<th></th>
<th>$S. tenacissima$</th>
<th>$A. cytisoides$</th>
<th>$R. sphaerocarpa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_s$ per plant (in m$^3$s$^{-1}$)</td>
<td>0.23±0.04</td>
<td>0.23±0.05</td>
<td>1.21±0.69</td>
</tr>
<tr>
<td>$g_s$ on a total surface area basis (in m s$^{-1}$)</td>
<td>0.21±0.08</td>
<td>0.15±0.05</td>
<td>0.94±0.52</td>
</tr>
<tr>
<td>$g_s$ on a projected canopy area basis (in m s$^{-1}$)</td>
<td>1.36±0.42</td>
<td>0.65±0.32</td>
<td>0.52±0.29</td>
</tr>
<tr>
<td>$g_s$ on a total ground area basis (in m s$^{-1}$)</td>
<td>0.82±0.25</td>
<td>0.25±0.12</td>
<td>0.18±0.1</td>
</tr>
</tbody>
</table>

Wind speed: 1–2 m s$^{-1}$
Fig. 4. The relationship between the drainage rate of water ($D/dt$) (logarithmic scale) and the amount of water on the canopy ($C$), for typical individuals of *Stipa tenacissima* (a and d), *Anthyllis cytisoides* (b and e) and *Retama sphaerocarpa* (c and f). In (a)–(c) $C$ is calculated on a projected canopy area basis and in (d)–(f) $C$ is calculated on a total canopy surface area basis. Solid lines indicate a fit of the power equation $D/dt=\alpha C^\beta$, dashed lines indicate a fit of the exponential equation $D/dt=\alpha e^{\beta C}$. 
boundary layer conductance is expressed on a total surface area basis (m$^3$ s$^{-1}$ m$^{-2}$) (Table 4). However, when boundary layer conductance is expressed on a projected canopy area basis (m$^3$ s$^{-1}$ m$^{-2}$) the values obtained are significantly lower for *R. sphaerocarpa* and *A. cytisoides* than for *S. tenacissima* (Table 4). The model calculates the interception per canopy based on the values of boundary layer conductance expressed on a projected canopy area basis, as the field values of rainfall partitioning (throughfall and stemflow, and hence interception) were also derived in this manner.

4.3. Comparison of field rainfall interception measurements with the values predicted by the model

The Rutter type model was used for calculating total rainfall interception ($I_t$, mm) per rain event for each species (Table 1). The model was run with the parameters contained in Table 3 and measured meteorological data for rainfall events. The boundary layer conductance used in the model was the corresponding average value for a range of wind speeds between 1–2 m s$^{-1}$, the same range of wind speeds found during the actual rainfall events (Table 4). These values were compared with those observed in the Rambla Honda ($I_o$, mm). The model for *R. sphaerocarpa* (open circles) and *A. cytisoides* (closed circles) showed a significant agreement between calculated and observed values of interception (Fig. 5), and no significant differences were found using F-test to compare variances ($F=0.73$, $n=7$, $p=0.71$ and $F=1.38$, $n=8$, $p=0.68$ for *R. sphaerocarpa* and *A. cytisoides*, respectively), t-test to compare means ($t=0.05$, $n=7$, $p=0.96$ and $t=0.29$, $n=8$, $p=0.78$, for *R. sphaerocarpa* and *A. cytisoides* respectively) and paired sample comparison t-test to test if the mean of calculated values minus observed values are significantly different from zero ($t=0.23$, $n=7$, $p=0.83$ and $t=1.29$, $n=8$, $p=0.24$, for *R. sphaerocarpa* and *A. cytisoides* respectively).

The model was also run to calculate interception loss during an actual rainfall event (Fig. 6). Given the same rainfall conditions, evaporation, water on the canopy and effective rainfall will vary between species. These results show relevant differences in interception loss among species resulting from their different input parameter values (Table 3). *R. sphaerocarpa* showed the lowest values of evaporation ($E$) while *S. tenacissima* showed the highest, with *A. cytisoides* being intermediate. The low values of interception by *R. sphaerocarpa* can be explained by its low total surface area index, leading to high free throughfall, high water drainage rate and, therefore, low stored water on the canopy for evaporation. On the other hand, *S. tenacissima* and, to a lesser extent, *A. cytisoides*, show a low free throughfall and drainage rate per projected canopy area because of their high aerial biomass density and closed individual canopies.

The model was also run for eight simulated rainfall intensities: 2, 4, 6, 8, 10, 12, 14 and 16 mm h$^{-1}$, and three sets of environmental conditions: high humidity and low temperature (Fig. 7a–c), intermediate humidity and temperature (Fig. 7d–f) and low humidity and high temperature (Fig. 7g–i). The above conditions were chosen because they were typical of this area (Table 1).

For all three species, when the rainfall volume and rainfall rate increase (Fig. 7), interception fraction decreases, at first quickly and later slowly. Firstly, at any constant rainfall rate that exceeds the mean...
Fig. 6. Time series of evaporation of intercepted water ($E$), effective rainfall ($R_e$) and water on the canopy ($C$) predicted by the interception model during an example (11 March 1995, see Table 1) of an actual rainfall event ($R$) for (a) *S. tenacissima* (b) *A. cytisoides* and (c) *R. sphaerocarpa*. 
evaporation rate from the canopy, small rainfall volumes will fail to completely wet the canopy, net throughfall will equal free throughfall and interception loss will be near 100%. As the rainfall volume increases (at the same rainfall rate) the canopy will eventually become fully saturated (i.e. $C=\delta$) and throughfall drip will occur (assuming that drip does not occur until the canopy is fully saturated). This point is close to the minimum interception loss. After this point, further rainfall will only contribute to increase drip as the evaporation rate (provided all other climate variables are equal) is at equilibrium and little or no change will occur to interception loss. A change in rainfall intensity will, through increased mechanical deformation of leaves and splashing, tend to decrease the depth of water on the leaf surfaces, thus, increasing the drip rate and volume and, therefore, lower the interception loss further. Another factor is that for a constant volume rainfall event, increasing intensity reduces the storm length thus reducing the time available for evaporation of intercepted water. This will again reduce interception loss.

The initial decrease of these curves is less pronounced in the case of $S.\ tenacissima$ (Fig. 7a, d, and g)
because its canopy drainage is lower compared to the other two species when the storage is low, thus storage increases quickly per unit of input of water but it needs more water to reach the corresponding value of \( s \). Accordingly, under higher evaporation demand (Fig. 7g) (high temperature and low humidity), evaporation from \( S. \) tenacissima is more sensitive to atmospheric conditions than evaporation from the other species (comparing Fig. 7a and g), since there is less water on canopy and it is quickly evaporated. Main differences between \( A. \) cytisoides and \( R. \) sphaerocarpa can be seen under low volume rainfalls and conditions of high evaporation rates, where \( A. \) cytisoides has significantly higher interception than \( R. \) sphaerocarpa.

5. Discussion and conclusions

Since accurate estimation of evaporation rate of intercepted water is dominated by the boundary layer conductance, it is critical to accurately determine this parameter, as a small error in the estimation of \( g_a \) can have a very large effect on estimates of evaporation rate and interception loss. Rutter and Morton (1977) and Gash et al. (1980) demonstrated that errors in estimating evaporation could largely be attributed to the effect of error in estimating roughness length on \( g_a \). As the rainfall interception model used in this study gave values of interception that were not significantly different from those measured during actual events for the species studied, it appears that the method of Teklehaimanot and Jarvis (1991a) for calculating whole canopy boundary layer conductance per plant was adequate. Moreover, good agreement between measured and modelled values of interception suggests that the assumption made by previous authors (Stewart, 1977; McNaughton and Jarvis, 1983; Teklehaimanot et al., 1991) of not including the radiation term in the Penman equation was valid. It was also supported by our field meteorological conditions of usually high saturation deficit and hence enhancing the dependence of the evaporation rate on the saturation deficit term.

Differences in rainfall interception values found between species can be explained by their structural differences which in turn, influence canopy drainage rates and boundary layer conductances. The canopy drainage rates are related to the plants structural organisation (Fig. 4). \( R. \) sphaerocarpa and \( A. \) cytisoides branches form a ‘funnel’ shape giving them a lower canopy storage capacity than found for \( S. \) tenacissima which has a rigid mat of dead litter at its base (Figs. 8–10).

Our results concerning canopy boundary layer conductance (Table 4) can be explained in terms of the relative structure of the plant canopies. Open canopies of \( R. \) sphaerocarpa plants allow a better penetration of the wind and creating less shelter for leaves. This structure may also result in a flapping motion of the shoots that would tend to create higher turbulence (Parlange et al., 1971; Schuepp, 1972; Grace, 1978). \( A. \) cytisoides and \( S. \) tenacissima individuals are shorter having a dense foliage which increases the resistance to air flow in the canopy leading to a low canopy boundary layer conductance. For instance, the dense accumulation of dead foliage or litter into \( S. \) tenacissima canopies, up six times the green leaf dry weight (Puigdefabregas et al., 1996), may further
significantly contribute to lowering boundary layer conductance.

Previous studies performed at the leaf scale showed that leaf boundary layer conductance inside the canopy was significantly lower in *S. tenacissima* than in *R. sphaerocarpa* (Domingo et al., 1996). These authors also found significant differences in the relationship between leaf boundary layer conductance and wind speed inside the canopy and in the open suggesting that sheltering effects rather than increased turbulence caused this effect. Our results for whole individual canopies obtained applying the method of Teklehaimanot and Jarvis (1991a) also emphasised the importance of the shelter effects influencing wind speed and thus boundary layer conductance.

Rainfall partitioning in the species studied during natural rain events highlighted the significance of contrasting canopy structures allowing preferential
ways for the rain water in producing throughfall and stemflow. *A. cytisoides* showed high rainfall interception loss due to its high accumulation of green material (leaves and shoots) per unit area. Therefore, rainfalls of high intensity and/or high volume are needed to produce effective rainfall. *R. sphaerocarpa* possesses a different structure, (leafless shrub, modular growth, low total area index) driving to opposite results by the effect of free throughfall and low canopy storage capacity. There was no significant effect of both, gross rainfall volume and size of *R. sphaerocarpa* individuals upon the relative rainfall partitioning between effective rainfall and interception loss (Moro et al., unpublished data). This seems to be caused by the predominance of free throughfall and the modular growth of this species. Our data showed that both *R. sphaerocarpa* and *A. cytisoides* channelled rainfall to a small area giving high rates of stemflow per unit basal area. Stemflow in *A. cytisoides* seems to be strongly facilitated by the particular arrangement of its branches, giving a characteristic ‘funnel’ geometry. In this species the average stemflow percentage (20% of gross rainfall) is one of the highest values for woody shrubs found in the bibliography. For example, in Mediterranean areas, Bellot (1989) estimated a percentage of 4.1% for *Arbutus unedo* and 1.3% for *Phillyrea angustifolia* L., whereas Domingo et al. (1994) found that stemflow accounted for 7.2% for *Cistus laurifolius* and 4.4% for *Adenocarpus decoraticans*. The higher values of stemflow found in *A. cytisoides* shows the potential relevance of this flux to supply water to the soil and, therefore, removing water from the canopy that would be otherwise evaporated.

What is the ecological significance of these differences in canopy structure? We can examine the ecological significance of contrasting canopy structures by relating our results with others already described on physiological aspects on the same species. Tussocks of *S. tenacissima* have a shallow root system and retain dead leaves and litterfall as standing part of the plant. It has been shown that the resulting dense canopy causes higher interception losses (low stemflow and throughfall, as well as large basal area). However, in sparse plant cover conditions, this possible disadvantage is balanced by its higher efficiency in using top soil water and in capturing lateral runoff water and runoff-transported sediments (Puigdefábregas and Sanchez, 1996). Shrubs of *R. sphaerocarpa* have a very open canopy and an extensive root system able to exploit deep water resources. These traits suggest a less conservative strategy of water use but require a large investment of resources to maintain the root system. On the other hand, *A. cytisoides* has an intermediate root system and despite having a high total mass per unit area as *S. tenacissima*, optimises its canopy structure to drain a high proportion of rainfall as stemflow. This adaptation in both *A. cytisoides* and *R. sphaerocarpa* may play an important role in directing rainfall to deeper soil layers adjacent to the plant roots. This would help increasing deep soil water storage and improving the potential for hydraulic lift, (Caldwell and Richard, 1989) which may become important during periods of high water stress. Although the percentage of rainfall as effective rainfall, measured in the field for *A. cytisoides* or *R. sphaerocarpa* is similar, the pathways for the flow of water clearly differ. The significance of these differences in the survival of these species in different parts of the valley requires further investigation.

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SPSS, 1992. SPSS statistical package for Windows 5.01. Copyright (C) SPSS Inc.