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DIFFICULTIES WITH MICROMETEOROLOGICAL METHODS TO ESTIMATE EVAPOTRANSPIRATION IN A SMALL CITRUS ORCHARD[1]

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ABSTRACT

The suitability of the Bowen ratio (BR) and aerodynamic (AE) methods to estimate evapotranspiration (ET) of a small citrus orchard was tested. Net radiation was measured over a tree crown, and soil heat flux by three sensors. Dry and wet bulb temperature, and wind speed (u) were measured at four levels above the ground. The topmost level was taken as representative of the above canopy atmospheric conditions resulting in three combinations of vertical differences (Δz) to compute the gradients; the corresponding ET estimates were compared to check their consistency. The BR gave consistent LE during the dry period; but, during the wet period, the relationships deviated from the 1:1 line. The AE gave unreliable ET estimates as Δz decreased, because small $\Delta u/\Delta z$ resulted in erroneous gradient Richardson number (Ri), giving exaggerated correction factors under unstable conditions. Logarithmic wind speed profile seldom occurred above the orchard, but the error introduced by the use of an empirical zero-plane displacement height was far less than that resulted from an erroneous Ri. Based on the FAO reference evapotranspiration, the AE estimates were taken as the most likely to correspond to the unknown orchard ET.

Key words: Bowen ratio, aerodynamic approach, Richardson number, zero-plane displacement

RESUMO: DIFICULDADES COM MÉTODOS MICROMETEOROLÓGICOS PARA ESTIMAR A EVAPOTRANSPIRAÇÃO NUM PEQUENO POMAR DE CITROS

Testou-se a adequação da Razão de Bowen (RB) e do método aerodinâmico (AE) para estimar a evapotranspiração (ET) de um pomar de citros. Mediu-se o saldo de radiação sobre uma copa, e o fluxo de calor no solo. Temperaturas de bulbo seco e molhado, e a velocidade do vento (u) foram medidas em quatro níveis acima do solo. O nível mais alto foi adotado como representativo das condições atmosféricas acima do pomar, resultando em três combinações de diferenças (Δz) para computar os gradientes; as estimativas de ET foram comparadas entre si para verificar suas consistências. A RB deu estimativas mais consistentes durante o período seco; mas, durante o período úmido as relações desviaram da linha de 1:1. As comparações do AE mostraram estimativas não confiáveis de ET à medida que Δz diminuiu, resultando em $\Delta u/\Delta z$ pequeno, com Número de Richardson (Ri) e fator de correção exagerado, sob condições de instabilidade. Raramente ocorreu um perfil logarítmico, mas o erro introduzido pelo uso de um valor empírico do deslocamento do plano zero foi muito menor do que aquele resultante de erro em Ri. Baseado na evapotranspiração de referência da FAO, as estimativas do AE têm mais chances de corresponder ao valor desconhecido da ET do pomar.

Palavras-chave: Razão de Bowen, Método aerodinâmico, Número de Richardson, deslocamento do plano zero.

1. INTRODUCTION

Orchard is an artificial arrangement of plants cultivated in a way that does not cover completely the ground surface and the inter-plant spacing is commonly about the height of the plants. The discontinuous spacial distribution of trees in orchards increases the roughness of the surface and interacts more strongly with the atmosphere, enhancing the energy and momentum exchanges. Such spatial arrangement of natural obstacles modifies the surface boundary conditions and in small orchards it poses practical difficulties with the use of micrometeorological methods to estimate turbulent fluxes due to lack of appropriate fetch area. The vertical profile of wind speed, air temperature, and specific humidity is also modified around each tree.

Many micrometerological experiments have been carried out in orchards, but few with citrus (Kalma & Stanhill, 1972; Kalma & Fuchs, 1976; Daamen et al., 1999), and very few with the objective of determining the evapotranspiration (van Bavel et al., 1967; Kalma & Stanhill, 1969; Daamen et al., 1999). For a sheltered lemon orchard (42m x 124m), Daamen et al. (1999) found that the Bowen ratio (BR) method gave inconsistent estimates when compared with the eddy correlation measurements above the orchard near the height of the shelters. Similar results were reported by Braun et al. (2000) for an apple orchard. Lopes et al. (2001) found up to 30% of relative error for the estimates given by the BR in a small mango orchard.

The flux-gradient theory is based on the assumption that within the surface boundary layer, at a given time, the turbulent flux is constant and independent of the vertical distance (Δz) used to compute the gradients. To check the validity of such assumption for an heterogenous ground cover, one experiment was setup to compute the fluxes with three different combinations of Δz. Consequently, the objective of this work is to verify the adequacy ot two micrometeorological methods, i.e., BR and aerodynamic (AE) approaches, to estimate the latent heat flux from a small irregular citrus orchard near a 15m tall Pinus windbreak. It seems that the AE method have not been tested over orchards since no published report was found.

2. MATERIAL AND METHODS

The experiment was performed at Piracicaba, SP, Brazil (22° 42´S; 47° 30´W; 546m amsl) during two periods. One, from 15/01 to 18/02/2000 (rainy season, summer), with 27 days of complete data; and another from 23/06 to 15/07/2000 (dry period, winter), when 32 days were selected. The dry period was preceded by 110 days without rain and the orchard was irrigated with micro-sprinklers to wet the area under the crowns. A small 8 years old "Tahiti" (*Citrus latifolia* Tanaka) acid lime orchard (≈ 0.6 ha, 140 trees in a 8m x 7m spacing, and average tree height of 4.5m).

Meteorological sensors were mounted in a 10m mast located at the center of the orchard in a row between two trees and about 60m from a single line 15m tall Pinus windbreak parallel to the west border. The sensors were monitored by a CR7 datalogger every 10s to give 15 min averages for each sensor throughout the daylight hours. Dry and wet bulb ventilated psychrometers (copper-constantan thermocouple, Marin et al., 2001) were placed at 2.5m, 3.5m, 4.5m and 6.5m above the ground. Wind speed was measured with Met-One anemometers (model OA14; 0.45 m s^{-1} starting speed) at the same heights, with an extra sensor at 8.5m above the ground to determine the zero-plane displacement height. Only one net radiometer (REBS Q7) was available at this site and it was located over a tree crown at 7m above the ground because the orchard was irrigated and the tree was the major source of latent heat. To minimize problems with soil heat storage three sensors (REBS HTF3.1) were placed at 0.03m depth to measure the soil heat fluxes, being one below a tree crown and the others halfway between two trees to obtain a spatial average flux with only three sensors.

Bowen ratio (β) was estimated as a function of the differences in wet (ΔTu) and dry (ΔTs) bulb temperatures between two heights (Fuchs & Tanner, 1970), and a temperature dependent weighting factor (W), or

$$\beta = [\frac{\Delta Tu}{(1-W)\ \Delta Ts} - 1]^{-1}, \qquad (1)$$

being W computed by the following equations (Wilson & Rouse, 1972; Viswanadham et al., 1991; Pereira et al., 1997)

$$W = 0.407 + 0.0145\ Tu, \qquad 0 < \mathrm{Tu} \leq 16°\mathrm{C} \qquad (2)$$

$$W = 0.483 + 0.01\ Tu, \qquad 16 < \mathrm{Tu} \leq 32°\mathrm{C} \qquad (3)$$

By the Bowen ratio method the latent heat flux (λE, W m^{-2}) is given by

$$\lambda E = \frac{Rn - G}{(1+\beta)} \qquad (\beta \neq -1) \qquad (4)$$

being Rn the net radiation (W m^{-2}), and G the soil heat flux (W m^{-2}). When $\beta < -0.75$ this method gives unrealistic estimates (Tanner, 1960), and $\lambda E = Rn - G$ was used at that time as suggested by Perez et al. (1999). Values of β close to –1 occur near sunrise and sunset when vertical gradients of air temperature and vapour pressure are very small and difficult to measure with the instruments used.

With the aerodynamic method, λE (W m^{-2}) is given by the following equation (Thom, 1975)

$$\lambda E = -\rho\ \lambda\ k^2\ \frac{0,622}{P}(\bar{z}-d)^2\ \frac{\Delta u\ \Delta e}{\Delta z^2}\ fe \qquad (5)$$

being ρ the air density (= 1.26 kg m^{-3}); λ is the latent heat of the water (= 2.45 MJ kg^{-1}); k is the von Karman constant (= 0.4); P is the local atmospheric pressure (kPa); $\overline{z}$ is the average between two measurement heights (Δz, m); d is the zero plane displacement height (m); Δu is the wind speed difference between two heights (m s^{-1}); De is the difference in water vapor pressure at the same two heights (kPa); and *fe* is an empirical generalized correction function that takes into account the atmospheric stability described as (Thom, 1975; Monteith & Unsworth, 1990):

- $fe = (1 - 16\,Ri)^{0.75}$ $\quad Ri < -0.01$ $\quad$ (unstable) $\quad$ (6)
- $fe = (1 + 16\,Ri)^{-2}$ $\quad Ri > 0.01$ $\quad$ (stable) $\quad$ (7)
- $fe = 1$ $\quad -0.01 \le Ri \le 0.01$ $\quad$ (neutral) $\quad$ (8)

and

$$Ri = g\left(\frac{\Delta\Theta}{\Delta z}\right) \Big/ \Theta\left(\frac{\Delta u}{\Delta z}\right)^2 \qquad (9)$$

being Ri the gradient Richardson number; g the gravitational acceleration (= 9.8 m s^{-2}); $\Delta\theta$ the vertical difference in potential temperature (K); and θ the average potential temperature in the corresponding Δz.

For both methods, 15min averages were computed and added to give daily (period of Rn > 0) totals. Rainfall days were discarded from the analysis due to technical difficulties with the sensors.

3. RESULTS AND DISCUSSION

Measurements at 6.5m above the ground were considered to be representative of the air immediately above the orchard, and the lower heights were assumed to represent the air within the orchard. Consequently, three combinations of Δz for the vertical gradients were possible, i.e., 2.5-6.5m, 3.5-6.5m, and 4.5-6.5m. Theoretically, the temperature and the vapour pressure gradients are easier to measure with the largest Δz, and the evapotranspiration (ET) computed with the 2.5-6.5m combination (the largest Δz) was used as a reference for comparisons.

For the Bowen ratio (BR) method, during the dry period, after 110 days without rain, when the irrigated trees were the only source of water vapor to the atmosphere, all combinations of Δz resulted in equivalent ET estimates with most of the points falling around the 1:1 line (Figure 1). In that environmental condition, when the soil around each tree was wetted only by irrigation and the surrounding region was dry, there was a coupling between the orchard ET and the governing atmospheric conditions within and above the canopy, as suggested by McNaughton & Jarvis (1983). In general, ET was less than 4 mm d^{-1}.

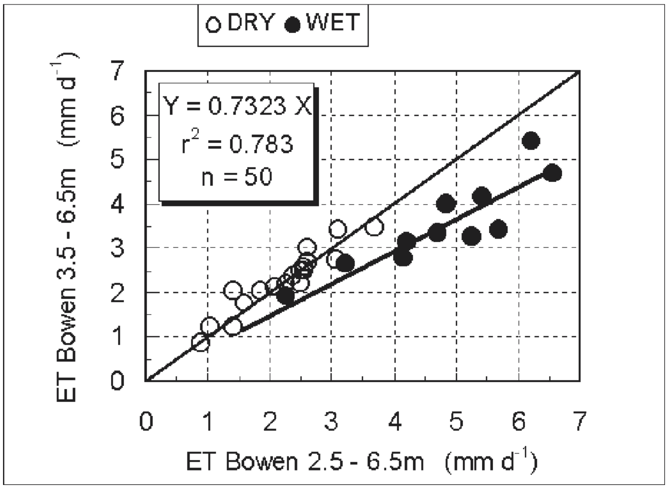

Figure 1a.

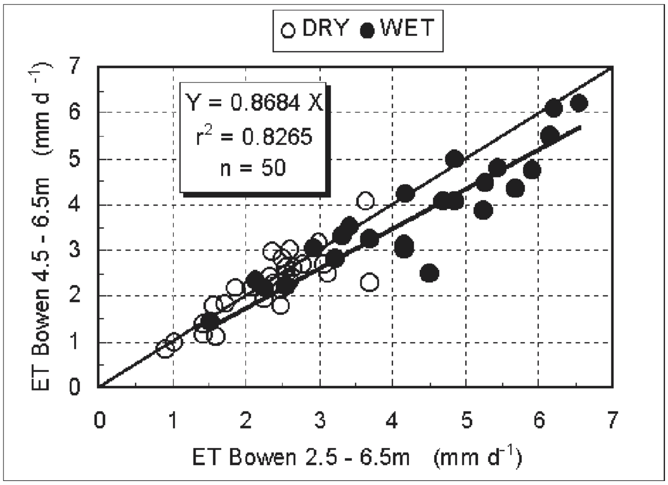

Figure 1b.

When the region was wetted by frequent rains (235 mm in 11 events during 37 days) and ET was larger than 4 mm d^{-1}, there was a tendency for the regression points to deviate from the perfect fit line (1:1). On average, ET with the 3.5-6.5m combination underestimated by 27% the ET given by the 2.5-6.5m (Figure 1a), while the 4.5-6.5m combinaton underestimated it by 13% (Figure 1b). The largest ET estimates were given by the 2.5-6.5m followed by the 4.5-6.5m, and then by the 3.5-6.5m. The wet ground surface and the vegetation between rows contributed also with the orchard ET, and the coupling between the within and the above canopy atmospheric conditions were less intense than during the dry period.

One important aspect of the BR method is the effect of Rn - G upon ET. Even though it is obvious that Rn should be representative of the underlying surface this is a difficult task to achieve with a single static net radiometer. During the hours of high solar elevation Rn was primarily determined by radiation balance of only one tree crown, minimizing the contribution of the smaller inter-row vegetation. Alternatives to such setup can be either the use of more than one sensor to increase the spatial description of the measurements, or the positioning a single sensor at a much higher height to increase the sampled area under its view angle. Such difficulty was detected only after the analysis of the data but it should be mentioned to help in future experiments in orchards.

The soil heat flux (G) measurement indicates that the daytime values represented less than 10% of Rn during the wet season, and less than 15% of Rn during the dry period. The smaller fraction during the wet season was determined by the presence of green grass covering the inter-row space. During the dry period the soil surface was exposed directly to the sun rays increasing G. The heat flux through the sensor located under the tree crown was always less than 10 W m^{-2} and it could be discarded without significant loss of accuracy in the final estimates of ET.

In regard to the aerodynamic (AE) approach, the results obtained with eq.(5) to (9) were not encouraging but they provided experimental evidence for understanding the difficulties with its use in orchard conditions. Taking the same kind of comparisons discussed above, Figure 2 shows that the regression points deviated substantially from the perfect fit line (1:1). Regardless of the regional moisture conditions, the 3.5-6.5m estimates were, on average, 81% higher than those obtained with the 2.5-6.5m (Figure 2a). The 4.5-6.5m combination resulted in worse ET estimates with values that are not supported by the available energy, being the estimates about 4.18 times larger than the 2.5-6.5m (Figure 2b). Such exaggerated ET estimates (> 25 mm d^{-1}) cannot be attributed to advection either since the region was wetted by frequent rains. This fact was also detected by Cellier & Brunet (1987) as reported by Pieri & Fuchs (1990). The most consistent ET estimates with this approach were those obtained with 2.5-6.5m combination. These results show the sensibility of the AE method when applied to very rough heterogeneous small orchard.

Searching for the cause of such large discrepancies in ET estimates with the AE method, the mean values and standard deviation for $\Delta u/\Delta z$ and for $\Delta e_a/\Delta z$ for each Δz combination were compared. Apparently, the variations shown in Table 1 were not enough to explain the inconsistent ET values found for the different combinations of measurement heights, mainly with the 4.5-6.5m. The product of the mean values of $\Delta u/\Delta z$ and $\Delta e_a/\Delta z$ used in eq.(5) is almost constant for the three Δz combinations. It should be noted that the standard deviations were as large as the means indicating large variability in the gradients, but the large discrepancies in ET estimates cannot be accounted for by such product. Also, the same vapour pressure gradients were indirectly used in the BR method and resulted in fairly consistent ET estimates. Therefore, the source of such large errors in the AE approach resides either in the determination of $(\overline{z} - d)^2$, due to the difficulties in finding an appropriate value for the zero-plane displacement height (d) for such heterogeneous vegetation, or in the correction factor *fe*.

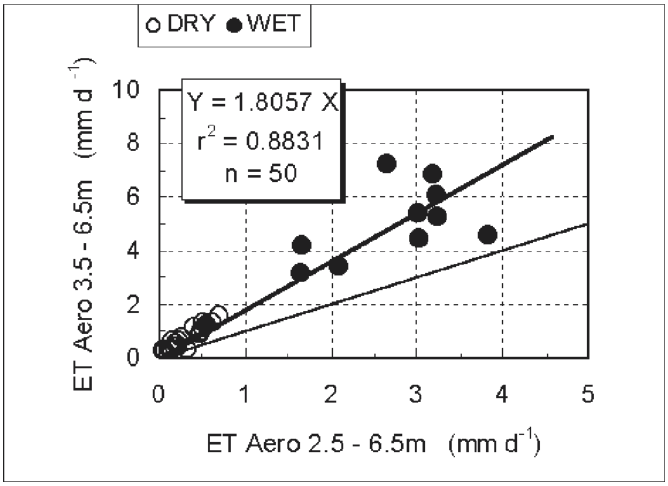

Figure 2a.

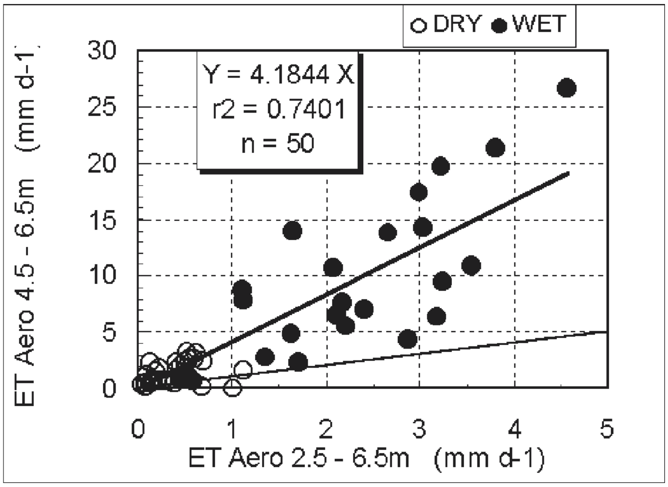

Figure 2b.

The effect of $(\overline{z} - d)^2$ in eq.(5) becomes evident with numerical values. Setting d = 2.5m (mean value during the wet period) results in $(\overline{z} - d)^2 = 4$ for the 2.5-6.5m combination (being $\overline{z} = 4.5$m) but in $(\overline{z} - d)^2 = 9$ for the 4.5-6.5m (being $\overline{z} = 5.5$m), without the equivalent reduction in the product $\Delta u/\Delta z\ \Delta e/\Delta z$ in order to keep the same numerical result. The

Table 1 – Mean and standard deviation of the gradient of wind speed ($\Delta u/\Delta z$) and water vapour pressure ($\Delta e/\Delta z$), during daytime, for three measurements height combinations, in a small acid lime citrus orchard.

	$\Delta u/\Delta z$		$\Delta e/\Delta z$	
Heights, m (Z_1 e Z_2)	Mean (s^{-1})	Std. Deviation (s^{-1})	Mean (kPa m^{-1})	Std. Deviation (kPa m^{-1})
2.5 & 6.5	0.191	0.133	-0.015	0.016
3.5 & 6.5	0.181	0.137	-0.017	0.020
4.5 & 6.5	0.124	0.121	-0.023	0.024

appropriate value for d depends on a logarithmic wind speed profile above the canopy, a condition that seldom occurred, limiting the determination of d to a very few times. Several factors contributed to this anomaly but the small size of the rough orchard associated with the presence of a 15m tall Pinus trees windbreak about 60m in the west side of the measuring mast had an impact upon the wind profile. Even with the reduced wind speed coming from that direction the 60m fetch was not enough to allow the development of a boundary layer characteristic of the orchard. Wind blowing from the S and SE directions (the most frequent) had a much larger fetch including about 50m with citrus trees plus an extra 50m covered with a 4m tall mango orchard; but even during such events the wind profile was not logarithmic immediately above the orchard. In fact, Garratt (1978) have found that the log-profile is likely to occur only above a minimum height equivalent to 4.5 times the average height of the trees for a natural sparse tall vegetation, and in the lemon orchard this would amount to over 20m.

This brings another point of difficulty since the topmost anemometer positioned above the canopy was at 1.89 times the average citrus tree height. This was theoretically necessary to make sure that the temperature and vapour pressure gradients were taken inside the orchard surface boundary layer, but it restricted the use of only four sensors above the trees to determine d. The thickness (t) of the internal boundary layer at the site of the measurements were computed using the Munro & Oke (1975) equation ($t = X^{0.8}\ Zo^{0.2}$), that resulted in t = 19.5m with Zo = 0.22m (roughness length), in the least appropriate condition, when X = 60m, and t = 30m with the wind coming from the south (X = 100m). Assuming that the lowest 10% of the boundary layer was in equilibrium with the orchard surface (Brutsaert, 1982), the 4.5m sensors were located close to the transition between the equilibrium and the internal boundary layer (= 0.1 t + d).

The vertical distance (Δz) between the sensors was 1m for the lowest three sensors and 2m between the top two, and it was similar to that used by Braun et al. (2000) in an 2.5m tall apple orchard with measurements up to 6m. The ideal distance should double upwards between adjacent sensors, but the small fetch did not permit such arrangements in this small rough orchard.

With the few moments when the wind profile was logarithmic during the measurement period the following average values were found for d and Zo, respectively: a) 2.5m and 0.22m during the wet season; b) 3.1m and 0.01m during the dry season. Due to the above described difficulties such values were then taken as representative of the entire season, and this is a source of uncertainty, but not enough to result in gross ET estimates as those here reported. Taking the average tree height (h = 4.5m) as reference resulted in $0.56 \leq d/h \leq 0.69$ and $0.002 \leq Zo/h \leq 0.05$, values similar to those derived theoretically by Cowan (1968) and determined experimentally in several positions of a citrus orchard by Kalma & Stanhill (1972) and Kalma & Fuchs (1976).

The last possible source of error in the AE method is the atmospheric stability correction factor *fe* computed as a function of the gradient Richardson number (Ri). The main problem in determining Ri is the term $(\Delta u/\Delta z)^2$ in situations where Δz is small and the wind speed is not very large, resulting in exaggerated Ri and *fe* values under unstable atmospheric conditions. In order to check the effect of *fe* on the daily ET estimates it was set equal to 1, regardless of the atmospheric condition, and the same comparisons described above were performed between the ET estimates with the different Δz combinations (Figure 3). Neglecting *fe* reduced substantially the ET estimates (< 6 mm d^{-1}), and resulted in a better relationship between the 3.5-6.5m the 2.5-6.5m ET (Figure 3a). During the wet period the 3.5-6.5m ET was, on average, 16% larger than the corresponding 2.5-6.5m ET, with three days (out of 10 days) of almost identical values. However, during the dry period the relationship did not change very much from that including *fe*, with an average overprediction of 71%. Pooling all the data from both periods resulted in an overall overestimation of about 22%, but such relationship did not fit well the dry period data.

The effect of *fe* was most felt in the 4.5-6.5m combination. Neglecting its effect reduced the ET estimates from a previous maximum of over 27 mm d^{-1} to about 5 mm d^{-1} (Figure 3b). Such huge reduction in the ET estimates indicates that *fe* was grossly overestimated and an inspection of the raw data indicated that it was caused by the small $\Delta u/\Delta z$ frequently observed with that Δz combination. Consequently, Ri was in error most of the time resulting in large *fe* and ET estimates. The spread of the points resulted in unreliable statistical relations indicating that the 4.5-6.5m combination should not be considered as an alternative to estimate the orchard ET.

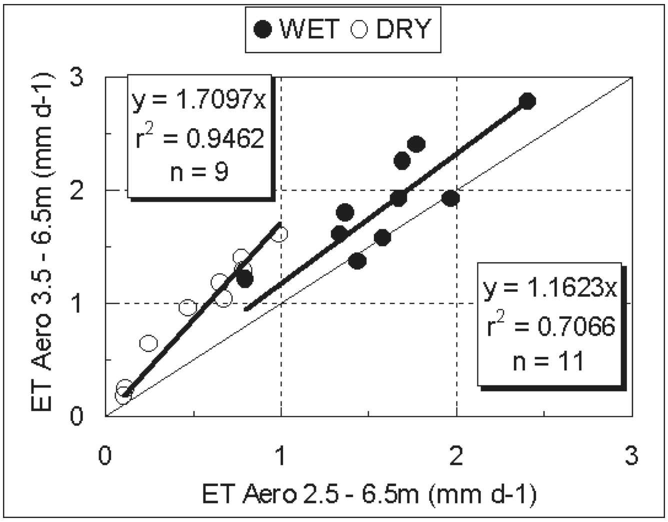

Figure 3a.

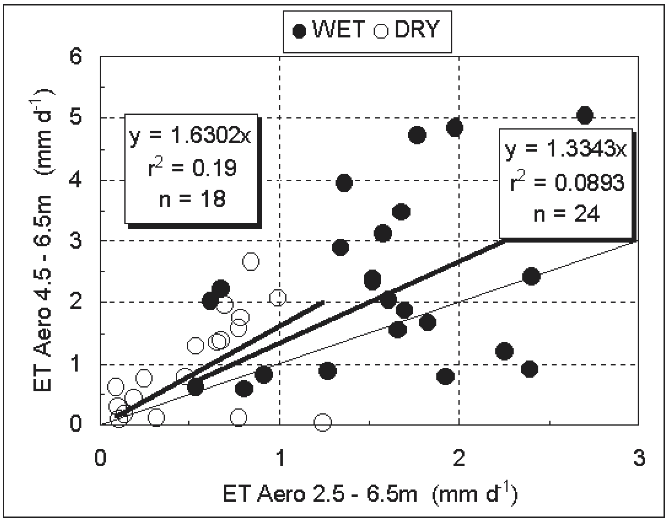

Figure 3b.

Comparing the 2.5-6.5m ET estimates with and without the atmospheric stability correction factor it became evident that *fe* had little effect on the daily ET estimates during the dry period (ET < 1 mm d^{-1}), a condition very close to the neutral atmospheric stability (Figure 4). During the wet period (summer), *fe* had a substantial effect on ET estimates and it cannot be ignored. On average, its effect represented about 36% of the daily ET. The atmospheric instability enhanced significantly the water vapor transport.

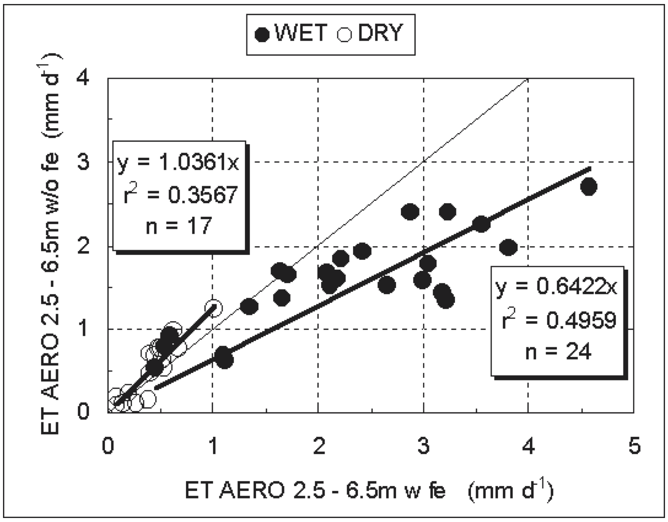

Figure 4.

Finally, comparing the ET from the BR method with that given by the AE approach, both with the 2.5-6.5m combination (taken as reference for all comparisons), the agreement between them was very poor with large deviation from the perfect fit line (Figure 5). The AE estimates represented only about 35% of that given by the BR during the wet period, and only 23% during the dry period, both with large spread of the points. Considering the periods together resulted in an overall relationship around 33%.

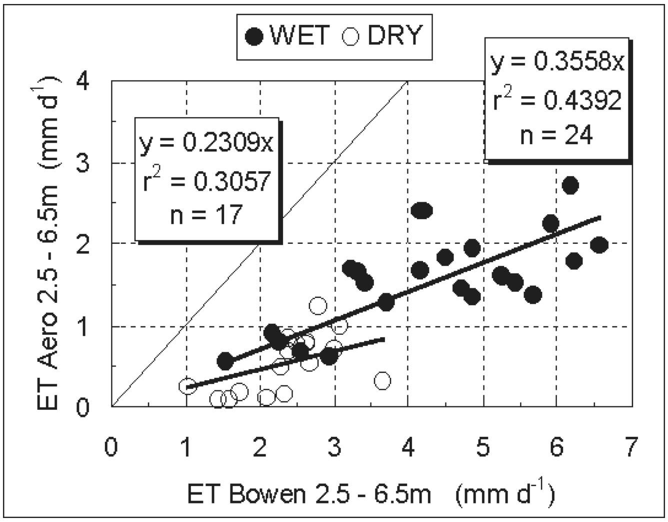

Figure 5.

It is difficult to decide which estimate is closer to the true orchard ET. An alternative is to compare them with the hypothetical reference evapotranspiration (ETo) given by the Penman-Monteith equation with the parameterization recommended by FAO (Allen et al., 1998) and the input data measured at the weather station close to the orchard. Figure 6 displays such comparisons and it shows that the BR ET were closer to the ETo than those from the AE method. BR ET and ETo differed by less than 8%, on average, with a tendency for overprediction by the former mainly during the wet period (Figure 6a). The AE estimates were always less than ETo, but the spread of the points were almost parallel to the 1:1 line, and if this line is moved slightly upwards it becomes evident that the AE estimates were off by a constant value close to 1.6 mm d^{-1}, i.e., ETo ≈ ETaero + 1.6 (Figure 6b).

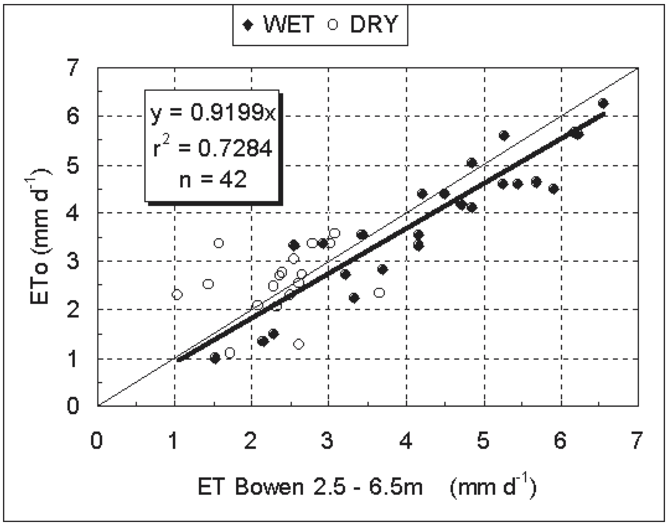

Figure 6a.

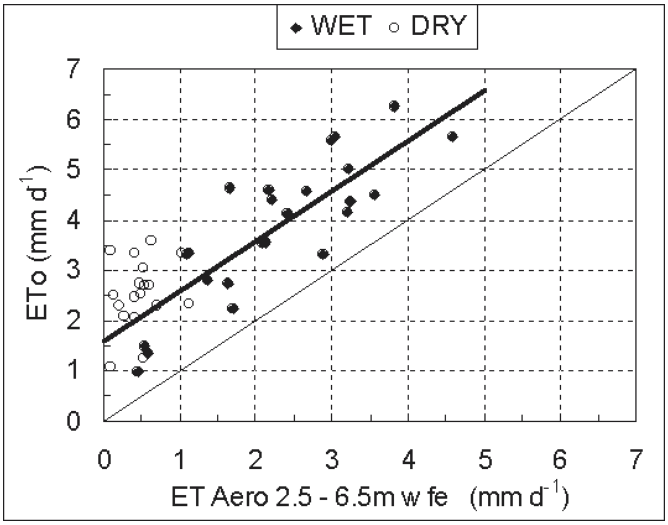

Figure 6b.

Therefore, one might be inclined to conclude that the BR ET is likely to be the correct estimate; however, it is well accepted in the evapotranspiration and irrigation literature that the crop coefficient (Kc = ETcrop / ETo) for citrus orchards is between 0.65 and 0.90 (Doorenbos & Kassam, 1994), and this seems to substantiate the aerodynamic results.

4. CONCLUSIONS

The results indicate the operational difficulties with the BR and the AE methods to estimate ET of a small citrus orchard close to a tall windbreak. The BR method is less sensitive to the vertical distance between the sensors than the AE approach. While the BR requires the vertical gradients of wet and dry bulb temperatures, the aerodynamic method needs also the vertical gradient of wind speed, and this is the most difficult element to measure correctly very close to rough surfaces, as is the case in orchards.

Very small vertical gradients of the average wind speed resulted in very large gradient Richardson numbers under unstable conditions, giving unreliable atmospheric stability correction factor. Such erroneous correction resulted in exaggeratedly large estimates of orchard ET that were not supported either by the available net radiation nor by the local advection. The vertical distance between the wind sensors should be large enough to measure the average speed differences with the sensitivity of the available instruments in order to avoid the Richardson number discrepancy.

The theoretically expected logarithmic wind speed profile above the vegetation seldom occurred during the experiment, but the effect of assuming a constant zero-plane displacement height throughout the corresponding periods was less critical than the effect of the stability factor. The zero-plane displacement height can be estimated from empirical relationships, as a fraction of the tree height, without the burden of measuring the vertical wind speed profile.

The orchard ET given by the two methods differed substantially, with the AE estimates representing grossly about one third of the corresponding BR estimates. Based on the evapotranspiration and irrigation literature, the AE estimates with appropriate Δz seems to give the most appropriate results.

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