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Estimation of soil boundary-layer resistance in sparse semiarid stands for evapotranspiration modelling

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Boundary-layer resistance; Sparse semiarid vegetation; Sensitivity analysis; Diffusion theory; Energy balance

Summary The aim of this work was first, to compare two methods for obtaining soil boundary-layer resistance, one based on the turbulent diffusion theory (TD) and another based on the energy balance of heated and unheated sensors (EB), and secondly, to analyse how the results obtained from both methods are affected by canopy structure parameters in typical sparse vegetation. The study was carried out in stands of three different species characteristic of the semiarid South East of Spain (Retama sphaerocarpa, Anthyllis cytisoides and Stipa tenacissima). Comparison of the two methods showed that EB boundary-layer resistances, unlike TD, implicitly considers the peculiarities of the plant architecture and structure, as well as its distribution in the field and the presence or absence of substrate under the canopies. In contrast, for the TD method, quantitative attributes of the vegetation (average vegetation height, $h$, leaf area index, $L$, fractional vegetative cover, $f$, drag coefficient, $c_d$ and the eddy diffusivity decay constant, $n$) are necessary, which are not only sometimes difficult to obtain in the field, but also seem to be insufficient to explain the development of the soil boundary layer in sparse semiarid vegetation. The advantages of using the EB method are both practical and theoretical. Positioning of the sensors and data storage with automatic data loggers is easy, and does not require knowledge of the aerodynamic attributes of the vegetated area. Furthermore, it allows qualitative interpretation of the effect of non-transpirable vegetative elements, as well as the architecture of the vegetation and its distribution in the field, neither of which are considered in the turbulent diffusion theory.

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Introduction

The increase in arid and semiarid lands due to climate change and over-exploitation of water resources have led to the need for measuring and modelling the water balance over surfaces composed by different density and type of plant cover. One of the main water balance components is the actual evapotranspiration flux (AET). In the last few decades, much effort has addressed its measurement and modelling through an understanding of the role of each evaporative source, vegetation and soil. Among the many evaporation models that have been developed, mainly for agricultural crops, the best known is the single-source Penman–Monteith evaporation model (Monteith, 1965) which has been successfully applied to crops and canopies over the last 30 years. This model assumes that canopies can be regarded as a single uniform surface or ‘big-leaf’. Semi-arid lands, characterised by patches of vegetation and open spaces, are not appropriate for the big-leaf assumption, as flux sources/sinks may occur at canopy or soil surfaces that are significantly separated. Hence, the single-source Penman–Monteith model was later extended to two or more sources according to two approaches. The multi-source approach, where the Penman–Monteith equation is applied for each of the sources and total evapotranspiration is calculated by adding the different sources weighted by their fractional covers. The other approach, called the multi-layer approach, assumes that each of the evaporating sources are linked via an aerodynamic resistance network where temperature and water vapour deficit within the canopy are modified by the interaction of the different sources (Huntingford et al., 1995). In this approach total evapotranspiration is calculated as the sum of the Penman–Monteith equations of each source, weighted by their fractional covers, and a set of coefficients that represent the combination of the resistances considered. According to this, different authors have developed two-layer models (plant and soil; e.g. Shuttleworth and Wallace, 1985; or two types of plants; e.g. Huntingford et al., 1995; Wallace, 1997), three-layer models (plant, soil under plant and bare soil; e.g. Brenner and Incoll, 1997; Domingo et al., 1999) and more (bare soil and three types of plants; e.g. Verhoef and Allen, 2000). All these models explicitly specify energy exchanges in canopy and soil leading to improved predictions of evaporation from sparsely vegetated surfaces (Rouse et al., 1992; Nichols, 1992).

All these AET models consider that water vapour originates from different evaporating sources, and that AET is driven by water vapour concentration gradients, turbulent diffusion produced by the effect of the roughness elements present in any vegetated area on the wind that crosses over it, and by the radiative energy available for evaporation. These models also consider that the water vapour flux from the sources is constrained by surface and boundary-layer (or aerodynamic) resistances. These boundary-layer resistances have usually been calculated for AET models using the turbulent diffusion theory for water vapour (Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990; Huntingford et al., 1995; Brenner and Incoll, 1997; Verhoef and Allen, 2000; Roberts, 2000; Komatsu, 2003). Turbulent diffusion theory needs information of numerous aerodynamic variables characteristic of the area studied (leaf area index, fractional vegetative cover, vegetation height, leaf dimensions, and eddy diffusivity decay or extinction coefficient for wind speed) which are difficult to obtain. However, other works have developed empirical measurements for soil transfer coefficients (related with the soil boundary-layer resistance) for heat and water vapour with the source plate technique (Sauer et al., 1995). Others have developed empirical measurements of boundary-layer resistance based on the energy balance of pairs of heated leaf replicas for measuring the leaf and whole plant boundary resistance ($r_{a}^{L}$) (Leuning and Foster, 1990; Brenner and Jarvis, 1995; Domingo et al., 1996; Smith et al., 1997; Smith and Jarvis, 1998), and of pairs of heated sensors for measuring soil aerodynamic resistance ($r_{s}^{L}$) (McInnes et al., 1994 and McInnes et al., 1996; Tarara and Ham, 1999). These last methods do not need the knowledge of the aerodynamic variables mentioned before.

The objective of this study is therefore twofold. First, it compares the two above-mentioned methods of obtaining soil boundary-layer resistance, one based on the turbulent diffusion theory (called TD here), calculated according to Shuttleworth and Gurney (1990) and Brenner and Incoll (1997), and the other based on the energy balance of heated sensors (here called EB), following the method proposed by McInnes et al. (1994) and McInnes et al. (1996). Secondly it analyses how the results obtained by the TD method are affected by structural parameters, such as leaf area index, average vegetation height and fractional vegetative cover, and by aerodynamic parameters, such as drag coefficient and eddy diffusivity decay, in typical sparse semiarid vegetation. The study was carried out on stands of three different species characteristic of the semiarid southeast of Spain (Retama sphaerocarpa, Anthyllis cytisoides and Stipa tenacissima). This study is relevant for better surface flux modelling, the development of aggregation approaches (Dolman and Blyth, 1997; Blyth and Harding, 1995; Blyth, 1997) and the estimation of sensible heat flux from remotely sensed temperatures (e.g., Kustas et al., 1998; Sugita and Brutsaert, 1990; Stewart, 1995; Burke and Stewart, 1997; Farah and Bastiaanssen, 2001; Melesse and Nangia, 2005).

Theory

Both the EB and TD methods estimate soil boundary-layer resistance from the soil surface to the mean surface flow height ($z_{m}$). In this study, soil is differentiated between the soil below the plant canopy, with its aerodynamic resistance ($r_{a}^{s}$) directly influenced by the vegetation, and bare soil, with its boundary-layer resistance ($r_{s}^{b}$) not influenced by the vegetation (Fig. 1). Another consideration is related to the difference between heat transport and momentum, the latter being the more effective due to its additional drag mechanism, and thereby, to a different roughness length for energy exchange and momentum. Although this difference is more important in closed than in sparse canopies (Shuttleworth and Gurney, 1990; Kaimal and Finnigan, 1994), when comparing the EB and TD methods, we assume an approximate equivalence between the eddy diffusion of momentum and energy through the canopy. The theoretical background of both methods is described below.
Measurement of soil boundary-layer resistance by heated sensor energy balance (EB)

Boundary-layer resistance for heat transport can be determined empirically from the energy balances of heated and unheated pairs of adjacent sensors following the method of McInnes et al. (1994). Assuming negligible heat storage in the sensors, the boundary-layer resistance for heat \( r_h \) can be obtained as

\[
r_h = \left[ \frac{\rho_a C_p (T_H - T_U)}{(-\varepsilon a T_H) + (G_H - G_U) + P_H} \right] \tag{1}
\]

where \( \rho_a \) is the density of air (kg m\(^{-3}\)), \( C_p \) is the specific heat capacity of air (J kg\(^{-1}\) K\(^{-1}\)), \( T_H \) and \( T_U \) are the temperatures (K) of the heated and unheated surfaces, respectively, \( \varepsilon \) is the thermal emissivity of aluminium, \( a \) is the Stephan–Boltzmann constant (W m\(^{-2}\) K\(^{-4}\)), \( P_H \) is the electrical power input of the heater and \( G_H \) and \( G_U \) are the heat flux densities conducted through the polystyrene foam for the heated and unheated sources, respectively. Eq. (1) enables \( r_h \) and \( r_{bs} \) to be calculated by locating pairs of sensors under the canopy and bare soil, respectively. These resistances can be related to wind speed measured at the reference height \( (u_r) \), and the equations for these relationships can be used to easily determine soil boundary-layer resistance.

Estimation of soil boundary-layer resistance using the turbulent diffusion theory (TD)

A detailed description of this method can be found in Shuttleworth and Gurney (1990). This method was developed for agriculture where the calculation of soil boundary-layer resistance is related to the stand leaf area index \( (L_a) \) and average plant height \( (h) \), where \( L_a \) can be obtained as the product of the average leaf area index of individual plants \( (L) \) and the fractional vegetation cover \( (f) \). The mean surface flow height \( (z_m) \) is assumed to be the effective source of energy flux, and remains constant at the height of the sink of momentum relevant to 'closed-canopy' conditions. \( z_m \) was calculated as the sum of the roughness length \( (z_0) \) and zero-plane displacement height \( (d) \) \( (z_m = z_0 + d) \). These latter vary with \( L_p \) and \( h \) according to:

\[
d = 1.1 h \ln (1 + X^{0.25}) \tag{2}
\]

\[
z_0 = Z_0 + 0.3 h X^{0.5} \quad \text{when} \ 0 < X < 0.2 \tag{3}
\]

\[
z_0 = 0.3 h (1 - d/h) \quad \text{when} \ 0.2 < X < 1.5 \tag{4}
\]

where \( X = c_d L_p \), \( z_0 \) is the roughness length of the bare substrate (Shuttleworth and Gurney, 1990), and \( c_d \) is the drag coefficient.

\( r_s \) is the boundary-layer resistance between the soil surface below the canopy and \( z_m \) (Fig. 1) and is given in Shuttleworth and Gurney (1990) by the following equation:

\[
r_s = \left[ \frac{\rho a}{k u_r^2} \right] \left[ e^{-\frac{z_0}{h}} - e^{-\frac{z_m}{h}} \right] \tag{5}
\]

where \( k_0 \) is the value of the eddy diffusion coefficient (K) at the top of the canopy and \( n \) is the eddy diffusivity decay constant (dimensionless extinction coefficient for windspeed).

When Brenner and Incoll (1997) extended the Dolman approximation (1993) to consider the soil between plants as a third evaporative source, the aerodynamic resistance between the bare soil surface and the reference height \( (z_r) \) \( (r_{bs} \ Fig. 1) \) was calculated by assuming that bare soil is totally unaffected by adjacent vegetation so that aerodynamic resistance equals \( r_{bs} \) (Brenner and Incoll, 1997), which is defined by

\[
r_{bs} = \frac{\ln (z_r - d/z_r)}{k u_r^2} \tag{6}
\]

where \( u_r \) is wind speed at \( z_r \) and \( d \) is zero for bare soil (Daamen and Simmonds, 1996).

Actual \( r_{bs} \) varies between \( r_{bs} \) (Eq. (6)) when \( f = 0 \) and \( r_s \) (Eq. (5)) when \( f = 1 \). Since the functional relationship of this change was unknown, \( r_{bs} \) was varied linearly between \( r_{bs} \) (Eq. (6)) and \( r_s \) (Eq. (5)) as \( f \) changed from 0 to 1 by

\[
r_{bs} = [fr_s + (1 - f)r_{bs}] \tag{7}
\]

This approach has been successfully used for calculating \( r_{bs} \) in three-layer models of evapotranspiration (Brenner and Incoll, 1997; Domingo et al., 1999).

Several works (Choudhury et al., 1986; Choudhury and Monteith, 1988; Daamen and Simmonds, 1996; Daamen, 1997) have shown that in non-neutral conditions the aerodynamic resistance can vary on account of the buoyancy, and have corrected aerodynamic resistance equations (Eqs. (5) and (7)) by multiplying by a factor \((1 + \delta)^i\)

\[
\delta = \frac{5g(z_r - d)(T_s - T_r) + (T_s u_r^2)}{2T_s u_r^2} \tag{8}
\]

\[
\varepsilon = -2. \quad \delta < 0 \quad \text{stable conditions}
\]

\[
\varepsilon = -0.75, \quad \delta > 0 \quad \text{unstable conditions}
\]

where \( g \) is the gravitational acceleration and \( T_s \) is the soil temperature. As data from the meteorological variables at \( z_m \) were not available, in this work air temperature and wind speed at the reference height \( (T_r \ and \ u_r \ respectively) \) were used.

Material and methods

Field experiments for obtaining soil boundary-layer resistance by both methods were carried out in homogeneous stands of sparse semiarid vegetation of three contrasting species characteristic of the Southeast of Spain (R. sphaero-carpa, A. cypsoides and S. lenacissima) present at the Rambla Honda Field Site (Tabernas, Almeria, Spain).
Site description

The field site is located in the Rambla Honda, a dry valley near Tabernas, Almería, Spain (37°8'N, 2°22'W, 630 m altitude). The field site has previously been described in detail by Puigdefábregas and Sánchez (1996). The valley has been abandoned for several decades, and currently has little agricultural activity apart from small-scale sheep herding. Vegetation is dominated by three perennial species, *R. sphaerocarpa* (L.) Boiss. shrubs on the valley floor, *S. tenacissima* L. tussocks on steep valley walls and *A. cytisoides* L. shrubs on alluvial fans between the two. The valley bottom has deep loamy soils that overlay mica schist bedrock. The field site has an average annual rainfall of 220 mm, average mean temperature of 16 °C and a dry season from around June to September.

*R. sphaerocarpa* is a woody leguminous shrub with ephemeral leaves, which grows up to 4 m tall and 6 m diameter, with cylindrical photosynthetic stems (cladodes) (Fig. 2a). The shrub has an open canopy structure with an abundant grass substrate under the canopy and deep root system which can extract water from depths below 25 m (Haase et al., 1996; Domingo et al., 1999; Domingo et al., 2001). Woody branches represent the majority of its aerial biomass and the proportion of its standing dead biomass is very small compared to *S. tenacissima* and *A. cytisoides* (Fig. 2). At the experiment site, *R. sphaerocarpa* covers an average of 0.3 ($f = 0.3$) (Domingo et al., 2001) of the valley bottom.

*S. tenacissima* is a perennial tussock grass that grows up to 1.5 m tall and 3 m diameter. Leaves are long, narrow, cylindrical, evergreen, and usually live more than a year. After dying, leaves accumulate in 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 standing for some time after the leaves have died, forming a clump. Clumps from a common origin joined by the same branching system form a module (Fig. 2b). Tussocks are usually formed by several physiologically independent modules physically interconnected by dead leaves (Sánchez and Puigdefábregas, 1994). *S. tenacissima* has a dense superficial rooting system which provides rapid access to water from even small rain events (Domingo et al., 2003). In mature tussocks much of the mass is standing dead leaf litter, which produces a very high plant mass per unit area. *S. tenacissima* covers 0.3 of the experimental site (Villagarcía, 2000).

*A. cytisoides* is a drought-deciduous leguminous shrub, growing up to 1.5 m tall and 1 m diameter, and has mesophyllous leaves. It has a moderately deep root system that goes down to 5 m. Shrubs are highly branched and dense with no grass substrate under the canopy. Their shape changes with age, with young bushes forming an inverted funnel, while old ones tend to be hemispherical (Fig. 2c). The density of aerial biomass, the majority of which is branches, although high, is smaller than *S. tenacissima*. *A. cytisoides* covers 0.4 of the experimental site (Villagarcía, 2000).

Field measurements for the energy balance method (EB)

The system used in this study was built following McInnes et al. (1994) and consists of paired sensors, each sensor consisting of:

- two 0.1 m diameter polystyrene-foam disks, the top one 0.01 m thick and the lower one 0.025 m thick.
- a thin round heater placed on top of the upper foam disk.
- three fine-wire copper–constantan thermocouples (0.27 mm diameter, Type T, Omega Engineering, Broughton Astley, UK) installed to measure temperatures on the top and bottom heater surfaces (the two thermocouples are separated from the heater by two thin sheets of aluminium foil) and at 0.01 m underneath the heater disk surfaces (i.e., between the two foam disks) (Fig. 3).

![Figure 3](image_url)  
**Figure 3** Schematic representation of a sensor for measuring the soil boundary-layer resistance (EB method) under the plant canopy (black dop).
Two different experiments were carried out in selected plots within the area covered by each of the three species. For the first experiment, carried out in all three species, five pairs of sensors were placed in a line from lesser to greater influence of the canopy in a gradient from the centre of an individual canopy to the open (bare) soil. One of the pairs was positioned under the plant (under the substrate in the case of R. sphaerocarpa and S. tenacissima) and another on bare soil. The other three were placed in intermediate positions. The second experiment was carried out to determine the effect of the spatial arrangement of vegetation on soil boundary-layer resistance. For this purpose the five pairs of sensors were placed at random in clearings between plants in the A. cytisoides and S. tenacissima stands.

Errors associated with the assumption that the radiation absorbed by the two sensors in each pair is the same (Brenner and Jarvis, 1995; Domingo et al., 1996) were diminished by alternately activating the heater on one sensor of each pair every 15 min, while the other served as the control, furthermore data were corrected for the temperature difference measured between the sensors when the power was switched off. Temperatures in sensor pairs were measured during the last 8 minutes of each 15 min interval, after the heaters had reached their maximum temperature. Temperatures were registered each second in a CR10 datalogger (Campbell Scientific Ltd., Logan, Utah, USA) from the eighth temperature at the reference height ($z_r$) and another on bare soil. The other three were placed in intermediate positions. The second experiment was carried out to determine the effect of the spatial arrangement of vegetation on soil boundary-layer resistance. For this purpose the five pairs of sensors were placed at random in clearings between plants in the A. cytisoides and S. tenacissima stands.

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According to McInnes et al. (1996) we limited our estimation of $r^2_s$ and $r^2_e$ to $u_1$ measurements greater than 1.5 m s$^{-1}$.

**Application of the turbulent diffusion theory (TD)**

**Fractional vegetation cover ($f$), plant leaf area index ($L$) and average plant height ($h$)**

The fractional vegetation cover ($f$) and the average plant height ($h$) were measured in all the stands of the three species. $f$ was measured in A. cytisoides and S. tenacissima by averaging the value obtained from six 30 m long transects selected at random in the stands. $f$ was calculated in R. sphaerocarpa by aerial photograph imaging analysis (Domingo et al., 2001). As mentioned above, $f$ obtained for A. cytisoides was 0.3, for S. tenacissima 0.4 and for R. sphaerocarpa 0.3. The average plant height ($h$) was 2.00 m in the R. sphaerocarpa stand, 0.90 m for A. cytisoides and 0.84 m S. tenacissima (Table 1).

Leaf area was estimated in R. sphaerocarpa by an indirect method based on measurements of radiation transmission through canopies (DEMON; CSIRO, Canberra, Australia). Brenner et al. (1995) developed a method for these species in which a linear relationship between total branch area per plant to projected canopy area is used to estimate the branch surface area of R. sphaerocarpa individuals present in the selected plot. This is then subtracted from indirect estimates of total surface area to obtain leaf surface area. The average leaf area index of individual plants ($L_p$), defined as the leaf surface of the plant per unit of projected canopy area, was 3.03 ± 0.37 in June 1993 and 2.00 ± 0.29 in June 1994 (Brenner and Incoll, 1997). To find $L_p$ for the period when the field experiments were carried out, 22 individuals were measured with the DEMON in April 1997, with $L_p$ being estimated as 2.5 ± 0.15. By multiplying this by $f$, the stand leaf area index ($L_s$) was estimated to be 0.75.

The A. cytisoides and S. tenacissima canopies are extremely tight, preventing measurement of radiation transmission. Therefore, $L$ for these two species was calculated by averaging the leaf area index measured by a destructive direct method, which yielded 1.05 ± 0.39 ($L_p = 0.42$) for A. cytisoides and 0.91 ± 0.16 ($L_p = 0.27$) for S. tenacissima, (Villagarcia, 2000). Table 1 summarizes the different values of $f$, $L$ and $h$ for the three species.

Other parameters needed for the TD method are the drag coefficient ($c_d$) and eddy diffusivity decay ($n$) (Eq. (5)). The value of $c_d$ was the one already used by Brenner and Incoll (1997) for the R. sphaerocarpa stand ($c_d = 0.07$), which is the value used in the reference work of Shuttleworth and Gurney (1990). Though $n$ can be calculated from the leaf area index (Pereira and Shaw, 1980; Wallace and Verhoef, 2000) in this work a value of 2.5 was used which is often adopted for closed and dense canopies (Shuttleworth and Wallace, 1985; Choudhury and Monteith, 1988) and for sparse vegetation (Domingo et al., 1999; Verhoef and Allen, 2000).

**Measurements for the atmospheric instability term ($1 + 4d$)**

For applying the correction term for atmospheric instability in Eqs. (5) and (7) we measured soil temperature ($T_s$) and air temperature at the reference height ($T_r$). Six thermocouples (0.5 mm diameter, Type T, Omega Engineering Broughton Astley, UK) were slightly buried in each one of the three stands studied; three of them were located under the plants and the other three in the bare soil. $T_r$ was calculated averaging soil under plant and bare soil temperature corrected by the fractional vegetation cover ($f$) of each stand. $T_r$ was measured at each reference height with fine-wire

---

**Table 1** Fractional vegetation cover ($f$), average vegetation height ($h$), average plant leaf area index ($L$), reference height ($z_r$) and mean surface flow height ($z_m$) used to calculate $r^2_s$ and $r^2_e$ with the TD method for R. sphaerocarpa, S. tenacissima and A. cytisoides stands.

<table>
<thead>
<tr>
<th>Species</th>
<th>$f$</th>
<th>$h$ (m)</th>
<th>$L$</th>
<th>$z_r$ (m)</th>
<th>$z_m$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R. sphaerocarpa</td>
<td>0.3</td>
<td>2.00</td>
<td>2.5</td>
<td>5.0</td>
<td>1.50</td>
</tr>
<tr>
<td>S. tenacissima</td>
<td>0.3</td>
<td>0.84</td>
<td>0.91</td>
<td>3.5</td>
<td>0.63</td>
</tr>
<tr>
<td>A. cytisoides</td>
<td>0.4</td>
<td>0.90</td>
<td>1.05</td>
<td>3.0</td>
<td>0.68</td>
</tr>
</tbody>
</table>
Results and discussion

Soil boundary-layer resistances \(r^s_s\) obtained by the EB method

Boundary-layer resistance for soil under the canopy \(r^s_s\) and for bare soil \(r^{bs}_s\) in \(R.\) sphaerocarpa, \(A.\) cytisoides and \(S.\) tenacissima stands measured by the EB method tended to decrease with increasing wind speed \((u_s)\) (Fig. 4).

These results agreed with empirical observations of forced convection across a heated horizontal plate in a free air stream (Kays and Crawford, 1980) and with the results obtained for sparse crops using the same method (McInnes et al., 1994, 1996; Sauer et al., 1995; Sauer and Norman, 1995; Tarara and Ham, 1999; Domingo et al., 1999; Verhoef et al., 2006). The figure shows only the relationships found using the EB method for extreme positions, i.e., soil under plant and bare soil. The result of the sensors located between these extreme positions produced intermediate curves. Fig. 4a shows that \(S.\) tenacissima stand had \(r^s_s\) intermediate values (\(R.\) sphaerocarpa is higher and \(A.\) cytisoides lower). However \(r^{bs}_s\) values were similar in the three stands, although somewhat higher in the \(R.\) sphaerocarpa stand. The relationships found for \(r^s_s\) and \(r^{bs}_s\) in the three stands fitted power equations significantly \((p < 0.05)\) (Table 2).

Differences between \(r^s_s\) for \(R.\) sphaerocarpa and \(r^{bs}_s\) for \(A.\) cytisoides, or \(S.\) tenacissima varied from 21% to 25% (Fig. 5b). On the contrary, \(r^s_s\) for the three stands were different (Fig. 5a). Thus, comparing \(r^s_s\) for \(R.\) sphaerocarpa with the other two, the difference with \(r^s_s\) for \(A.\) cytisoides increased (from 36% to 43%) with \(u_s\), while the difference with \(r^{bs}_s\) for \(S.\) tenacissima decreased (from 27% to 21%) with higher values of \(u_s\). The difference between \(r^s_s\) for \(S.\) tenacissima and \(r^s_s\) for \(A.\) cytisoides showed the higher variation, increasing with \(u_s\) from 12% to 28%. These results indicate how the architecture of the three species and their spatial distribution can affect in a different way the turbulence crossing each of the stands, and therefore \(r^s_s\) and \(r^{bs}_s\).

According to this, results show that \(r^{bs}_s\) was similar on \(A.\) cytisoides and \(S.\) tenacissima stands, both having similar values of \(h, L\) and \(f\). However, \(r^s_s\) was different for the three stands, not only in its value, but also in its relation with \(u_s\).

The above description of the three species will help to understand these results (Fig. 2). \(R.\) sphaerocarpa shrubs have a high open canopy, with a dense substrate of annual and perennial plants within their area of influence, while the lower layers of the closed canopies of \(A.\) cytisoides plants are clear and have little vegetated substrate under their canopy. \(S.\) tenacissima does not have vegetation under its area of influence, but its canopy, close to the soil surface, and the accumulation of litterfall from previous years protect the fraction of soil underneath the plant (Puigdefà bregas and Sánchez, 1996). These species characteristics could explain the lower values of \(r^s_s\) for \(A.\) cytisoides, because the more exposed under-canopy area of \(A.\) cytisoides and the absence of vegetated substrate implied that the air circulation under the canopy was not hindered. In the case of \(S.\) tenacissima, the shape of the canopy together with the accumulation of litterfall would explain that the values of \(r^s_s\) were higher than those of \(A.\) cytisoides. Finally, the higher values of \(h\) and \(L\), and the presence of vegetated substrate under the canopy of \(R.\) sphaerocarpa would explain the high values \(r^s_s\) for this specie.

![Figure 4](image-url)  
**Figure 4** Relationship between boundary-layer resistance and wind speed at reference height \((u_s)\) obtained for soil under plants (a) and bare soil (b) for the three species \(R.\) sphaerocarpa (○), \(S.\) tenacissima (●) and \(A.\) cytisoides (□).

<table>
<thead>
<tr>
<th>Soil type</th>
<th>(r^s_s)</th>
<th>(r^{bs}_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R.) sphaerocarpa</td>
<td>(r^s_s = 107.62 \ u_s^{-0.26})</td>
<td>(r^{bs}_s = 81.68 \ u_s^{-0.32})</td>
</tr>
<tr>
<td>(A.) cytisoides</td>
<td>(r^s_s = 70.52 \ u_s^{-0.33})</td>
<td>(r^{bs}_s = 62.00 \ u_s^{-0.30})</td>
</tr>
<tr>
<td>(S.) tenacissima</td>
<td>(r^s_s = 76.71 \ u_s^{-0.21})</td>
<td>(r^{bs}_s = 60.46 \ u_s^{-0.29})</td>
</tr>
</tbody>
</table>

These relationships are represented in Fig. 4.
The second experiment carried out with the EB method, consisted in setting randomly five pairs of plates in clearings of the *A. cytisoides* and *S. tenacissima* stands. The \( r_{bs} \) values obtained for each stand were average and the standard deviation calculated.

It is known that the flow field in sparse vegetation is no longer horizontally uniform, and the effect of individual plants is appreciable (Lee, 2000). The roles of the plant elements can be twofold, mechanical (generation of wakes and sheltering) (Green et al., 1995) and thermal (differential heating/cooling between plants and gaps) (Sun and Mahrt, 1995). Despite the similarity in \( r_{bs} \) in stands of *A. cytisoides* and *S. tenacissima* (Figs. 4b and 5b), analysis of \( r_{bs} \) measured by the EB when the pairs of sensors were placed randomly in clearings showed that the standard deviations of the average \( r_{bs} \) (obtained from their relationships with \( u_r \) for each pair of adjacent sensors using discrete values for \( u_r \)) evolved differently in the two stands (Fig. 6). Variability of \( r_{bs} \) was greater in *S. tenacissima* clearings than in those of *A. cytisoides*. This result together with the differences found between the two species despite the similar \( h, L \) and \( f \) of both stands, shows that there must be other factors playing an important role in the development of eddies in the clearings between plants. Some of these factors are related to the plant architecture (i.e. vertical distribution of leaves and branches) or the proportion of woody elements in the plant as it is explained below.

**Figure 5** Differences (%) in boundary-layer resistance at similar positions (soil under plant [a] and bare soil [b]) with the EB method the three stands studied (Dotted line; *S. tenacissima* – *A. cytisoides*. Dashed line; *R. sphaerocarpa* – *S. tenacissima*. Continuous line; *R. sphaerocarpa* – *A. cytisoides*).

**Figure 6** Standard deviation (SD) of aerodynamic resistance of bare soil \( (r_{ba}^s) \) estimated with wind speed at reference height \( (u_r) \) in *A. cytisoides* (C; \( n = 8 \)) and *S. tenacissima* (○; \( n = 10 \)).

Soil boundary-layer resistances \( (r_{a}^s, r_{a}^{bs}) \) obtained by the TD method and their comparison with the EB method

Previously to the application of the TD method we analysed the effect of the atmospheric stability correction term in the soil boundary-layer resistances. This term was developed as an attempt to model the effect of the non-neutral atmospheric conditions on the development of the boundary-layers (Choudhury et al., 1986). To understand how useful this correction term is in our field conditions (sparse vegetation and semiarid climate), this term was used in the calculation of \( r_{as} \) in the *R. sphaerocarpa* stand as an example. In Fig. 7 it can be observed how the calculation of \( r_{as} \) in neutral conditions is affected by the correction
term. For $\delta > 0$ that corresponds to unstable conditions, that favours the vertical mixing (Fig. 7a), the stability correction decreased the value of $r_s^a$. However, for $\delta < 0$ that corresponds to stable conditions (Fig. 7b), the air temperature near the soil surface ($T_s$) is lower than that of upper layers ($T_d$), therefore the vertical mixing is reduced. In this case it would be expected that the aerodynamic resistances would be higher than those calculated in neutral conditions. However, Fig. 7 shows that this does not occur in our case, as the correction factor for buoyancy decreases the values of this resistance. This is due to the fact that the correction term was developed for small temperature gradients ($T_s - T_d$) characteristic of temperate areas with continuous vegetation. However, in semiarid areas highly negative temperature gradients are found and therefore the corrected resistances reach lower values (Eq. (7)). According to this, the correction for atmospheric stability caused more problems than it solved. Therefore, as the main objective of this work is to compare the two methods for calculating $r_s^a$, from now the TD method is applied without taking into account the atmospheric stability correction.

The values of $r_s^a$ and $r_s^{bs}$ obtained with the TD method were very similar for the three stands (Fig. 8). Thus $r_s^a$ of the R. sphaerocarpa stand was 2.8% and 4.0% higher than $r_s^a$ of the A. cytisoides and S. tenacissima stands, respectively. However, $r_s^{bs}$ of the R. sphaerocarpa stand was lower than $r_s^{bs}$ of the A. cytisoides and S. tenacissima stands ($-5.2\%$ and $-10\%$, respectively). These differences were constant for the whole range of $u_r$.

Fig. 9 shows the differences between the resistances obtained by TD and EB methods in the three stands for positions soil under plant (a and c) and bare soil (b and d). Only for low values of $u_r$ both methods show similar results. However, as $u_r$ increased these differences were higher, especially in the R. sphaerocarpa stand where differences of more than 400% and 300% were obtained for bare soil and soil under plant, respectively.

A sensitivity analysis of the TD method results was carried out by varying the actual average leaf area index ($L$) and average plant height ($h$) of individual plants as well as...
The sensitivity analysis was performed for the three main structural and aerodynamic descriptive parameters of the canopy used in the turbulent diffusion theory. \( f \) and \( c_d \) were excluded from this analysis because \( r_s^a \) is affected by the leaf area index of the stand \( (L_p; \text{Eqs. (2) and (3)}) \), which is calculated as the product of \( L \) and \( f \) and hence, the 25\% and \( 50\% \) variations in \( f \) and \( c_d \) yielded the same result as when \( L \) was varied by the same percentages.

The sensitivity analysis (Fig. 10 and Table 3) showed that the TD method is about three times more sensitive to variations in \( h \) than to variations in \( L \) and therefore, this is the more important structural parameter when calculating \( r_s^a \) by this method. In spite of this, a variation of \(-50\% \) in \( h \) only involved about \(-20\% \) (2.5 times lower) of the variation of the calculation of \( r_s^a \). The TD method, on the contrary, is highly sensitive to variation in \( n \) (a \( 50\% \) variation of \( n \) involved a \( 139\% \) variation in \( r_s^a \)) which implies that this parameter must be determined precisely for this method. According to this, Pereira and Shaw (1980) and Wallace and Verhoe (2000) used \( n \) as function of the projected area of total plant material per unit ground area \( (P) \), though it is often estimated using the canopy leaf area index \( (L_p) \) (Wallace and Verhoe, 2000). In many agricultural species both variables can be equivalent as the woody parts are inexistent or not significant at an aerodynamic level. However, for many crops or natural vegetation, and particularly in semiarid climates, \( P \) can be much higher than \( L_p \), and therefore it must be calculated. In this sense, more research should be carried out to formalize the effect of the plant architecture and the proportion of woody elements in the turbulent diffusion equations and in their parameters.

Conclusions

Analysis of a comparison of two methods for calculating soil boundary-layer resistance showed that the EB method implicitly considers the peculiarities of the plant architecture and structure, as well as its distribution in the field and the presence or absence of substrate under the canopy. On the other hand, the TD method requires quantitative attributes of the vegetation \( (h, L \text{ and } n) \), that sometimes are difficult to obtain in the field and that are insufficient to explain the aerodynamic behavior of the sparse semiarid vegetation. A sensitivity analysis of the TD method for \( h, L \) and \( n \) in the \( r_s^a \), showed that TD was more sensitive to variation in \( n \) and \( h \), and that these parameters are therefore the most important in the calculations. More precisely, future investigation should stress on how the woody parts of the vegetation can affect the variation in \( n \), and therefore
affect the calculation of the boundary-layer resistances. On the contrary, when \( r^2 \) was obtained by the EB method, differences found in \( r^2 \) for stands with similar \( h \) (\( \text{A. cytisoides} \) and \( \text{S. tenacissima} \)) showed that the differences in \( r^2 \) over the whole range of \( u_\star \) could not be explained by the effect of \( h \) alone, and that other implicit factors, such as the distribution of the canopy leaves, the presence of litter underneath the plants and the existence or not of substrate under the canopies must also be taken into account.

The advantages of using the EB method appear to be both practical and theoretical. On the one hand, the positioning of the sensors and data storage can be done easily with automatic dataloggers without having to know the aerodynamic attributes of the vegetated area. On the other hand, the EB method allows qualitative interpretation of the effect of the non-transpirable plant elements, as well as the architecture of the vegetation and its distribution on the field, which are not fully described by the turbulent diffusion theory.

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References


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