Evolatranspiration, given its importance for an appropriate water management both at the farm and the irrigation project level, has been a very intensive field of research, specially in the last thirty years. One of the most important issues in this area was unquestionably the publication of “FAO-24” by Doorenbos and Pruitt (1977), with its “two-step approach”, the crop evapotranspiration being determined using a reference evapotranspiration (ETo) and a crop coefficient (Kc) being widely adopted. However, the studies made since indicated that the methodology proposed by FAO and based on the Penman equation overestimates ETo and that the most accurate estimates are given by a slightly different version known as the Penman-Monteith equation (Jensen et al., 1990). This led to a joint collaboration between FAO and ICID in order to revise the Doorenbos and Pruitt (1977) work, and new methodologies to calculate ETo using the Penman-Monteith equation are now available (Allen et al., 1994a,b). The focus on this approach also encourages the emergence of a new concept, the one-step calculation of crop evapotranspiration. However, there are still some problems in its practical application, namely in the calculation of the necessary aerodynamic (ra) and surface (rs) resistances.

This study was conducted initially to determine the aerodynamic and surface resistances of two different crops, a summer crop (lettuce) and a winter crop (wheat), their evolution throughout the daytime, and to study the factors that influence them so as to propose methodologies for their evaluation.

**THEORETICAL BACKGROUND**

It is useful to recall that in the derivation of the Penman-Monteith equation, the first and critical step is to reduce the three dimensional crop (that must be also homogeneous, level, continuous and extensive) to a one-dimensional “big leaf” where all the net radiation (Rn) is absorbed and from where water vapor and heat escape from the canopy (fig. 1). Since this “big leaf” is not saturated, it is also necessary to consider that there is another surface, at the same temperature, that is saturated and from where water vapor flux originates. So, while heat flux is commanded by a single resistance, the aerodynamic resistance to heat transfer (raH), vapor flux encounters two resistances in series, the surface resistance and the aerodynamic resistance to vapor transfer (raV). It is usually assumed that raH = raV = ra.

Aerodynamic resistances can be determined given values of roughness length (zo) and zero plane displacement height (zd). The Penman-Monteith equation is based on the assumption that the canopy can be reduced to a “big leaf”. Given the most commonly used formulation of aerodynamic resistance (ra), this “big leaf” is considered to be, implicitly, at the d + zoH level (where d is zero plane displacement height and zoH is roughness length for heat transfer). This can lead to negative values of surface resistance (rs) when the leaves of the top of the canopy (between d + zoH and crop height hc) are the ones that most contribute to total water loss to the atmosphere. To avoid this, rs should be computed from the top of the canopy to the reference height in the atmosphere. Also, one concludes that ra for complete cover crops cannot be computed by simply averaging stomatal resistance since the main condition, the driving force being the same in all of the elements of the “circuit”, is violated. **Keywords.** Crop evapotranspiration, Penman-Monteith, Lettuce, Wheat.
displacement height (d), that depend mainly on crop height, soil cover, leaf area and structure of the canopy (Massman, 1987; Perrier, 1982; Shaw and Pereira, 1982). If no specific data are available, they can be estimated following the results presented by Shaw and Pereira (1982) or Perrier (1982). To determine \( r_a \), an analogy is made with the resistance to momentum transfer and hence calculated with the expression:

\[
\frac{\ln \left( \frac{z - d}{z_0} \right)}{k u^*} = \frac{\ln \left( \frac{z - d}{z_0} \right) \ln \left( \frac{z - d}{z_0} \right)}{k^2 u_x}
\]

where \( d \) and \( z_H \) are, respectively, the zero plane displacement heights for momentum and heat (m), \( z_0 \) and \( z_{OH} \) are, respectively, the roughness lengths for momentum and heat (m), \( k \) is the von Karman constant (dimensionless), \( u^* \) is friction velocity (m/s), \( u_x \) is the wind velocity (m/s) measured at height \( z \) (m), and \( r_a \) has units of s/m. This equation implicitly places the “big leaf” at the \( d + z_0H \) level (fig. 1). \( z_{OH} \) is considered to be a fraction of \( z_0 \) in the range of 10 to 20% and accounts for the greater resistance that heat flux encounters relative to momentum, given the different driving forces involved (Verma and Barfield, 1978). Though this is the most used expression for \( r_a \), in fact it is not entirely correct, since it assumes a logarithmic profile from the source height (\( d + z_{OH} \)) up to the reference height \( z \) in the atmosphere. In reality, inside the canopy (and therefore between the levels \( d + z_{OH} \) and \( h_c \)) the wind decreases exponentially, following the general expression (Thom, 1975):

\[
u_x = u_h \exp \left[ -\eta \left( 1 - \frac{z}{h_c} \right) \right]
\]

with \( u_h \) being the wind velocity (m/s) at the top of the canopy (\( h_c \)) and \( \eta \) an extinction factor. It would be thus more accurate to use the approach derived by Shuttleworth and Wallace (1985), that has the form:

\[
r_a = \frac{\ln \left( \frac{z - d}{z_0} \right)}{k^2 u_x} \times \left( \ln \frac{z - d}{h_c} + \frac{h_c}{\eta (h_c - d)} \left( \exp \left[ \eta \left( 1 - \frac{d + z_0}{h_c} \right) \right] - 1 \right) \right)
\]

where fluxes still escape from the \( d + z_{OH} \) level, or the approach by Perrier (1975), where the “big leaf” is placed at the level \( h_c \) and so \( r_a \) is computed from the top of the canopy (\( h_c \)) to the height \( z \) as:

\[
r_a = \frac{\ln \left( \frac{z - d}{h_c - d} \right) \ln \left( \frac{z - d}{z_0} \right)}{k^2 u_x}
\]

This last approach would have the advantage of not requiring any assumptions about \( z_{OH} \) which, in fact, has no precise physical meaning.

The surface resistance term, \( r_s \), has been the most discussed in literature. There are several components to be considered (fig. 2) (Perrier, 1975):

- The resistances to water vapor at the evaporating surfaces: plants and their stomata (\( r_{sc} \)) and soil (\( r_{ss} \));
- The resistance to vapor transfer inside the canopy from these evaporating surfaces up to the “big leaf” (\( r_{sa} \)).

It is not then a purely physiological parameter, though it is commonly assumed that it represents mainly a stomatal response, thus reducing to \( r_s = r_{sc} \). Also, it is considered that the leaves act in parallel and, using the electrical analogue, a weighted stomatal resistance can be calculated (Monteith, 1973), either as:

\[
r_{sc} = \sum_{i=1}^{n} \frac{1}{r_{st,i}} - 1
\]

or

\[
r_{sc} = \sum_{i=1}^{m} \frac{1}{r_{st,i}} / \text{LAI}
\]

where \( r_{st} \) is the single leaf stomatal resistance (s/m), LAI is the leaf area index, \( n \) is the number of leaves, and \( m \) is the number of layers. Though the assumption \( r_s = r_{sc} \) seems to give good results in the case of very rough surfaces, like forests, and partial cover crops with a dry soil it is well established that the values of \( r_{sc} \) on complete cover crops are normally lower than the values of \( r_s \) obtained as a residual term of the Penman-Monteith equation (Baldocchi et al., 1991; Rochette et al., 1991). This results in over estimation of evapotranspiration (Paw U and Meyers, 1989), even if leaf boundary layer resistance \( r_b \) is added to stomatal resistance. This has been attributed as to the fact that not all leaves actually contribute to the total water loss by the canopy. The concept of “effective” leaf area (LAIeff) has therefore been introduced. This “effectiveness” is normally linked to the absorption of radiation since the upper, well illuminated leaves are those that most contribute to transpiration. A large fraction of the

\[
\text{Figure 2–Schematic representation of the components of surface resistance.}
\]
total radiation available to a canopy is absorbed by the top half of the canopy, which is the basis of the formulation adopted by Allen et al. (1994a):

\[ r_s = \frac{e}{0.5 \text{ LAI}} \quad (6) \]

where \( r_s \) is the resistance of a full illuminated leaf.

Soil resistance \( (r_s) \) can be modeled either as a function of the time after the last wetting (Grant, 1975) or as a function of soil moisture (Camillo and Gurney, 1985). More comprehensive approaches, like the one by Menenti (1984) or Choudhury and Monteith (1988), are based on assumptions similar to the Penman-Monteith equation but consider several soil physical properties which are not easily measured nor estimated.

The resistance to water vapor from the evaporating surfaces up to the “big leaf” \( (r_s) \) is not easily measured. When not just neglected, it can be evaluated using diffusion models that normally assume an exponential profile for the transfer coefficient inside the canopy (Thom, 1975), such as:

\[ K_z = K_{hc} \exp \left(-\frac{z}{h_c} \right) \quad (7) \]

where \( K_z \) is the transfer coefficient at height \( z \) \((z < h_c)\) and \( K_{hc} \) is the transfer coefficient at the top of the canopy, with \( \xi \) being an extinction coefficient, or the one developed by Perrier (1976) that considers a variable extinction factor, based on leaf area distribution. Aerodynamic resistance in the canopy will then be computed as:

\[ r^l_s = \int_0^{h_c} \frac{dz}{K_z} \quad (8) \]

A value for \( r_s \) can also be obtained by inversion of the Penman-Monteith equation (“top down” approach) using:

\[ r_s = r_a \left( \frac{\Delta}{\gamma} \beta - 1 \right) + \frac{\rho_a c_p VPD}{\gamma \lambda E} \quad (9) \]

where \( \beta = H/\lambda E \) is the Bowen ratio, \( \Delta \) is the slope of the curve of saturated vapor pressure versus temperature \((\text{Pa/}^\circ \text{C})\), \( \rho_a \) is air density \((\text{kg/m}^3)\), \( c_p \) is the specific heat of air \((\text{J kg}^{-1} \text{ }^\circ \text{C}^{-1})\), VPD is the vapor pressure deficit \((\text{Pa})\) at the reference height, and \( \gamma \) is the psychrometric constant \((\text{Pa}/^\circ \text{C})\).

**Materials and Methods**

**Site and Crop Characteristics**

Field trials were conducted at an Experimental Station belonging to INIA (National Institute for Agricultural Research) located at Coruche, Portugal \((\text{lat. } 38^\circ 57' \text{N, long. } 8^\circ 32' \text{W, alt. } 30 \text{ m})\), some 80 km northeast from Lisbon. The Station has a total area of 42.5 ha and is located inside an irrigated area of several hundred hectares.

**Instruments and Data Acquisition**

In both crops, the equipment consisted of:

- 5 anemometers, Young (models 12102 and 12102D), at different heights above the crop (from 0.55 to 1.63

The Station has a total area of 42.5 ha and is located inside an irrigated area of several hundred hectares.

During the summer of 1992, a trial was conducted with an iceberg lettuce crop \((\text{Lactuca sativa var. capitata cv. Saladin})\). Planting was made on 28 May with a density of 8 plants/m\(^2\) in lines 0.75 m apart on a 0.5 ha field \((50 \times 100 \text{ m})\) of a sandy soil \((\text{see characteristics in tables 1 and 2})\). Neighboring plots, totalling an approximate area of 8 ha, were cultivated with tomato and pepper. The crop was drip irrigated almost every day, mostly during the night or early morning, so maintaining the humidity in the root zone permanently near field capacity. Fertilization was made in order to optimize plant growth. Measurements were performed between day of year \((\text{DOY})\) 177 and 212 when the crop completely covered the soil and plant height varied from 0.15 to 0.20 m.

During the winter of 1992-1993, a 1 ha \((100 \times 100 \text{ m})\) plot was seeded with wheat \((\text{Triticum aestivum})\) on the 28 October and a population of 100 plants/m\(^2\) was obtained. The surrounding area was occupied by a mixed crop \((\text{Avena sativa } \times \text{ Vicia benghalensis})\) for hay. Soil is sandy loam, with an available water capacity of 240 mm/m \((\text{table 3})\). Measurements were made between DOY 339 \((1992)\) and 88 \((1993)\), covering establishment, tillering and stem elongation. Plant height was measured five times during the measurement period at 10 to 20 random locations. Plant height varied between 0.40 and 0.70 m and the LAI between 2.0 and 3.5; daily estimates were linearly interpolated between measurements.

### Table 1. Soil textural analysis, lettuce trial

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Coarse Sand</th>
<th>Fine Sand</th>
<th>Loam</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 30</td>
<td>65.4</td>
<td>25.3</td>
<td>5.2</td>
<td>4.1</td>
</tr>
<tr>
<td>30 - 50</td>
<td>67.9</td>
<td>22.8</td>
<td>5.6</td>
<td>3.7</td>
</tr>
<tr>
<td>50 - 80</td>
<td>74.7</td>
<td>16.1</td>
<td>6.4</td>
<td>2.8</td>
</tr>
</tbody>
</table>

### Table 2. Soil water characteristics, lettuce trial

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Field Capacity (% V/V)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10</td>
<td>16.5</td>
</tr>
<tr>
<td>10 - 20</td>
<td>18.7</td>
</tr>
<tr>
<td>20 - 30</td>
<td>17.2</td>
</tr>
<tr>
<td>30 - 40</td>
<td>13.9</td>
</tr>
<tr>
<td>40 - 50</td>
<td>11.9</td>
</tr>
</tbody>
</table>

* Measured in situ.

### Table 3. Soil characteristics, wheat trial

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Soil Humidity (% V/V)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 20</td>
<td>33.3</td>
</tr>
<tr>
<td>20 - 40</td>
<td>32.5</td>
</tr>
<tr>
<td>40 - 60</td>
<td>31.3</td>
</tr>
<tr>
<td>60 - 80</td>
<td>31.3</td>
</tr>
<tr>
<td>80 - 100</td>
<td>30.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Textural Analysis (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Sand</td>
<td>52.3</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>52.8</td>
</tr>
<tr>
<td>Loam</td>
<td>65.3</td>
</tr>
</tbody>
</table>

* Laboratory measurements.
m in the lettuce crop and 0.77 to 2.49 m in the wheat).

- 1 wind direction sensor, Vector Instruments, model W200P, at the height of the highest anemometer.
- 2 psychrometers, made from ventilated double-shielded copper-constantan thermocouples (mounted on fixed arms at the heights of 0.85 and 1.46 m in the lettuce crop, 0.77 and 1.67 m in the wheat).
- 1 net radiometer, Schenk, at 1.5 m height over a plant row and south oriented.

The net radiometer was calibrated against a new instrument, and a linear relationship was found ($r^2 = 0.9988$). The thermocouples used in the psychrometers were calibrated in the laboratory, giving an output of 39 µV/°C. Later, the psychrometers themselves were compared by placing them at the same height. Differences between the two were within ±0.02°C. The anemometers were compared the same way, the differences between them being not greater than 1%.

The instruments were installed on a measurement tower that was placed near the edge of the plot, in order to benefit from at least 80 m of fetch in both crops. The instruments were connected to a Campbell Scientific 21X datalogger that scanned the sensors every second and stored the average values at 10-min intervals.

**DATA HANDLING**

Only the values recorded during the periods when the fetch was adequate were kept. Atmospheric stability was evaluated through the Richardson number in its finite difference form:

$$\text{Ri} = \frac{g \Delta t}{\Delta z} \left(\frac{\Delta u}{\Delta T}\right)^2$$

where $g$ is acceleration of gravity (9.8 m/s²), $\Delta t$ and $\Delta u$ are, respectively, the temperature (°C) and wind velocity (m/s) differences between levels $z_1$ and $z_2$ ($\Delta z$), in meters, and $\Delta T$ is the average absolute temperature (K). Wind profiles obtained in neutral conditions (|Ri| < 0.1) and with adequate fetch were used to calculate the values of $d$ (zero level displacement height) and $z_o$ (roughness length), using linear regression techniques. Further details and results are given in Alves (1995). Values used in subsequent calculations were:

- for the lettuce crop: $d/h_c = 0.67 z_o/h_c = 0.126$
- for the wheat crop: $d/h_c = 0.67 z_o/h_c = 0.08$

The aerodynamic resistance was calculated according to equation 1, with $z_{o\text{H}} = 0.2 z_o$, as proposed by Campbell (1977) and Thom (1972).

When calculating $r_s$ by inversion of the Penman-Monteith equation using equation 9, only values obtained for |Ri| < 1 were retained. By using a set of data with all the information necessary it was verified that, in these conditions, ignoring the stability corrections in $r_a$ conducted to errors that were less than 10% in this parameter, which finally led to errors that were less than 5% in $r_s$. $\lambda E$ was calculated by the Bowen ratio ($\beta$) method. Only the values of $|\beta| < 0.3$ were used, as this is the range to be found in well watered crops, transpiring at the maximum rate (Angus and Watts, 1984). Soil heat flux was estimated to be 10% of the measured net radiation, following the studies by Clothier et al. (1986) on closed canopies. All necessary parameters were calculated with the algorithms proposed by Allen et al. (1994b).

**FETCH REQUIREMENTS**

According to Elliot (1958), the depth ($\delta$) of the equilibrium boundary layer above a given surface is given by:

$$\delta = L^{4/5} z_o^{1/5}$$

where L is the distance of traverse (fetch) across a uniformly surface of roughness $z_o$. Considering that only the lowest 15% of this layer is fully adjusted (Monteith and Unsworth, 1990), measurements should then be made up to $\delta' = 0.15 L^{4/5} z_o^{1/5}$. We then will have:

<table>
<thead>
<tr>
<th>Crop</th>
<th>$h_c$ (m)</th>
<th>$z_o$ (m)</th>
<th>L (m)</th>
<th>$\delta'$ (m)</th>
<th>Ratio height:fetch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lettuce</td>
<td>0.20</td>
<td>0.0252</td>
<td>80</td>
<td>2.39</td>
<td>1:33</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.70</td>
<td>0.056</td>
<td>80</td>
<td>2.81</td>
<td>1:29</td>
</tr>
</tbody>
</table>

This approach, validated by Munro and Oke (1975), shows that the generally accepted figure of 1:100 as the adequate height:fetch ratio for micrometeorological measurements is too conservative. Heilman et al. (1989) have also concluded that a ratio as low as 1:20 can be enough when $\beta$ is small. We can therefore assume that the measurements were made inside the constant flux layer, thus being representative of the surface below. Further supporting the validity of the data is the fact that, using the summed daily values of $\lambda E$ and the reference evapotranspiration calculated with the new FAO-Penman-Monteith equation (Allen et al., 1994b), computed crop coefficients were 0.93 for lettuce and 1.04 for wheat, which compare favorably to values reported in the literature (Doorenbos and Pruitt, 1977).

**RESULTS AND DISCUSSION**

Figure 3 presents the results obtained using equation 9 with $r_a$ computed using equation 1 and $z_{o\text{H}} = 0.2 z_o$, showing the evolution of $r_s$ throughout the daytime. The general shape follows what has been described in the literature and reflects the daily course of the environmental variables that influence $r_s$. However, negative values have been obtained, on the contrary of what has been reported in literature.

Since $r_s$ is a resistance, and if it were a purely physiological parameter ($r_s = r_s^\infty$), no negative values should be possible. However, negative values do have a physical meaning, indicating that the virtual evaporating surface is above the presumed level of the “big leaf” ($d + z_{o\text{H}}$) when adopting eq. 1). This can happen if the leaves that most contribute to evaporation are the ones at the top of the canopy, between heights $d + z_{o\text{H}}$ and $h_c$.

While observing the crops and collecting data it was observed that the soil surface was generally wet due to irrigation or rain, and that there was liquid water (from dew) in the basal leaves up to 1200 h in lettuce and even

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after 1400 h in the wheat crop. Observing figure 3, it can be seen that the negative values of \( r_s \) occur during this same period. How could the presence of water inside the canopy increase the height of the evaporating surface, putting it above the “big leaf”?

Remembering the electrical analogue of Ohm that a flux is always the result of a gradient and a resistance, and considering that the water transpired by a canopy is the sum of the water transpired by all its leaves, the following relationship can be written:

\[
\lambda E = \frac{\rho_a c_p}{\gamma} \sum_{i=1}^{n} \frac{e_{ai} - e_{si}}{r_{si} + r_{bi}}
\]

(12)

where \( n \) is the number of leaves, \( e_a \) is the vapor pressure of the air inside the canopy at the same level of the leaf, \( e_s \) is the vapor pressure at the evaporating surface, \( r_{si} \) is the mean stomatal resistance of the leaf, and \( r_b \) is the leaf boundary layer resistance. The leaf being the evaporative surface, it can be assumed that the leaf is saturated (inside the stomatal cavities) and therefore \( e_s = e_s^* \). Soil surface can be considered as an extra leaf so as to consider total evapotranspiration. For ease of formulation the resistances to the transport of vapor inside the canopy have not been considered in equation 12. A more complete formulation is given by Lhomme and Katerji (1985).

One simple conclusion that can be derived by examining equation 12 is that there will be no water loss by a leaf, whatever its \( r_{si} \), if no gradient of vapor exists between the leaf and the air. The presence of liquid water in the lower canopy indicates that the surrounding air is saturated (thus VPD = 0) and hinders vapor fluxes from leaf to air at this level. Consequently, only the upper leaves in contact with the outer, non saturated, atmosphere, are effective in transpiration under these conditions. Measurements by other authors show that air inside a complete canopy is, especially if the soil surface is wet, indeed more humid, if not saturated, than the air at the reference height (Bisoe et al., 1975; Norman, 1982). This has the practical consequence of, using the nomenclature first used by Jarvis and McNaughton (1986), decoupling the canopy from the airstream above it. The other extreme, the air inside the canopy having almost the same characteristics of the air at the reference height, is found in partial cover crops with rugous surfaces where mixing is important.

It is then possible to solve the apparent conflict that has for long been reported in the literature between the “bottom up” and the “top down” approach to the determination of \( r_s \). The conflict, however, is only apparent and lies in the averaging process. A summing like the one in equation 5 can only be made if the potential difference in each element of the circuit is the same (fig. 4a). As the driving force for vapor flux is vapor pressure deficit and given the previous discussion, equation 5 can be applied to an open canopy but obviously not to a full cover crop, where there is a non constant profile of humidity (fig. 4b). In this case, a value for \( r_s \) can only be obtained by inversion of the Penman-Monteith equation. Stomatal resistances could still be used but to calculate \( AE \) as in equation 12 or following the approach by Lhomme and Katerji (1985) but not to compute \( r_s \), that must always be obtained by back calculation. Also, the concept of “effective” leaf area is still valid but should be redefined, linking it to vapor pressure deficit and not to radiation. The apparent dependence on radiation arises because the top half of the canopy, where most radiation is absorbed, is also the layer that is in contact with the outer, unsaturated air. In fact, as there is a dependence between stomatal resistance and radiation (\( r_{st} = f(R) \), where \( f \) is an hyperbolic function) (Jarvis, 1976) the

\[
\lambda E = \frac{\rho_a c_p}{\gamma} \sum_{i=1}^{n} \frac{e_{ai} - e_{si}}{r_{si} + r_{bi}}
\]

(12)
effect of radiation should be reflected in the stomatal resistance itself.

Finally, as the evaporating surface clearly changes its position inside the canopy throughout the day (as the humid air gradually is transferred to the atmosphere, there is an increasing contribution from progressively lower leaves to total water loss, thus gradually lowering the apparent mean source height), and to avoid negative values of \( r_s \) when the top leaves are the most active in the transpiration process, the aerodynamic resistance can advantageously be calculated between the top of the canopy and the reference height, as in equation 3. In this way, it also becomes easier to understand that the computed surface resistance \( r_s \) includes not only all leaf (stomatal and boundary layer) resistances weighted by the respective fluxes and leaf area indices, but also the aerodynamic resistance to the flux inside the canopy, though not in a simple additive way (as schematically represented in fig. 4b). This is in agreement with Raupach and Finnigan (1988) in that \( r_s \) is not a purely physiological parameter and so cannot be defined in terms of individual leaf stomatal resistances alone.

Figure 5 presents the results obtained when \( r_a \) is calculated using equation 3. It shows that this approach leads to positive values for \( r_s \). The few small negative values that still occur simply reflect the accumulated errors in all the other variables (specially \( G \)) and do not invalidate this proposal.

**CONCLUSIONS**

The results obtained and their related theoretical discussion allow one to conclude that the surface resistance \( r_s \) of dense crops cannot be obtained by simply averaging stomatal resistances because the driving force (vapor pressure deficit) is not kept constant within the canopy. It is also proposed to regard the vapor flux as leaving the canopy at its top, that is, to place the “big leaf” at the level \( h_c \) and not \( d + z_{oH} \). In this way: (1) the calculation of \( r_a \) does not require any artificial assumption about \( z_{oH} \); (2) the estimation of \( r_a \) becomes more accurate since the logarithmic wind profile is valid only above the canopy; and (3) it becomes easier to understand that \( r_s \) has not only a physiological component (evaporation through the stomata) but also an aerodynamic term, corresponding to the vapor transfer from the evaporating surfaces up to the surface level.

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Camillo, P. J., and R. J. Gurney. 1985. A resistance parameter for transpiration process, the aerodynamic resistance can advantageously be calculated between the top of the canopy and the reference height, as in equation 3. In this way, it also becomes easier to understand that the computed surface resistance \( r_s \) includes not only all leaf (stomatal and boundary layer) resistances weighted by the respective fluxes and leaf area indices, but also the aerodynamic resistance to the flux inside the canopy, though not in a simple additive way (as schematically represented in fig. 4b). This is in agreement with Raupach and Finnigan (1988) in that \( r_s \) is not a purely physiological parameter and so cannot be defined in terms of individual leaf stomatal resistances alone.

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