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Bulk Surface Resistance and Its Effect on Evapotranspiration Rates in Irrigated Wheat

A. Luchiari, Jr. and S. J. Riha*

ABSTRACT

Use of the combination model to predict evapotranspiration (ET) from a crop has been limited by uncertainty in the value and behavior of the bulk surface resistance (r_b). The purpose of this study was to characterize r_b for irrigated wheat (*Triticum aestivum* L.) and evaluate its use for predictive purposes. Hourly Bowen ratio measurements were made over a field of irrigated 'Anahuac' wheat during the entire growing season of 1983. Data from 4 d were used to calculate r_b using both the energy balance and residual methods. Crop surface temperatures predicted from measurement of wind speed and air temperature at one height above the canopy were within 0.4 °C of infrared measured canopy temperatures. Both the energy balance and residual methods gave similar values for r_b. From 0830 h to 1430 h the day before irrigation, values for r_b ranged from 50 to 100 s m^{-1} whereas after irrigation, r_b for the same period ranged from 15 to 50 s m^{-1}. In both cases, r_b rapidly increased after 1430 h to values above 200 s m^{-1} by 1630 h. At the same time, latent heat loss in proportion to net radiation increased and canopy temperature decreased more rapidly than air temperature, suggesting that the increase in r_b at this time is not due to a lag in the supply of water to the canopy. The combination model was used to predict ET on both an hourly and daily basis for several periods during another crop growing season. Mean predicted values were within 6% of Bowen ratio measurements and were highly correlated with hourly and daily measured rates of ET, suggesting that the combination model can be used for predictive purposes when r_b is well characterized.

In the combination model to predict evapotranspiration (ET) from a crop canopy (Monteith et al., 1965), one term, the bulk surface resistance, incorporates the resistance to the diffusion of water vapor within the evaporating surface. Despite being simple in formulation and requiring measurements at only one height above the canopy (Stewart, 1983), the practical application of the combination model has been limited by the difficulty of obtaining values for aerodynamic (r_a) and bulk surface (r_b) resistances (Szeicz and Long, 1969). Its use has been restricted to that of a diagnostic tool for estimating r_b when the latent heat of evaporation (LE) is known (Bailey and Davies, 1981; Munro, 1987), rather than as a prognostic tool for estimating LE when r_b is assumed (Monteith, 1985). Difficulty in using r_b to predict ET from crops growing in the field arises because r_b is a complex function of several environmental and biological factors (Monteith, 1985) whose effects on r_b are not easily isolated (Munro, 1987). However, for an irrigated crop grown in a relatively stable and predictable environment, determining the relative effects of soil, plant, and atmosphere on r_b may be possible since stomatal control of the flux of water from well-watered crops is not the main factor influencing ET (Van Bavel, 1966, 1967; Van Bavel and Ehrler, 1968; Johns et al., 1983). Hatfield (1985), studying wheat, showed that r_b varied linearly as a function of available soil water. Therefore, for an irrigated crop r_b presumably will vary within limits dictated by irrigation timing.

In this paper, the energy balance method and the residual method (Szeicz and Long, 1969) for estimating r_b are compared. In both cases, to estimate r_b, r_a must be known. Therefore, the importance of correcting for atmospheric stability is evaluated. For the residual method, canopy temperature must be known. It can be measured or estimated using an aerodynamic approach. The aerodynamic temperature predicted from similarity theory is compared to crop radiative temperatures. Implications of using measured or estimated values of surface temperature in determining r_b are discussed. The behavior of r_b over the course of a day and between irrigation events is analyzed. Lastly, the use of r_b to predict ET is evaluated.

THEORY

According to Monteith (1965), the combination model for estimating ET is given by

$$LE = \frac{s(Rn - G) + \rho C_p(e_s - e_z)/r_a}{s + \gamma\left(1 + \frac{r_b}{r_a}\right)} \quad [1]$$

where LE is latent heat of vaporization (W m^{-2}), Rn is net radiation (W m^{-2}), G is soil heat flux density (W m^{-2}), ρ is air density (1.2 kg m^{-3}), C_p is the specific heat capacity of the air at constant pressure (1010 J kg^{-1} °C^{-1}), e_s is the saturated vapor pressure of the surface (Pa), e_z is the vapor pressure at reference height z, s is the slope of the saturation vapor pressure − temperature curve (Pa °C^{-1}), and γ is the psychrometric constant (66 Pa °C^{-1}). In this study, Rn, G, and e_z were measured directly, LE was obtained using the Bowen ratio method, and s and e_s were obtained using the relations proposed by Murray (1967). Therefore, r_b and r_a were the only unknowns in Eq. [1]. In this paper, r_a is the aerodynamic resistance to heat or vapor transfer from $d + z_o$ to z, where d is the zero plane displacement, z_o is a roughness parameter, and z is the height of measurement above the ground. Bulk surface resistance, r_b, is the resistance to the diffusion of water vapor within the evaporating surface (Monteith et al., 1965).

The combination model (Eq. [1]) combines the Ohm's Law analogy for heat and vapor transfer and the energy budget equation to solve for latent heat loss when surface temperature (T_s) is not known. if T_s is known or can be estimated, then LE can be obtained directly from the Ohm's Law analogy:

$$LE = \frac{\rho C_p}{\gamma} \frac{[e_{s(T_s)} - e_z]}{r_b + r_a} \quad [2]$$

To calculate r_a (Eq. [1] and [2]) and T_s (Eq. [2]), we make

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Abbreviations: ET, evapotranspiration; r_b, bulk surface resistance; r_a, aerodynamic resistance; Rn, net radiation; T_s, crop surface temperature; G, soil heat flux density; H, sensible heat flux; and LAI, leaf area index.

use of boundary-layer theory. Within the surface layer (Businger, 1973) and under neutral stratification, wind speed increases as a function of the logarithm of height (z) above a level $d + z_o$, where d is the zero plane displacement (m) and z_o is the momentum roughness parameter (m). The log-wind profile is given by

$$u(z) = \frac{u_*}{k} \ln \frac{z - d}{z_o} \qquad [3]$$

where $u(z)$ is the windspeed (s m^{-1}) at height z, u_* is the friction velocity (m s^{-1}) and k is von Karman's constant (0.4). We assume d = 0.63 crop height and z_o = 0.13 crop height (Campbell, 1977) and solve for u_* with wind velocity measured at one height. Knowing u_*, the wind profile over the crop can be calculated. However, the log-wind profile can be altered by thermal stratification and consequently we consider correcting for non-neutral conditions before using Eq. [3] to predict windspeed as a function of height. The Monin-Obukhov stability parameter (ζ) expresses the ratio of convective (buoyant) to mechanical production of turbulent kinetic energy. This stability parameter is calculated according to Campbell (1977) as:

$$\zeta = \frac{kzgH}{\rho C_p T u_*^3} \qquad [4]$$

where H is the sensible heat flux (W m^{-2}) determined from Bowen ratio measurements, and g is the acceleration due to gravity (9.8 m s^{-2}).

A correction factor for momentum transport (ψ_m) related to ζ is given in an integral form for wind by Businger (1973) for stable ($\zeta < 0$) and unstable ($\zeta > 0$) conditions. Including ψ_m in Eq. [3], it becomes

$$u(z) = \frac{u_*}{k}\left[\ln\left(\frac{z - d}{z_o}\right) + \psi_m\right] \qquad [5]$$

Under unstable conditions, ψ_m is negative and therefore the wind velocity is lower than that predicted by Eq. [3]. Under stable conditions, ψ_m is positive and therefore the wind velocity is higher than that calculated by the log wind profile. An iterative approach was used to obtain values for u_*, ζ, and ψ_m.

The aerodynamic resistance (r_a), from $d + z_o$ to z, can now be calculated according to Heilman and Kanemasu (1976) as

$$r_a = \frac{\left[\ln\left(\frac{z - d}{z_o}\right) + \psi_m\right]^2}{k^2 u} \qquad [6]$$

It is clear from Eq. [6] that r_a will decrease under unstable conditions and increase under stable conditions when compared to neutral conditions.

Equation [2] requires T_s be known in order to calculate e_s (saturated vapor pressure at T_s). Surface temperature can be estimated based on the similarity of the surface layer, where fluxes are assumed constant with height. According to Campbell (1977) and Brutsaert (1982), an expression for T_s is given by

$$T_s = T_z + \frac{H}{\rho C_p k u_*}\left[\ln\left(\frac{z - d}{z_h}\right) + \psi_h\right] \qquad [7]$$

where z_h is the heat roughness parameter (0.2 z_o) (Campbell, 1977) and ψ_h is a correction factor for heat transport related to ζ (Businger, 1973). Brutsaert (1982) suggests that when $\zeta > 1$, ψ_m and ψ_h in Eq. [5] and [7], respectively, can be set equal to a constant of 5 for practical computations.

Using the above approach and having measured LE, Rn, G, e_z, u_z, T_z, and crop height, the only unknown in Eq. [1] and [2] is r_b. When the value of r_b in Eq. [1] is taken as zero and assuming that all other parameters in this equation remain unchanged, an upper limit of evapotranspiration rate (LE_m) is defined. Dividing Eq. [1] with r_b set equal to zero, by Eq. [1] with all other terms identical, and solving for r_b, we obtain

$$r_b = r_a\left(1 + \frac{s}{\gamma}\right)\left(\frac{LE_m}{LE} - 1\right) \qquad [8]$$

This is referred to as the energy balance method for calculating r_b (Szeicz and Long, 1969).

Solving Eq. [2] for r_b, we obtain

$$r_b = \frac{\rho C_p}{\gamma}\frac{[e_s(T_s) - e_z]}{LE} - r_a \qquad [9]$$

This is referred to as the residual method for calculating r_b (Szeicz and Long, 1969).

EXPERIMENTAL PROCEDURE

The data used in this study were collected during the dry seasons of 1982 and 1983, over a sprinkler irrigated wheat field at the Centro de Pesquisa Agropecuaria dos Cerrados in Planaltina, DF, Brazil, located at 15° 35′ S and 47° 42′ W, and 1000 m in altitude.

The soil of the experimental field is a Dark Red Latosol (Brazilian Soil Taxonomy) or a isohyperthermic, fine, kaolinitic Typic Haplustox (U.S. Soil Taxonomy) with a 2% slope in the SW-NE direction. The size of the experimental field differed for the 2 yr. During 1982, it was a 1-ha rectangular plot, in which sensors were mounted in such a way as to give a maximum fetch of 75 m in the SE-NE direction (the predominant wind direction), 50 m in the SW-SE direction and 25 m in the W direction. During 1983, the experimental area was augmented to 4 ha, in such a way as to give a minimum fetch of 100 m in all directions, with 250 m in the predominant wind direction (SE-NE). The area was planted with a low stature (80-cm maximum height) Mexican wheat on 6 June 1982 and on 16 June 1983, in rows oriented SE-NW 17 cm apart with 82 seeds per linear meter. Four sets of tensiometers were installed at various sites within the plot and at various depths (to a maximum of 1 m) in the soil profile. Irrigation water was applied in amounts sufficient to bring the whole soil profile (0–1 m) to a water potential of approximately −10 J kg^{-1} whenever the average (four sampling sites) soil water potential at the 5-cm layer reached −60 to −70 J kg^{-1}.

Evapotranspiration rates were measured using the Bowen ratio method. Wet and dry bulb temperatures were made at two levels, 10 and 170 cm above the canopy, by shielded, ventilated platinum resistance thermometers (Model 111, Chino Works, Tokyo, Japan). A mechanism for reversing sensors was not available at the research station. The thermometers were calibrated prior to field installation in a covered polystyrene box using a standard mercury thermometer located in the middle of the box. Dry and wet bulb thermometers were adjusted in order to give temperature differences of less than 0.2 °C. During the experiment, calibrations of the thermometers were checked weekly using the same procedure. Calibrations were not found to change over the course of the experiment. Net radiation was measured at 2 m above the canopy by a net radiometer (Model H211, Eko Instruments Trading Co., Tokyo, Japan). Soil heat flux density was measured at a depth of 3 cm with three soil heat flux plates (Eko Instruments Trading Co., Tokyo, Japan) placed at different locations. After field installation, the sensors were continually monitored. The output from these sensors were recorded at 1-min intervals during the entire period of measurement using electronic analog chart

recorders. These values were then averaged hourly in order to calculate ET rates as well as other energy balance components.

In 1983, T_s of the crop was measured from 10 to 20 August (56–66 d after planting). During this period the crop was at the yield formation stage, with a leaf area index (LAI) of approximately 5 and height varying from 45 to 56 cm. Two methods were used for measuring surface temperature. The tip of six copper-constantan (Cu-Cn) thermocouples (0.1 mm in diameter and 15 cm in length) were attached to the abaxial surface of leaves by porous medical adhesive tape. The first three upper leaves selected had different orientations in order to give good spatial representation of the upper canopy. The Cu-Cn thermocouples (0.1 mm in diameter) were connected to Cu-Cn wires (0.65 mm in diameter). From the Cn wire, a Cu-Cn junction was made and placed in a thermos bottle filled with crushed ice in order to define a cold junction. The Cu leads of the cold and hot junctions were connected to a digital data-logger (Model PROCOS VII, Chino Works, Tokyo, Japan) and temperature was recorded every 30 min. The ice in the bottle was replaced twice a day (0800 h and 1800 h). The reproducibility of the thermocouples was within 0.2 °C. Canopy temperature was also measured with an infrared thermometer (National-Matsushita Industrial Communication Co., Yokohama City, Japan) with a field view angle of 5° and a spectral range of 8 to 14 μm. Longwave emissivity of the crop was assumed to be 0.98. Averaged values were obtained from six measurements made manually every 30 min at an angle of about 30° from the horizontal. The sensitivity of the infrared thermometer was ±0.1 °C.

Wind speed was measured at a height of 7 m with a propeller anemometer (Nakassa Trading Co., Tokyo, Japan) located in an agrometeorological station immediately adjacent to the experimental field. The signal of this anemometer was recorded in a data logger programmed to produce hourly averaged values. The values obtained were reduced to reference height above ground level (z = 1.8 + crop height) using Eq. [3].

From the period of canopy temperature measurements, 4 d were selected for a detailed analysis: 11 and 18 August (1 d before irrigation events) and 12 and 19 August (days following nighttime irrigations). All 4 d had clear skies except for 19 August, which had some clouds after 1400 h (Fig. 1). In discussing our results, emphasis will be placed on the period beginning at 0830 h and ending at 1630 h local time. Although shown in some figures, the period between 0700 h and 0800 h is a transition period from night to daytime for our conditions (15° 30′ S). The fluxes of latent and sensible heat may assume values of the same magnitude, but in different directions. The Bowen ratio method can fail under these conditions. Also Rn and G may assume negative or positive values.

RESULTS AND DISCUSSION

Estimated and Measured Values of Canopy Temperature

In order to solve Eq. [6] for r_a and Eq. [7] for T_s, correction factors for stability (ψ_m and ψ_h) must be determined. These correction factors are related to ζ, the stability parameter (Eq. [4]). Hourly values of ζ ranged from −0.2 (18 August) to 0.05 (12 and 19 August), indicating conditions close to neutrality. This can be attributed to the high wind velocities predominant in the region (from 2–5 m s^{-1} at reference height), which will produce a high value of u_*. Since H under conditions reported here was small (usually −30–60 W m^2, Fig. 1), the net effect was a low value of ζ, indicating the predominance of mechanical over convective forces. Although correction factors for stability were used to calculate T_s (Eq. [7]), analysis showed that ignoring these corrections would have changed predicted T_s at most by 0.4 °C ($T_{s\,corrected}$ = −0.65 + 1.02 $T_{s\,uncorrected}$, R = 1.00).

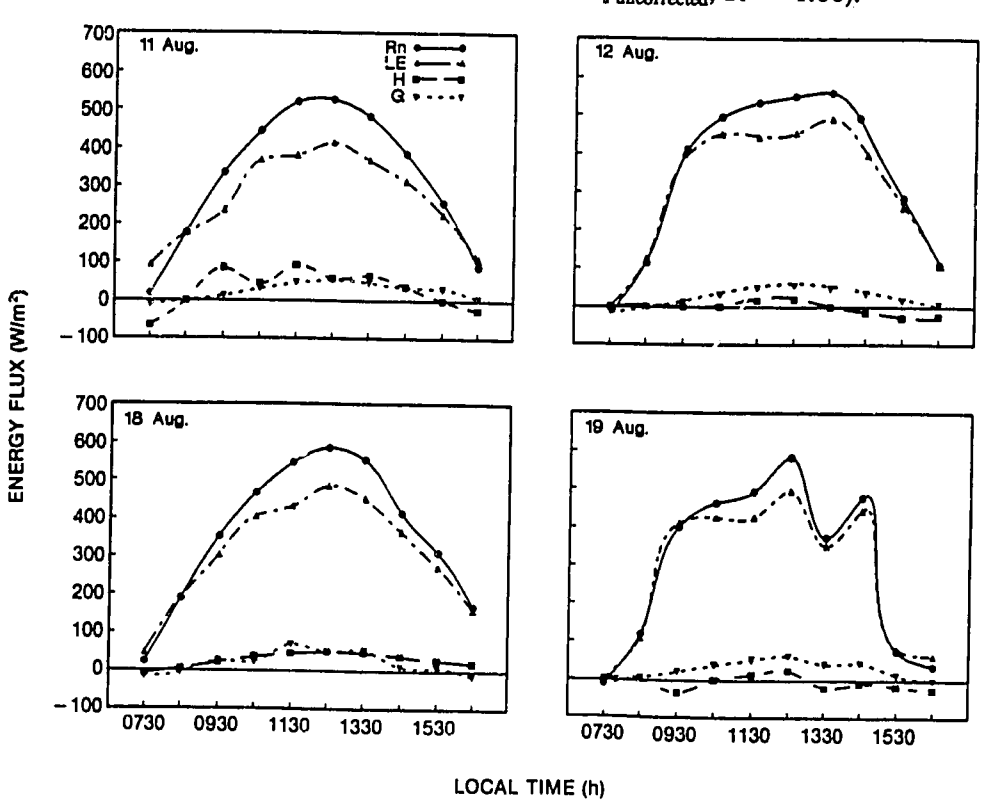

Fig. 1. Hourly measured net radiation (Rn), latent heat of vaporization (LE), sensible heat flux (H) and soil heat flux (G) before (11 and 18 August) and after (12 and 19 August) irrigation.

Hourly values for T_s estimated from Eq. [7] and measured using an array of thermocouples or an infrared thermometer are presented in Fig. 2. There is good agreement between predicted and infrared measured temperatures ($T_{s\,predicted} = 1.04 + 0.96\ T_{s\,infrared}$, $R = 0.99$) both under clear skies (most of the measurements) and under cloudy conditions (Fig. 2, 19 August—1300 h). Predicted temperatures were less than measured temperatures around midday on 11 and 12 August. The cause of this discrepancy is not known. The value of T_s in Eq. [7] is not necessarily the actual surface temperature, since it is in theory the temperature at $d + z_h$. A study by Huband and Monteith (1986) over a wheat crop showed that values of T_s were consistently 1 K hotter than the values obtained with an infrared thermometer. Choudhury et al. (1986) found T_s to be lower than infrared thermometric observations under stable atmospheric conditions and higher under unstable conditions. They attributed these results to variation in the location of sink/source height of heat within the canopy. Our results appear to be consistent with their observation. The period during which T_s values were lower than infrared measurements in our study coincided with periods of greatest atmospheric stability during the 4 d studied.

Agreement between predicted and thermocouple measured temperature was not as good as that obtained between predicted and infrared measured temperature. On 12 August (Fig. 2) good agreement was obtained, except during midday when thermocouple values were high. On 18 and 19 August (Fig. 2) thermocouple temperature was lower than both predicted and infrared measured temperature after 1530 h. This may have been due to heating of the ice jar which could cause ice to melt and thereby alter the reference junction temperature. Also, due to spatial variability of radiation and wind speed, six thermocouples may have been insufficient to obtain a representative average temperature of the canopy.

The crop surface was cooler the day following irrigation than the day before (Fig. 2). Daily average temperature at the reference height was similar on days 11 and 12 August (22.4 and 22.0 °C), and was 1.2° cooler on 19 August (26.0 °C) in relation to 18 August (27.2 °C). However, canopy temperature was about 3 to 4° lower from 1100 h to 1400 h on 12 and 19 August, in comparison to the corresponding previous days.

Aerodynamic and Bulk Surface Resistance

Hourly values of r_a were calculated using Eq. [6] without correcting for stability (Fig. [3]). Aerodynamic re-

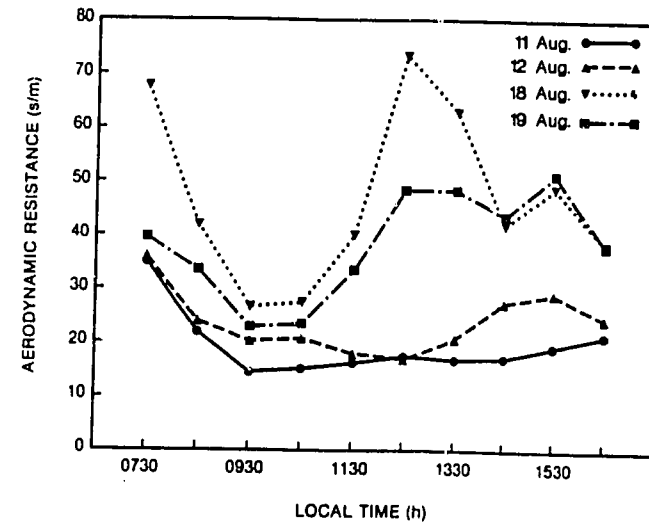

Fig. 3. Hourly values of aerodynamic resistance (r_a).

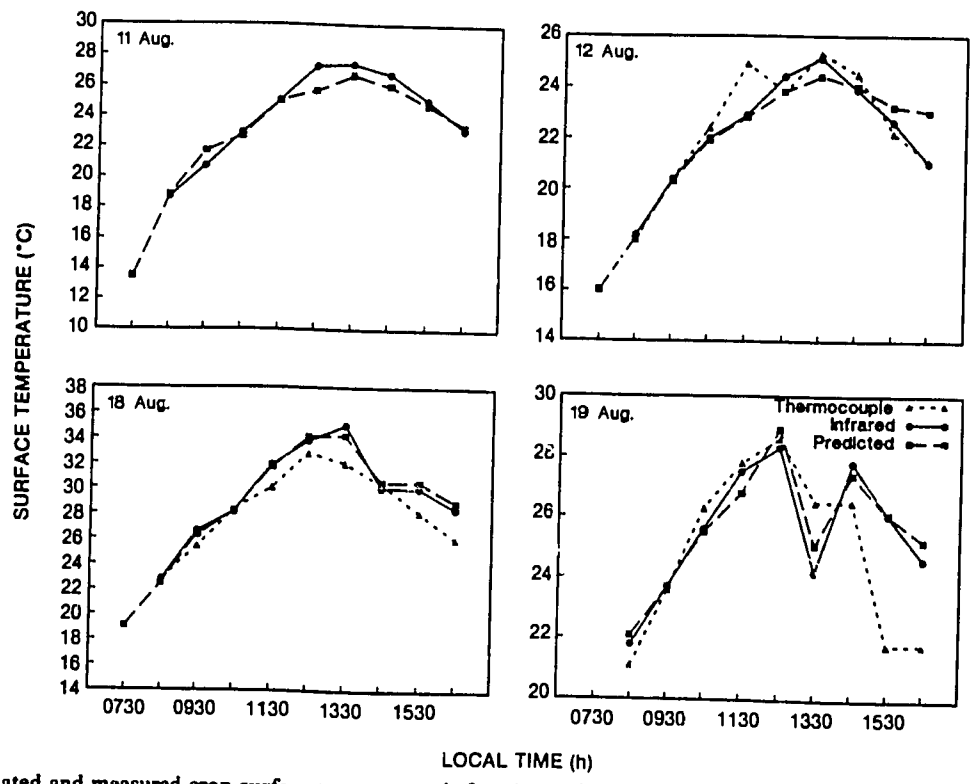

Fig. 2. Hourly estimated and measured crop surface temperature before (11 and 18 August) and after (12 and 19 August) irrigation.

sistance varied between 15 to 25 s m^{-1} on 11 and 12 August and between 25 to 75 s m^{-1} on 18 and 19 August. As previously mentioned, wind velocities were higher on 11 and 12 August than on 18 and 19 August. Since z_0 and d were assumed to be a function of crop height, which did not change much over the period of measurements, r_a was highly dependent on wind velocity and decreased as the wind velocity increased.

The energy balance (Eq. [8]) and the residual (Eq. [9]) methods were used to determine r_b. Values for surface temperature used in the residual method were obtained from estimation (Eq. [7]) and from infrared measurements. There was good agreement between the values obtained using these two methods when the estimated surface temperature was used to determine saturation vapor pressure at the surface in the residual method (Fig. 4). In calculating r_a, the equality of roughness of the surface to momentum and heat transfer is assumed (Eq. [6]). If we had assumed roughness to heat transfer is only 20% that to momentum transfer (Campbell, 1977), values for r_b at low windspeeds would have been approximately 20 s m^{-1} greater than those reported here. This difference decreases with increasing windspeed.

In general, r_b is small and stays relatively constant from 0800 until 1330 h. After this, r_b tends to increase gradually on days before irrigation and sharply increase after 1530 h on all days (Fig. 4). This phenomena has been observed previously in studies of this nature conducted over different kinds of vegetated surfaces (Monteith et al., 1965; Szeicz and Long, 1969; DeHeer-Amissah et al., 1981; Munro, 1987). It has been attributed to the ability of the plant to supply water to the evaporative surface at a rate sufficient to meet evaporative demand. When r_b remains relatively constant, it is presumed that supply and demand are in equilibrium. The increase in r_b in the afternoon suggests a lag between supply and demand. However, in this study there is no indication of a decrease in supply of water to the surface in the afternoon. Despite an increase in r_b, latent heat loss relative to net radiation is not decreasing, but rather increasing after midday (Fig. 1). Interestingly, this increase in r_b occurs after canopy temperatures have peaked and have actually begun decreasing relative to air temperature (Fig. 5). Clearly, the increase in resistance does not cause the temperature of the canopy to increase. In fact, an increase in r_b at this time appears to limit the cooling of the canopy below air temperature. The cause of this increase in r_b is not clear. Hatfield (1985), in studies with wheat, showed that r_b increased exponentially with decreasing solar radiation, with a rapid increase (from 100–225 s m^{-1}) below values of 200 W m^{-2}. Bailey and Davies (1981), in studies with soybean, also noticed the same effect below these values of solar radiation flux. In this study, after 1530 h the sun rays are impinging on the canopy at low elevation angles prevailing at this time of the year at this latitude. Consequently, less solar radiation may penetrate into the lower part of the canopy, leading to an increase in stomatal resistance of these leaves and thereby an increase in r_b.

As is clear from Fig. 4, r_b is influenced by irrigation. It is higher (around 70 s m^{-1}) on days before irrigation and it is smaller (around 30–40 s m^{-1}) on days following nighttime irrigation. This change in r_b could not be attributed solely to stomatal behavior, since the crop was irrigated when soil water potential at 10 cm

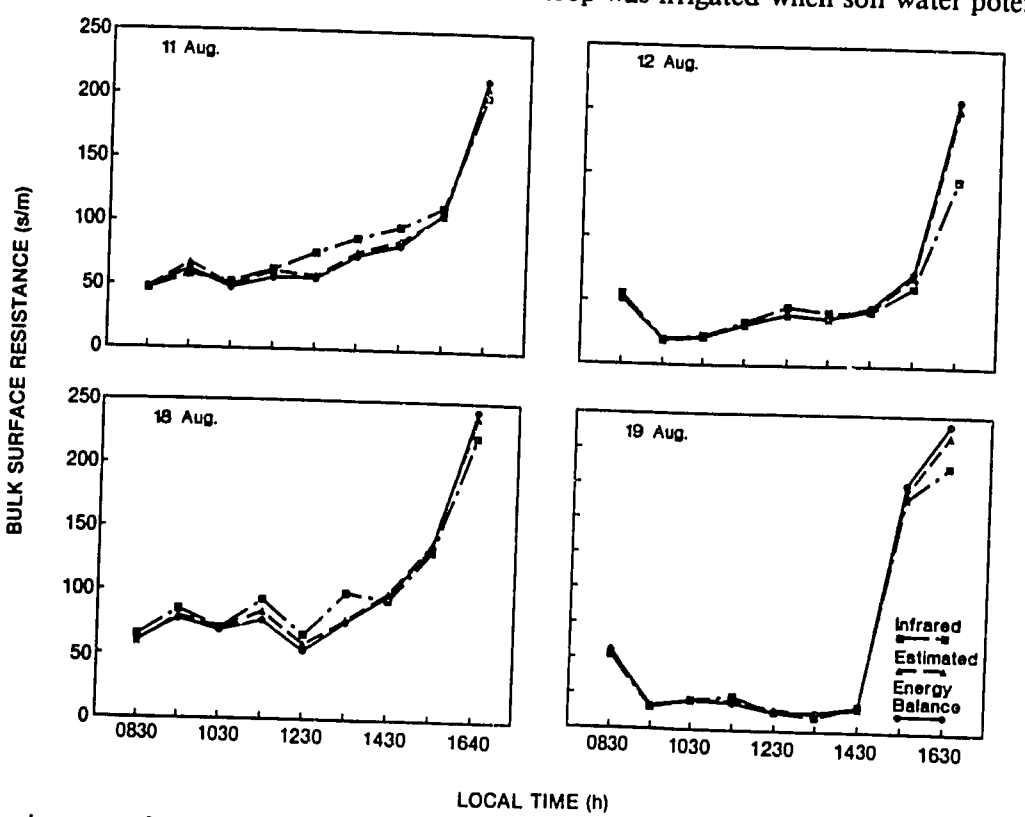

Fig. 4. Bulk canopy resistance as a function of time of day using the energy balance (Eq. [8]) and residual (Eq. [9]) methods. With the residual method, estimated and infrared measured temperatures were used to calculate r_b.

was -70 J kg^{-1} and soil water status was not considered limiting plant growth and yield (EMBRAPA/CPAC, 1987). Norman and Campbell (1983) and Fuchs et al. (1987) showed that following crop irrigation up to 50% of total evapotranspiration could be water evaporated from the soil. The hydraulic conductivity of the soil used in this study decreases rapidly with decreasing water content (Luchiari Jr., 1988). The rate of soil evaporation could have declined rapidly after irrigation if energy transfer to the soil surface was greater than that estimated from simple radiation penetration models which assume no sensible heat transfer to the soil surface (Luchiari Jr., 1988). This would result in an increase in r_b with time after irrigation even if there were little change in crop stomatal response. It is in agreement with the suggestion of Johns et al. (1983) that in well-irrigated crops, factors external to crops are controlling the flux of water vapor to a greater extent than plant physiological factors (stomatal resistance).

Use of the Combination Model for Predictive Purposes

The combination model (Eq. [1]) was used to predict hourly ET rates, which were then compared to Bowen ratio measurements during three crop growth stages in 1982. In the first stage (9–13 July), the average crop height was 0.3 m and green LAI ranged from 2 to 2.5. In the second stage (23–29 July) the average crop height was 0.5 m and green LAI averaged 5.0. In the third stage (23–29 August) the average crop height was 0.74 m and green LAI ranged from 4.0 to 3.0. Bulk surface resistance was assumed to vary between a minimum of 40 s m^{-1} (1 d after irrigation) with a daily gradual increase (45, 50, 55, 60, 65 s m^{-1}) to a maximum of 70 s m^{-1} (1 d before irrigation). On all days, r_b was assumed to equal 100 s m^{-1} after 1530 h. Values for r_a were obtained from the log-wind profile (Eq. [6]) assuming neutral conditions.

Hourly estimates of LE are presented for 3 d during three different crop growth periods (Fig. 6). Mean predicted and measured values are similar (x_{model} = 0.39 mm h^{-1}, SE = 0.03, $x_{measured}$ = 0.38 mm h^{-1}, SE = 0.04, $ET_{model} = 0.08 + 0.81\ ET_{measured}$, $R = 0.94$). The greatest discrepancy occurred during midday of 25 July, when predicted values were approximately 30% less than measured values. When this 3-h period was not considered, both the correlation and the correspondence between predicted and measured values improved ($ET_{model} = 0.04 + 0.94\ ET_{measured}$, $R = 0.97$). Daily total values of LE obtained by summing up hourly values are shown in Fig. 7 for all days used for this purpose. The combination model slightly over predicted LE (x_{model} = 3.77 mm d^{-1}, SE_{model} = 0.13, $x_{measured}$ = 3.55 mm day^{-1}, $SE_{measured}$ = 0.15). There were 3 d when measured values were considerably higher than model values, possibly due to advection. When these 3 d were excluded from analysis, both the correlation and the correspondence between predicted and measured values improved ($ET_{model} = 0.65 + 0.90\ ET_{measured}$, $R = 0.97$, $n = 15$; $ET_{model} = 0.78 + 0.84\ ET_{measured}$, $R = 0.93$, $n = 18$). Most of the predictions (hourly or daily) are within the limits of uncertainty in LE determined using the Bowen ratio method. This suggests that the values of r_b ranged between fixed limits as dictated by the soil water content and time of day. Although the assumption that r_b equalled 100 s m^{-1} after 1530 h was somewhat arbitrary, it produced reasonable estimates of LE. The results also indicate that neutral conditions can be

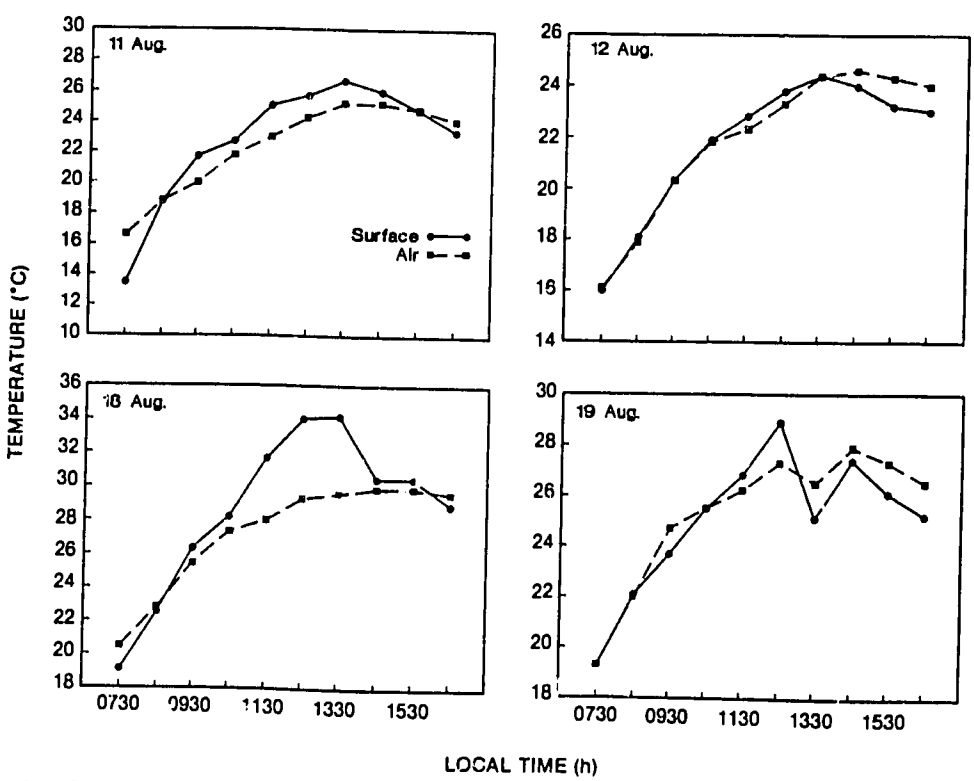

Fig. 5. Hourly calculated surface and air temperatures before (11 and 18 August) and after (12 and 19 August) irrigation.

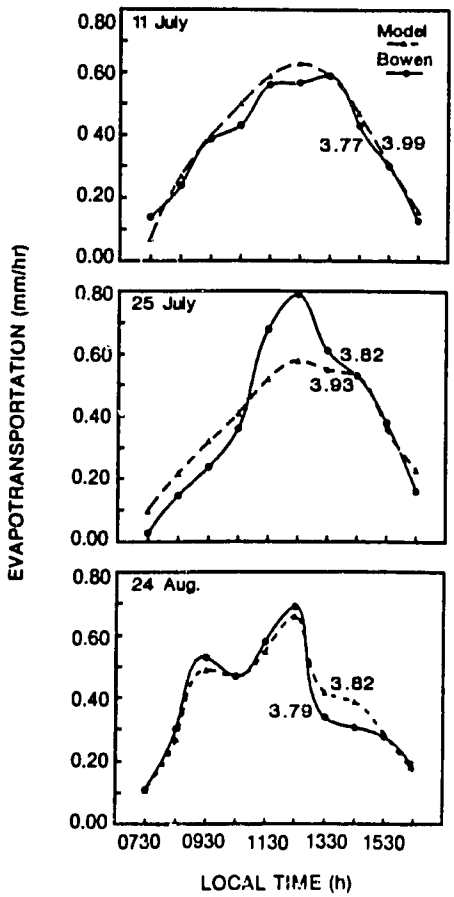

Fig. 6. Hourly predicted (model) and measured (Bowen ratio) latent heat loss in 1982. Total daily evapotranspiration (mm) included.

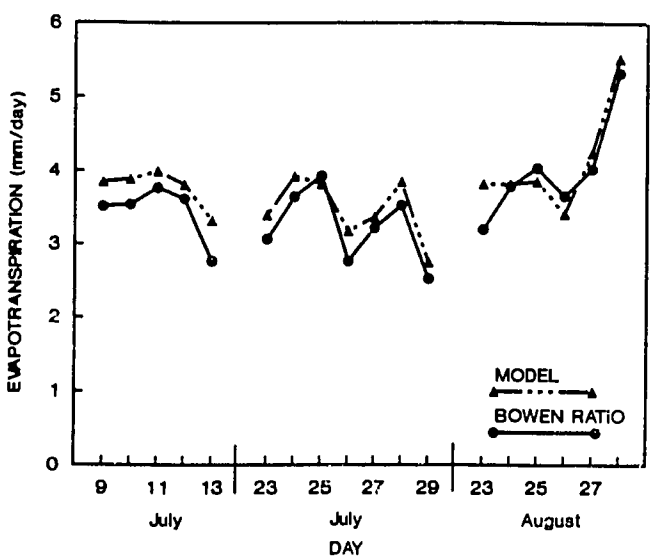

Fig. 7. Daily predicted (model) and measured (Bowen ratio) latent heat loss for three crop growth periods during 1982.

assumed without appreciable error in estimates of LE, due to the relatively high wind velocities prevailing in the region during this time of the year.

Using the same data and a coefficient of 1.26, the Priestley-Taylor model (Priestley and Taylor, 1972) was used to predict daily latent heat loss. The Priestley-Taylor model did not overpredict latent heat loss (x_{model} = 3.51 mm d^{-1}, SE_{model} = 0.15, $x_{measured}$ = 3.55 mm d^{-1}, $SE_{measured}$ = 0.15). However, both the correlation and the correspondence between measured and predicted values ($ET_{model} = 1.61 + 0.56\,ET_{measured}$, $R = 0.69$, $n = 15$, $ET_{model} = 1.81 + 0.58\,ET_{measured}$, $R = 0.58$, $n = 18$) were much poorer in comparison to the combination model.

CONCLUSIONS

In this study of well-irrigated wheat, the bulk surface resistance varied as a function of time of day and between irrigation events. The increase in r_b between irrigation events strongly suggests that the major evaporating surface controlling r_b throughout much of the day is the soil rather than the crop canopy, despite the presence of a closed canopy. A sharp increase in r_b after 1430 h does not appear to be caused by a lag in supply of water to the canopy compared to demand. Latent heat loss in proportion to net radiation actually increased as r_b increased. Increase in r_b after this time did not retard the cooling of the canopy, which was decreasing more rapidly than air temperature. Without this increase in r_b during this time, advective transport of heat to the crop surface would have increased, thereby increasing the energy load on the crop surface.

The combination model overpredicted measured values of ET by about 6%. The combination model had a fairly uniform bias and was very highly correlated with hourly and daily measured rates of ET. It was found to be a better daily predictor of ET than the Priestley-Taylor model. However, to apply the combination model to other soil types may require accounting for variable effects on r_b of the soil properties controlling evaporation from the soil surface under crop canopies.

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REFERENCES

Bailey, W.G., and J.A. Davies. 1981. Bulk stomatal resistance control on evaporation. Boundary Layer Meteorol. 20:401–415.

Brutsaert, W. 1982. Evaporation into the atmosphere: theory, history and applications. Reidel Publishing Co., Boston, MA.

Businger, J.A. 1973. Turbulent transfer in the atmospheric surface layer. p. 67–100. *In* D.A. Haugen (ed.) Workshop on micrometeorology. American Meterological Soc., Boston, MA.

Campbell, G.S. 1977. An introduction to environmental biophysics. Springer-Verlag, New York, NY.

Choudhury, B.J., R.J. Reginato, and S.B. Idso. 1986. An analysis of infrared temperature observations over wheat and calculation of latent heat flux. Agric. For. Meteorol. 37:75–88.

DeHeer-Amissah, A., U. Hogstrom, and A.S.S. Hogstrom. 1981. Calculation of sensible and latent heat fluxes, and surface resistance from profile data. Boundary Layer Meteorol. 20:35–49.

EMBRAPA/CPAC. 1987. Relatorio Tecnico do Centro de Pesquisas Agropecuaria dos Cerrados 1982-85. Planaltina, DF., Brazil.

Fuchs, M., Y. Cohen, and S. Moreshet. 1987. Determining transpiration from meteorological data and crop characteristics for irrigation management. Irrig. Sci. 8:91–99.

Hatfield, J.L. 1985. Wheat canopy resistance determined by energy balance techniques. Agron. J. 77:279–283.

Heilman, J.L., and E.T. Kanemasu. 1976. An evaluation of a resistance form of the energy balance to estimate evapotranspiration. Agron. J. 68:607–611.

Huband, N.D.S., and J.L. Monteith. 1986. Radiative temperature and energy balance of a wheat canopy. Part 1: Comparison of radiative and aerodynamic canopy temperature. Boundary Layer Meteorol. 36:1–17.

Johns, D., J.B. Beard, and C.H.M. van Bavel. 1983. Resistances to evapotranspiration from a St. Augustine grass turf canopy. Agron. J. 75:419–422.

Luchiari Jr., A. 1988. Measurements and predictions of evapotranspiration rates from irrigated wheat in the Cerrados region of

Central Brazil. Ph.D. disser. Cornell University, Ithaca, NY. (Diss. Abstr. 8821141).
Monteith, J.L. 1985. Evaporation from land surfaces: Progress in analysis and prediction since 1948. p. 4–12. *In* Advances in Evapotranspiration. Proc. of the Natl. Conf. on Adv. in Evapotranspiration, Chicago, IL. 16-17 Dec. 1985. ASAE, St. Joseph, MI.
Monteith, J.L., G. Szeicz, and P.E. Waggoner. 1965. The measurement and control of stomatal resistance in the field. J. Appl. Ecol. 2:345–355.
Munro, D.S. 1987. Surface conductance to evaporation from a wooded swamp. Agric. For. Meteorol. 41:249–258.
Murray, F.W. 1967. On the computation of saturation vapor pressure. J. Appl. Meteorol. 6:203–204.
Norman, J.N., and G.S. Campbell. 1983. Application of a plant-environmental model to problems in irrigation. Adv. Irrig. 2:155–188.
Priestley, C.H.B., and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100:81–92.
Stewart, J.B. 1983. A discussion of the relationships between the principal forms of the combination equation for estimating crop evapotranspiration. Agric. Meteorol. 30:111–127.
Szeicz, G., and I.F. Long. 1969. Surface resistance of crop canopies. Water Resour. Res. 5:622–633.
Van Bavel, C.H.M. 1966. Potential evaporation: the combination concept and its verification. Water Resour. Res. 2:455–468.
Van Bavel, C.H.M. 1967. Changes in canopy resistance to water loss from alfalfa induced by soil water depletion. Agric. Meteorol. 4:165–176.
Van Bavel, C.H.M., and W.L. Ehrler. 1968. Water loss from a sorghum field and stomatal control. Agron. J. 60:84–86.

Effect of Maize Maturity on Radiation-Use Efficiency

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ABSTRACT

Maize (*Zea mays* L.) production has expanded into short-season regions but it is not known whether the radiation-use efficiency (RUE, g MJ^{-1})[1] of new early hybrids differs from those grown in traditional maize-growing regions. In this study, spectral reflectance measurements were used to derive estimates of photosynthetically active radiation (PAR) absorbed to compare the RUE of 10 maize hybrids that varied in adaptation from Iowa 110-d relative maturity to the earliest 60-d relative maturity hybrids commercially available. Reflectance measurements were made radiometrically in the visible and near-infrared regions of the electromagnetic spectrum at approximately weekly intervals in 1985, 1986, and 1988. The 10 maize hybrids were grown at three densities at Lethbridge, Alberta, on an irrigated silty clay loam soil (Typic Haploboroll). The Scattering by Arbitrarily Inclined Leaves (SAIL) model of canopy reflectance was inverted to produce daily estimates of the fraction of absorbed PAR, *p*. Multiplying *p* by daily PAR irradiance gave daily estimates of absorbed PAR (APAR, MJ m^{-2}), which were summed for the season. Radiation use efficiency was obtained by dividing whole-plant yield at harvest by seasonal (emergence to harvest) APAR. Averaged over years, hybrids, and densities, RUE was 2.3 g MJ^{-1}. Radiation-use efficiency increased with population density across hybrids regardless of maturity. Seasonal RUE was lower than reported in the literature but there is evidence that chilling injury due to low night temperatures at the high elevation and semi-arid location of the study reduced photosynthesis. The results suggest that spectral reflectance can be used effectively by breeders to identify hybrids that are more efficient users of PAR and that maize hybrids resistant to chilling injury may be needed at high latitudes.

RADIATION-USE EFFICIENCY (RUE, grams per megajoule) is the aboveground dry matter production (grams) per megajoule of photosynthetically active radiation (PAR) absorbed by the crop. Thus it is an estimate that bears some similarity to net photosynthesis or net assimilation. Kanemasu and Arkin (1974) found a linear relationship between the square root of absorbed PAR and net photosynthesis defined as carbon exchange rate (CER). Seasonal estimates of absorbed PAR have been monitored by measuring incoming, transmitted, and PAR reflected from the canopy and soil throughout the growing season (Hipps et al., 1983; Gallo and Daughtry, 1986) but more automated methods, namely remote sensing, are now possible (Daughtry et al., 1983; Asrar et al., 1984).

Several approaches may be used for measuring RUE remotely, such as relating a spectrally based vegetation index to leaf area index (LAI) and then the LAI to the fraction of absorbed PAR (*p*). The vegetation index can also be related directly to *p* (Wiegand and Richardson 1984, 1987; Wiegand et al., 1989). A third method is to invert a canopy reflectance model to estimate *p*.

Remote measurements of canopy reflectance throughout the growing season can be used to estimate *p* because, as LAI increases and soil is gradually covered by the canopy, reflectance in the red region of the spectrum decreases while near-infrared reflectance increases. Observations in these two spectral regions are used to determine a vegetation index (VI), such as the normalized difference vegetation index (NDVI, Rouse et al., 1974) or the ratio vegetation index (RVI, Jordan, 1969). Both are highly correlated with LAI (Hipps et al., 1983; Asrar et al., 1984; Gallo et al., 1985) and reach limiting values asymptotically vs. LAI (Wiegand and Richardson, 1984; Sellers, 1985). Saturation of the vegetation index occurs from LAI 2 to 6 depending on the vegetation index used, the crop studied, and the experimental conditions (Daughtry et al., 1980; Ahlrichs and Bauer, 1983; Wanjura and Hatfield, 1987).

Asrar et al. (1989) defined the various components of the PAR budget as follows:

$$APAR = (PAR_o + PAR_s) - (PAR_c + PAR_s) \quad [1]$$

Where APAR is PAR absorbed by the crop, and the subscripts refer to portions that are incoming, o; reflected by the soil, s; reflected by the canopy, c; and

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Abbreviations: RUE, radiation-use efficiency; PAR, photosynthetically active radiation; SAIL, Scattering by Arbitrarily Inclined Leaves; *p*, estimate of fraction of absorbed PAR; APAR, estimate of absorbed PAR; CER, carbon exchange rate; LAI, leaf area index; VI, vegetative index; NDVI, normalized difference vegetation index; RVI, ratio vegetation index; LAD, leaf angle distribution; NIR, near infrared; and SAVI, soil-adjusted ratio vegetation index.