Agricultural and Forest Meteorology, 36 (1985) 55—64
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

ERRORS IN FIELD MEASUREMENT OF LEAF DIFFUSIVE CONDUCTANCE ASSOCIATED WITH LEAF TEMPERATURE

WAYNE S. MEYER[1], DON C. REICOSKY[2] and NICK L. SCHAEFER[1]

[1] *C.S.I.R.O., Centre for Irrigation Research, PMB, Griffith, N.S.W. 2680 (Australia)*
[2] *USDA-ARS, North Central Soil Conservation Research Center, Morris, MN 56267 (U.S.A.)*

(Received November 20, 1984; revision accepted April 23, 1985)

ABSTRACT

Meyer, W.S., Reicosky, D.C. and Schaefer, N.L., 1985. Errors in field measurement of leaf diffusive conductance associated with leaf temperature. Agric. For. Meterol., 36: 55—64.

The ability of leaf diffusive conductance (C_L) measurements to discriminate between different treatments in field studies has generally been disappointing. Since values of C_L are sensitive to leaf temperature and temperature gradients between the leaf and air, inaccurate temperature measurements will produce substantial errors. This work compared two methods of leaf temperature measurement from which values of C_L were calculated and subsequently compared.

Experiments using well-watered field- and glasshouse-grown cotton (*Gossypium hirsutum* L.) where diffusion porometer readings and leaf temperatures were measured indicated that the porometer thermistor reading differed markedly from leaf temperature as assessed with an infrared thermometer. Under high air vapor pressure deficit (AVPD) conditions (5.2 kPa), leaf temperature (T_L) to ambient air temperature (T_A) differences were as large as −8°C. Porometer thermistor temperature was strongly influenced by T_A and to a lesser extent by T_L. Values of C_L calculated from porometer measurements of T_L can be up to 96% less than true C_L values. This is the result of both incorrect T_L measurement and a failure to account for the effects of the leaf to porometer-cup temperature differential. Until these two sources of error are addressed, values of C_L obtained from diffusion porometer measurements in the field must be regarded as only qualitative.

INTRODUCTION

The use of diffusion porometers as an aid to assessing plant water status has become a widely accepted technique. The ease and rapidity of measurement that such instruments provide have lead to their use in a wide range of environments. In many field experiments measurements have been made without due consideration of the precautions outlined by Morrow and Slatyer (1971a), Slavik (1974) and McCree and van Bavel (1977). However, despite observance of most of these precautions the lack of relation between measured values of leaf diffusive conductance and plant water status (Meyer and Green, 1981; Sojka and Parsons, 1983) has been disappointing. One possible reason for such poor relationships is indicated by Walker and Hatfield (1983) who suggest the actual leaf temperature differed from that indicated by the porometer thermistor. This paper examines the effect that

0168-1923/85/$03.30

incorrect leaf temperature measurement can have on diffusive conductance values calculated from porometer readings taken in the field. Monteith and Bull (1970) and Gay (1983) have assessed theoretically the magnitude of such errors. Our data, gathered over a wide range of conditions verify their analyses.

MATERIALS AND METHODS

The porometer used was a Licor LI-65 Autoporometer* with a LI 20S sensor cup. The cup has an aperture of 10 × 20 mm and was covered with highly reflective polyester film to reduce the heating effects from incident radiant energy. The thermistor, located on the sensor cup body, was calibrated in a temperature controlled oil bath over the full range of temperatures expected in the field (10—40°C).

The porometer cup was mounted on the calibration plate as supplied by the manufacturer. A range of known diffusive conductances were obtained by placing thin "conductance" plates (0.65 mm thick) with holes of known diameter over the "open" position of the calibration plate. Each conductance plate had eight equally spaced holes either of 1.0, 1.5, 2.0, 2.5 or 3.0 mm diameter. The conductance plates conformed to the formula given by Slavik (1974, p. 308) which avoids the use of unrealistically low conductance pathways.

Calibration was carried out over a range of temperatures in a controlled environment cabinet with relative humidity exceeding 70% as recommended by McCree and van Bavel (1977). The diffusive path length and conductance for each calibration plate configuration was calculated using two "end-corrections" to account for vapor diffusion through the holes in the conductance plates. This procedure yielded the calibration equation

$$C_L = \alpha/(-5.53 + (0.055 - 0.003T + 0.00015T^2)\Delta t) \quad (1)$$

where C_L is leaf diffusive conductance (mm s^{-1}), T is the temperature (°C) calculated from the thermistor reading, Δt is the time ($s \times 10^{-2}$, i.e. centiseconds, cs) taken for the humidity sensor to respond between two set points and α is the diffusivity (mm^2 s^{-1}) of water vapor into air calculated from

$$\alpha = 22(1 + T/273.1)^{1.75} \quad (2)$$

The porometer sensor cup was normally stored in a sealed container of silica gel. Before measurements were taken the cup was attached to the meter and at least five wetting and drying cycles were performed (Morrow and Slatyer, 1971a). Measurements were made only on well-

---

* Use of trade or firm names is for reader information only and does not constitute endorsement by CSIRO or USDA-ARS of any commercial product or service.

watered cotton (*Gossypium hirsutum* L. var. Deltapine 61) plants within six weeks following first flowering and which were grown either in the field or in large pots in the glasshouse. Leaves chosen for measurement were young, fully developed and fully exposed to the sun at the top of the canopy. Porometer readings were made on upper and lower leaf surfaces of the same leaf and diffusive conductance values so obtained were summed to give a total C_L value for the leaf. The porometer transit time reading (Δt) generally took between 200 to 400 cs and was immediately followed by a reading from the thermistor in contact with the leaf surface. Apart from the reflective covering on the cup, no special precautions were taken to protect the cup from direct radiant energy during measurement although between measurement runs the sensor cup was stored in the container with silica gel.

An independent estimate of leaf temperature was made prior to the porometer measurement with an infrared thermometer (Everest Interscience, Model 110) with a 3° field of view. The thermometer was calibrated against a calibration source (Everest Interscience, Model 1000) with the emissivity set at 0.98. Fuchs and Tanner (1966) showed that infrared thermometer and thermocouple readings from single leaves agreed within 0.3°C with emissivity values measured between 0.96 and 0.97. The effect of the higher emissivity value that we used is to decrease apparent surface temperature by up to 0.5°C. This discrepancy is close to the combined accuracy of any two sensors used to measure leaf temperatures in the field. During measurement of leaf temperature the infrared thermometer was held at 90° to the natural leaf position and 150 to 200 mm away. Only the upper surface temperature was taken and it was assumed for calculation purposes that the lower surface had a similar value. Measurements were made on clear days except for four readings taken in the glasshouse during one day which was intermittently cloudy. All measurements were taken within two hours of solar noon. Concurrent readings from a Thesis aspirated psychrometer for air vapor pressure deficit (AVPD) were made together with solar radiant flux density (LI 185 meter with LI SR 190 sensor) at a position about one metre above the plant canopy. A comparative set of measurements were made on one day (13 April 1983) when a small area of plants was completely shaded from direct radiant energy with heavy canvas.

RESULTS AND DISCUSSION

The relation between temperature measured with the porometer thermistor (T_{TH}) in contact with the leaf, and that of the leaf as measured with the infrared thermometer (T_{IR}) and ambient (T_A) temperature are shown in Fig. 1. Under the evaporative conditions of these experiments, temperatures of exposed leaves (estimated from T_{IR}) were greater than ambient when $T_A < 27$°C and were less than ambient when

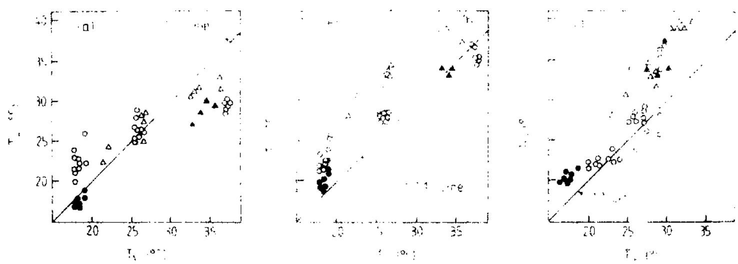

Fig. 1. Comparison of temperature measurements T_A, T_{TH} and T_{IR}. (○) Exposed leaves in the field; (●) shaded leaves in the field; (△) exposed leaves in the glasshouse (▲) glasshouse measurements during a period of cloudy conditions.

$T_A > 27°C$ (Fig. 1a). Shading of leaves in the field caused their temperature to be at or slightly below ambient temperature.

The thermistor-recorded leaf temperature was generally always above ambient except for the very high temperature values in the field (Fig. 1b). Reducing impinging radiant energy by shading, or as the result of cloud cover, causes T_{TH} to be similar to T_A. A check of the effect of the porometer measurement on leaf temperature by measuring it with the infrared thermometer before and after the sensor cup was attached showed a non-significant difference of $-0.2°C$. This lack of change in leaf temperature indicates that shading and evaporative cooling accompanying the porometer measurement offsets any heat transfer from the normally warmer porometer body (Fig. 1c).

If the temperature measured by the infrared thermometer (T_{IR}) is taken as true leaf temperature (T_L) then the porometer thermistor registered a temperature close to T_L when $T_A < 27°C$ in the field. When T_A is $> 27°C$ vapor pressure deficits (AVPD, Table I) are generally high and thermistor readings are closer to T_A than to T_L.

Thermistor temperature values measured in the glasshouse are generally well above both T_A and T_{IR} except for the cloudy period which caused T_{TH} to be close to T_A (Fig. 1b). This cloudy period (essentially a shading effect) was still insufficient to cause T_{TH} to approach T_{IR}. Thus the elimination of impinging radiant energy reduced T_{TH} by an average of 4.9°C and T_{IR} by 2.9°C, but T_{TH} was still overestimating T_L by about 6°C.

The temperature measured by the porometer thermistor is a composite of effects from both T_A and T_L. Although the thermistor bead touches the leaf surface during measurement it may not reflect actual leaf temperature since the cup body itself has a large thermal mass. The temperature that a leaf of a well-watered plant attains is determined by the balance between the net radiant energy and the latent heat flux to the air (Kanemasu et al., 1969; Jackson, 1982). This latter component is largely determined by AVPD and stomatal conductance. When AVPD is high, the temperature of fully exposed leaves on well-watered plants

TABLE I

Summary of observations made at the time of measurement of leaf diffusive conductance

Date	Field (F) or Glasshouse (G)	T_A range (°C)	Radiant flux density ($W m^{-2}$)	Mean AVPD (kPa)	Mean $T_L - T_A$ (°C)
15 Nov. 82	G	34.4–36.4	730	4.0	−4.7
18 Nov. 82	G	25.8–26.7	800	2.2	+1.4
23 Nov. 82	G	32.5–33.6	820	3.0	−1.5
18 Jan. 83	F	25.4–26.0	1075	2.3	+1.2
22 Jan. 83	F	37.0–37.5	1100	5.2	−8.1
13 April 83	F sun	17.8–18.3	690	0.9	+4.9
	F shade	17.8–18.3	—	0.9	−0.9

(with high stomatal conductance) can be considerably below ambient. Conversely, low AVPD conditions can result in $T_L > T_A$ (see Fig. 1a). This relationship is clearly shown in Fig. 2 where the temperature difference between leaf and air is strongly related to AVPD as has been indicated by Jackson (1982) for well-watered plants.

When $T_L \neq T_A$, it is apparent (Fig. 1c) that T_{TH} does not truly reflect the temperature of the evaporating surface, i.e. the leaf. This situation leads to two possible errors in the estimate of C_L. First, if T_{IR} rather than T_{TH} is used to calculate C_L, values of C_L increase (Fig. 3) indicating that when $T_L < T_A$ (usually when $T_A > 27°C$ in the field) an underestimate of C_L results. For example, data from 22 Jan. 1983 when both ambient temperature and AVPD were very high, shows that mean C_L values using T_{TH} underestimated C_L values using T_{IR} by an average of 36% from 20 comparative readings.

A second error arises when there is a temperature difference between the leaf and cup. The calibration procedure assumes that the evaporating surface and the porometer cup are at the same temperature and thus that water vapor diffuses along a vapor density gradient from the saturated evaporating surface into the drier porometer cup. The effects of a temperature gradient from the evaporating surface to the cup were discussed by Morrow and Slatyer (1971b). Their analysis was confined to the situation where $T_L > T_A$, a situation most likely to exist under controlled environment conditions and mild evaporative conditions (AVPD < 2.6 kPa, Fig. 2) in the field. If their analysis is extended to examine the case where $T_L < T_A$ an estimate of the size of the error (Fig. 4) in the calculated value of C_L can be made. The curves in Fig. 4 were generated from eq. 3 of Morrow and Slatyer (1971b) viz,

$$\frac{(r_p + r_l')/\Delta t'}{(r_p + r_l'')/\Delta t''} = \frac{(\rho_l' - \rho_p')}{(\rho_l'' - \rho_p')} \quad (3)$$

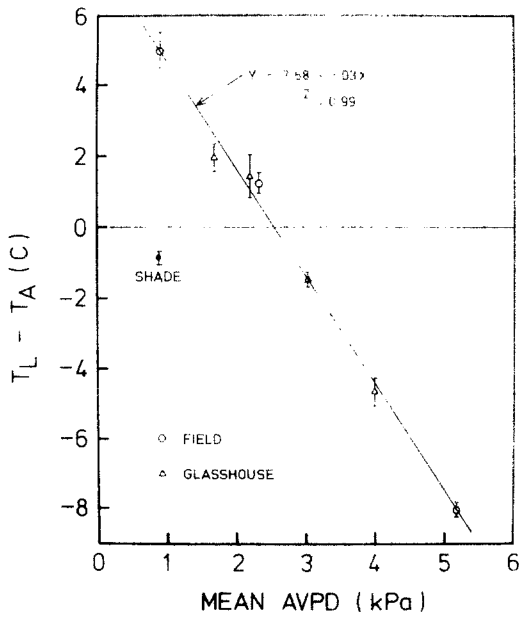

Fig. 2. Relationship of the leaf temperature T_L, ambient temperature T_A difference to mean vapor pressure deficit AVPD during the measurement period. Bars around mean points are SE estimates.

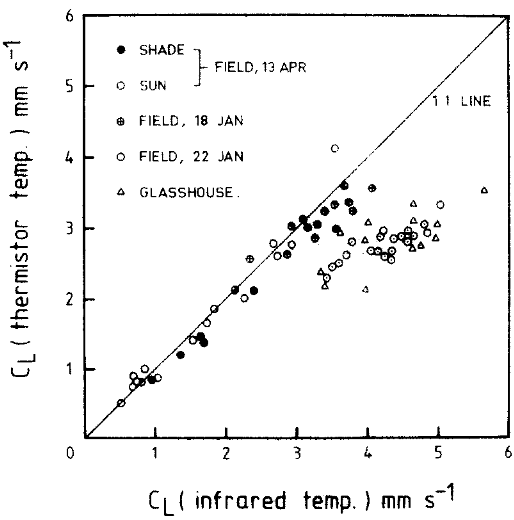

Fig. 3. Comparison of leaf diffusive conductance C_L ($mm\,s^{-1}$) calculated either using the thermistor measured temperature or the infrared thermometer measured temperature.

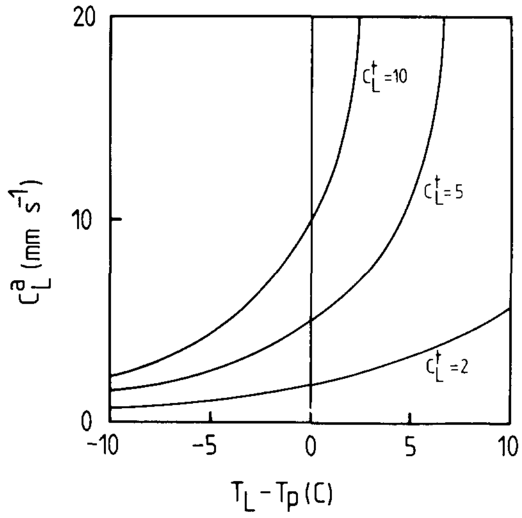

Fig. 4. Relationship of the apparent leaf diffusive conductance C_L^a to the temperature differential between the leaf T_L and the porometer cup T_p at different values of true leaf diffusive conductance C_L^t. The analysis was made assuming $T_p = 30°C$, RH of the cup = 20% and a cup diffusive conductance of 5 mm s^{-1}.

where r is resistance (s cm^{-1}), t is transit time (s), ρ is water vapor concentration (g cm^{-3}), subscripts p and l refer to the porometer and leaf respectively, and the superscript (′) refers to a given leaf and porometer temperature while the superscript (″) refers to the case when the leaf is at a temperature which is different from that of the porometer. Thus r_l' is the "apparent" leaf diffusive resistance which is calculated assuming that leaf and porometer temperature are equal, i.e. $T_L = T_p$ while r_l'' is the "true" leaf diffusive resistance which accounts for the fact that $T_L \neq T_p$. Equation 3 was rearranged to give conductance rather than resistance values and Fig. 4 was then constructed. In addition, the following assumptions (also used by Morrow and Slatyer (1971b)) were made: (1) porometer cup temperature, T_p was 30°C; (2) timing of the change in cup humidity occurred over a narrow range with 20% relative humidity as the mid point; (3) the cup configuration had a diffusive conductance of 5 mm s^{-1}; and (4) the leaf was a saturated surface.

Examination of Fig. 4 shows that when leaves have a "true" diffusive conductance (C_L^t) of 5 mm s^{-1} the apparent conductance (C_L^a) with $T_L - T_p = -5°C$ will be underestimated by 46%. This error becomes slightly less as the diffusive conductance becomes smaller. If assumption (1) above is changed such that the porometer cup temperature T_p increases from 20°C to 40°C, with $T_L - T_p = -5°C$ and $C_L^t = 5$ mm s^{-1}, the underestimate changes from 49% to 37%. By comparison, when T_p is at 30°C and $T_L - T_p$ changes from −5 to −10°C the underestimate changes from 46% to 70%. This indicates that the error is more sensitive to the temperature difference ($T_L - T_p$) than to the absolute value of T_p and thus is more critical on well-watered plants where ($T_L - T_p$) can be large.

The analysis by Monteith and Bull (1970) also indicated that the error associated with a temperature difference was greater than that associated with the absolute temperature. For well-watered plants they estimated the error associated with the absolute temperature to be about 10% °C^{-1} and for a temperature difference between leaf and cup to be about 13% °C^{-1}. This compares with our estimates from field-measured values of 4 to 6%°C^{-1} and 7 to 9%°C^{-1}, respectively.

It should be noted that because of the location of the thermistor on the porometer cup T_{TH} may not necessarily equal T_p although it is closely related, as discussed previously. However, no independent measures of T_p were made so, for the purposes of this paper, it was assumed that $T_p = T_{TH}$.

The above considerations show that when the diffusion porometer is used in a situation where $T_L < T_A$ estimates of C_L^a so obtained will be in error with the magntidue of the error related to AVPD. If the effects of inaccurately measuring leaf temperature and having a leaf to cup temperature difference are additive then calculated values of C_L^a may be 96% below C_L^t for $T_L - T_p = -8$°C and 32% below for $T_L - T_p = -2$°C.

In the field situation where comparison is made between the C_L^a values of well-watered plants and those from a drying treatment the errors will reduce the sensitivity of the measurement to distinguish between the two treatments for the following reasons. With well-watered plants C_L^t will be high, T_L is likely to be $< T_A$ when highly evaporative conditions exist and so C_L^a will be an underestimate. For the drying treatment C_L^t is likely to be smaller than for well-watered plants but T_L may become $> T_A$. Thus C_L^a for this treatment will be an overestimate of C_L^t.

The reduction in the range of C_L^a caused by the effects of these errors helps to explain why measures of diffusive conductance have been less discriminating than other measures of plant water status (Meyer and Green, 1981; Sojka and Parsons, 1983). Many other authors (listed by Sojka and Parsons, 1983) have found disturbing levels of scatter in data collected with porometers such as used here.

Most authors who have discussed the theory of operation of the diffusion porometer have mentioned the need to have leaf and cup temperature the same. One suggested method of achieving this (Morrow and Slatyer, 1971b) is by shading both leaf and cup until both, presumably, tend to approach T_A. However in the field situation this condition is unrealistic and impractical to achieve as shown by the shading results on 13 April 1983 (Fig. 1). Shading did cause T_{TH} to approach T_A but the response time was quite long (≈ 0.5 h) and T_{TH} was still greater than T_L because the leaves were transpiring. Leaf temperature would need to be assessed prior to cooling or heating the sensor cup to the same temperature. The technique would thus no longer be viable in the field.

The problem of incorrect leaf temperature measurement can be overcome using an independent measurement, thermally isolated from the porometer body. The problem of leaf to cup temperature differential is less amenable to solution. Recently, Gay (1983) has developed an analysis to correct transit times for situations where there is a temperature differential between leaf and porometer. He also demonstrates the seriousness of the errors involved if the temperature differential is left unaccounted. Further work is needed to assess his approach under field conditions. However, until this or some other method is shown to account for the errors, values of C_L obtained from the porometer used here must be regarded as qualitative only.

LIST OF SYMBOLS

AVPD	Air vapor pressure deficit (kPa)
C_L	Leaf diffusive conductance (mm s^{-1})
C_L^a	Apparent leaf diffusive conductance
C_L^t	True leaf diffusive conductance
T_A	Ambient temperature (°C)
T_{IR}	Leaf temperature measured with an infrared thermometer
T_L	True leaf temperature. Assumed $T_L = T_{IR}$
T_p	Porometer cup temperature. Assumed $T_p = T_{TH}$
T_{TH}	Temperature measured with the porometer thermistor

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the technical assistance given by R.L. Sides and N.S. White during collection of data.

REFERENCES

Fuchs, M. and Tanner, C.B., 1966. Infrared thermometry of vegetation. Agron. J., 58: 597—601.

Gay, A.P., 1983. Transit time diffusion porometer calibration: an analysis taking into account temperature differences and calibration non-linearity. J. Exp. Bot., 34: 461—469.

Jackson, R.D., 1982. Canopy temperature and crop water stress. Adv. Irrig., 1: 43—85.

Kanemasu, E.T., Thurtell, G.W. and Tanner, C.B., 1969. Design calibration and field use of a stomatal diffusion porometer. Plant Physiol., 44: 881—885.

McCree, K.J. and van Bavel, C.H.M., 1977. Calibration of leaf resistance porometers. Agron. J., 69: 724—726.

Meyer, W.S. and Green, G.C., 1981. Plant indicators of wheat and soybean crop water stress. Irrig. Sci., 2: 167—176.

Monteith, J.L. and Bull, T.A., 1970. A diffusive resistance porometer for field use. II. Theory, calibration and performance. J. Appl. Ecol., 7: 623—638.

Morrow, P.A. and Slatyer, R.O., 1971a. Resistance measurements with diffusion porometers: precautions in calibration and use. Agric. Meteorol., 8: 223—233.

Morrow, P.A. and Slatyer, R.O., 1971b. Leaf temperature effects on measurements of diffusive resistance to water vapor transfer. Plant Physiol., 47: 559—561.

Slavik, B., 1974. Methods of studying plant water relations. Ecological Studies 9 Academic Publ. House of the Czech. Acad. Sci, Prague, Springer.
Sojka, R.E. and Parsons, J.E., 1983. Soybean water status and canopy micro-climate relationships at four row spacings. Agron. J., 75: 961–968.
Walker, G.K. and Hatfield, J.L., 1983. Stress measurement using foliage temperatures Agron. J., 75: 623–629.