MEASUREMENT OF WATER POTENTIAL USING *IN SITU* THERMOCOUPLE HYGROMETERS

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I. INTRODUCTION

During the past decade, the potential energy of water in plants has gained wide acceptance as a fundamental measure of plant water status (Hsiao, 1973). Such acceptance has both theoretical and practical applications. Water potential gradients can be used to predict the direction of water movement in the soil, plant or atmosphere. If the liquid and vapor conductivities in this system are known, rates of water movement can be predicted and vice versa (Milburn, 1979). Water stress of plants may be inferred from measurements of water potential, as this thermodynamic quantity appears to be most closely related to the physiological and biochemical processes which control plant growth (Kramer, 1969; Begg and Turner, 1976; Milburn, 1979; Turner and Begg, 1981). Other methods of determining plant water stress involve soil water potential measurements or rate of evapotranspiration. Kramer (1972) points out that such determinations may be misleading. He maintains that the only reliable indicators of plant water stress are measurements on the plants themselves, as they integrate all internal and external factors determining the amount of stress at a particular time. The water relations of pasture plants have been discussed by Redmann (1976) and Brown (1977) and their responses to water deficits by Hsiao (1973) and Turner and Begg (1978). Water relations are affected by and affect many agricultural practices and occurrences: influences of water on microbial decomposition of crop residues (Myrold _et_ _al_., 1981); the effect of fire and the fire regime on grassland plant water relations (Savage, 1980; Savage and Vermeulen, 1983); drought responses of crops (Sojka _et_ _al_., 1979) being a few examples.

This review discusses some of the problems associated with the field use of _in_ _situ_ hygrometers for the non-destructive measurement of soil and leaf water potential, including measurement techniques associated with psychrometric and dewpoint methods.

II. HISTORICAL REVIEW

Spanner (1951) developed a thermocouple psychrometer technique for leaf water potential measurement of detached material. Richards and Ogata (1958) used a similar instrument, but with a small silver ring at the junction of the thermocouple, to measure soil water potential. A major limitation of the field use of soil and leaf hygrometers is the temperature dependence of the measurement techniques used for converting measured voltages to water potential (Savage, 1982; Savage et al., 1983a; Savage and Cass, 1983a). First attempts at water potential measurements of intact leaves were by Lambert and van Schilgaarde (1965) and Lang and Barrs (1965). In the latter case, a complicated temperature controller was used to eliminate temperature gradients. As early as 1972, Hoffman and Rawlins expressed the view that routine measurement of leaf water potential on intact plants in the field was possible. However, to date, very few researchers have attempted in situ field measurements of leaf water potential (Table I) largely because of problems associated with fluctuating temperature and temperature gradients within the hygrometer, sealing of the hygrometer chamber to the leaf, shading of the leaf by the hygrometer, and possible effects of resistance to water vapor diffusion by the cuticle when the stomates are closed (Savage, 1982; Savage et al., 1983c).

The principle of thermocouple psychrometry was first described by Hill (1930), who used aqueous solutions. He claimed that the method had been used by his co-workers since 1913. Spanner (1951) showed that it was possible to measure water potential using a thermocouple in vapor equilibrium with a leaf sample (psychrometric method). There have, however, been many modifications to the original Spanner psychrometer (Millar, 1971a,b; Chow and de Vries, 1973; Campbell and Campbell, 1974; Millar, 1974; Brown, 1976; Brown and Johnston, 1976; Campbell, 1979; Brown and Collins, 1980). The theory of psychrometry was developed by Rawlins (1966) and Peck (1968, 1969). An alternative hygrometric technique that uses the same thermocouple, the dewpoint technique, was first proposed by Neumann and Thurtell (1972), and modified by Campbell et al. (1973). The psychrometric and dewpoint techniques are currently the most popular. Other techniques for water potential measurement that have been developed are discussed by Slavik (1974). Psychrometric and dewpoint techniques appear to provide similar results although no field comparisons have apparently been attempted. There is some evidence indicating that the dewpoint method results in water potential measured under [illegible] conditions (Durand-Campero and Wiebe, 1981).

Thermocouple hygrometers have been used for measuring [illegible] various conditions and in many different applications. Some of the uses of thermocouple hygrometers in water relations research have appeared in Wiebe et al. (1971) and Brown and van Haveren (1972). Brown (1970) proposed that they could be used to measure the inflammability of pasture material. Wiebe (1981) and Wiebe et al. (1981) measured water potentials ranging from free water to oven dryness. Brown (1972) determined leaf osmotic potential using psychrometers and Oosterhuis (1981) used these instruments to investigate osmotic adjustment in cotton roots and leaves. Water relations of mine dumps and snow packs have been investigated (van Haveren, 1972). Walker et al. (1983) used these instruments in a field program to measure total and osmotic water potential of winter wheat. Wilson et al. (1979) determined the water relation characteristics of grasses and legumes while Richter (1978) and Kyriakopoulos and Richter (1981) investigated pressure-volume curves. Other workers have developed and pioneered the measurement of water potential in various organs of the plant, such as germinating peas (Manohar, 1966a,b,c), tree trunks (Wiebe et al., 1970), leaves (Campbell and Campbell, 1974), stems (Michel, 1977), pine needles (Roberts, 1977), and roots (Nnyamah and Black, 1977b; Nnyamah et al., 1978). Hygrometers have also been used to investigate the role of water potential in microbial growth and development of plant disease (Cook and Papendick, 1978).

Apart from water potential measurement on plants, the main application of hygrometry has been at measurement of soil water potential. Initially, these measurements were performed on small, fragmented soil samples using sample holders in which the thermojunction is contained above the soil sample (Richards and Ogata, 1958). More recently, a multiple sample chamber, used for soil or leaf water potential measurements, has been designed (Campbell et al., 1966). However, use of these techniques requires destruction of the soil or leaf system and therefore these measurements cannot be regarded as being in situ.

The use of screen-caged thermocouple psychrometers for measurement of leaf water potential requires destruction of the leaf while generally non-destructive measurement of water potential is preferred (Walker, Oosterhuis and Savage, 1984). For this reason, there is much interest in the in situ measurement of water potential (Brown, 1977). However, measurements of plant tissue water potential components still require that detached samples be used (Boyer, 1965). In situ thermocouple leaf hygrometers allow continuous monitoring of leaf water potential and avoid errors which may arise from excision, such as mixing and [illegible] changes ([illegible] et al., 1976) in tissue water (Baughn, 1974 p 12). Using these instruments, it is possible to investigate the effect of any induced perturbation of the plant on the leaf water potential, in the field, without removal of material from the plant. Similarly, use of *in situ* soil hygrometers avoid the effects of soil desiccation, structure destruction and perturbation of the intact root environment which accompanies sampling of the soil for water potential measurements.

Measurements of plant water potential using thermocouple hygrometers was reviewed by van Haveren and Brown (1972) and Brown (1977) and that of soil water potential by Rawlins (1976).

III. ISOTHERMALITY

Rawlins and Dalton (1967) identified four ways in which temperature effects measurement of water potential by thermocouple hygrometry:

a. through the Kelvin relationship between water potential ψ and relative humidity e/e_o [$\psi = (RT/\bar{V}_w) \ln(e/e_o)$ where R is the Universal gas constant, T is the Kelvin temperature and $\bar{V}_w$ is the partial molar volume of water];

b. through the temperature dependence of the relationship between wet-bulb depression and relative vapor pressure (Klute and Richards, 1962);

c. differences in temperature between the reference junction of the thermocouple and the sample arising from the presence of a temperature gradient in the sample-hygrometer system;

d. changes of temperature within the cavity formed by the hygrometer and sample will alter the relative humidity of the air in the cavity if water vapor cannot be exchanged with the surrounding system (Wiebe *et al.*, 1977).

The magnitude of the errors in measured water potential introduced by these four temperature effects varies. In the case of the temperature dependence of water potential and wet-bulb depression on relative humidity, the errors are relatively small, being about 0.3 and 2 %/°C respectively (Rawlins and Dalton, 1967). In a more formal analysis, Savage *et al.* (1983a) found this error to vary with temperature, ranging between about 10 % at 0 °C and 3 % at 40 °C for the psychrometric mode and about 7 % and 1.5 % at 0 and 40 °C respectively for the dewpoint mode. This source of error may be adequately controlled by adopting suitable calibration procedures which take account of the temperature dependence of the hygrometer sensitivity (Sections IV.A and IV.B).

Rawlins and Dalton (1967) stated that because of the effect of temperature changes on relative humidity, it had been necessary to control the temperature of the hygrometer chamber to within 0.001 °C for accurate water potential measurement. This precluded measurement of water potential in situ, outside the laboratory. Evidence for this may be inferred from the few field studies conducted to date (Table I). Rawlins and Dalton (1967) however, in a theoretical analysis, showed that with suitable design, it was possible to reduce the major effects of temperature fluctuation in soil hygrometry. Accordingly, it was theoretically possible to measure total water potential in the field, and they constructed a soil hygrometer which Rawlins et al. (1968) used to measure the water potential of a soil column placed in a greenhouse.

A more serious source of error arises from the presence of temperature gradients across the sensing junction and sample system. The nature of temperature gradients in leaf-atmosphere systems as opposed to soil systems differentiates the response of leaf and soil hygrometers in such systems (Sections V and VII respectively).

IV. MEASUREMENT TECHNIQUES

A. PSYCHROMETRIC TECHNIQUE

Peck (1968) showed that at steady state, the voltage following cooling uniquely determines the volumetric water potential (Savage, 1978) corresponding to a salt solution of known concentration (Lang, 1967; Campbell and Gardner, 1971). In theory, this steady state point appears easily determined, but in practice its definition has been one of the problems associated with thermocouple psychrometry (Bristow and de Jager, 1980). During condensation of water on the thermocouple junction, steady state is not reached within about 1 s as claimed by Peck (1968) (Fig. 1); the time for a constant voltage output to be achieved during cooling is greater than 60 s. In practice, this time period is too long and most workers have terminated cooling prior to attainment of steady state (during condensation). Consequently, during evaporation, a dis-equilibrium exists and voltage (corresponding to the wet-bulb temperature) will be dependent on the duration of cooling. It is therefore necessary to standardize procedures and use a cooling time of say 20 [illegible] water potentials greater than -3 500 kPa or 60 s for lower values (Savage, 1982).

The time dependent psychrometer output voltage (Fig. 1) indicates the temperature difference between the sensing and reference junctions as a function of time, due to the sensing junction being cooled for a specified time. The output voltage resulting from this temperature difference is given by $V = S_c(T - T_j)$ where S_c is the Seebeck coefficient (μV/K), T the reference junction temperature and T_j the sensing junction temperature. The curve AB of Fig. 1 represents the cooling cycle. Wiebe (1983) photographed water condensation on Peltier cooled thermocouple psychrometers. His observations show that many minute droplets condense on the entire sensing thermocouple within a second of being cooled and does not, as is predicted from theoretical arguments, form a uniform film of water on the junction.

At the cessation of the cooling cycle, the junction temperature T_j changes abruptly (indicated by curve BC of Fig. 1). Evaporation of the droplets on the thermojunction slows the rate of approach of the junction temperature T_j to the block temperature T, as a result of absorption of latent heat energy from the thermojunction. The voltage corresponding to point E uniquely defines the water potential for a given psychrometer at a specified temperature (Savage et al., 1981a,c). Theoretically, the line EF should be horizontal. The slight slope in the line could be due to the fact that a uniform water film does not form, with portions of the sensing junction not in direct contact with the water droplets (Wiebe, 1983).

In order to overcome the effects of Joule heating on thermocouple psychrometer water potential determination, Slack and Riggle (1980) used a cooling current of 3 to 4 mA for 15 s with the psychrometer output read 6 s after the cessation of cooling. Hoffman et al. (1969), Schimmelpfennig (1972) and Briscoe and Tippetts (1982) developed electronic switch systems that displayed or memory stored the voltage some short time after the cessation of cooling.

1. Psychrometer Calibration

Field measurement of water potential can only be as accurate as the calibration of the hygrometer used (Easter and Sosebee, 1974). Hygrometers are calibrated using segments of filter paper [illegible] saturated with salt solution of known water potential (Lang, 1967;

Campbell and Gardner, 1971). The leaf or soil hygrometer assembly is allowed to reach vapor and thermal equilibrium with the salt solution. No deflection, ignoring transient spikes, when the function switch is rotated from "READ" to "INPUT SHORT" indicates thermal equilibrium. This test should be performed prior to each water potential measurement. The test for vapor equilibrium is to repeat a set of measurements. If the voltage corresponding to the wet-bulb temperature is the same for each repeated measurement, then vapor equilibrium exists. Some workers have decreased the waiting period between consecutive measurements by using the "HEAT" mode available on some commercially available hygrometer microvoltmeters. This mode reverses the Peltier current causing heating of the sensing thermojunction relative to the two reference junctions. However, as Wiebe (1983) points out, the water driven off the sensing thermojunction condenses on any nearby surface such as that of the chamber wall. Any condensed water, which may also result from temperature gradients (Wiebe and Brown, 1979), will increase the local relative humidity and cause erroneously high water potential readings. In view of these problems, it is inadvisable to hasten consecutive or repeated measurements by using the "HEAT" mode.

The voltage-water potential relationship for thermocouple psychrometers is temperature dependent. To account for this, Wiebe et al. (1970) used an empirical equation for correcting voltages V corresponding to a particular water potential and block temperature T to V_{25}, the output voltage at 25 °C:

$$V_{25} = V/(a + bT). \tag{1}$$

The a and b values were determined by measuring the corresponding output voltage of a 0.5 mol/kg KCℓ solution (Meyn and White, 1972) at several temperatures between 4 and 25 °C (Wiebe et al., 1970). Brown (1970) found a = 0.325 and b = 0.027 $(°C)^{-1}$. At present the most common procedure is to calibrate the psychrometer at a temperature near 25 °C and then convert measured voltages at temperature T (≠ 25 °C) using Eq. (1) with a = 0.350 and b = 0.026 $(°C)^{-1}$ (Wiebe et al., 1970; Bristow and de Jager, 1980) to 25 °C. The (near) 25 °C calibration curve is then used to obtain Ψ_{25}, the water potential at 25 °C. Merrill and Rawlins (1972) used a similar technique for correcting measured voltages to 25 °C, but used various a and b values (Table II). From the data of Meyn and White (1972), the ratio of water potential to measured voltage, Ψ/V, is a linear function of temperature T.

However, Wheeler (1972) found that this was not the case for his empirical data. Wheeler avoided extensive regression analysis of his data through the use of graphical calibration curves. Wheeler et al. (1972) further state: "the temperature dependence of the psychrometers are themselves temperature dependent and a single bivariate equation could not be fitted to the calibration data."

The common procedure of correcting leaf psychrometer calibration slopes (or voltages) at temperature T to that at 25 °C using Eq. (1) has the main weakness that these values cannot be expected to apply to all psychrometers. Savage et al. (1981a) reviewed calibration data and calculated a and b values for a number of leaf and soil psychrometers (Table 2). In general, each psychrometer will possess a unique set of a and b values, as is evident from the differing values shown in the table.

2. Calculation of Error in Water Potential Measurements Using Thermocouple Psychrometers

One of the major limitations of the field use of psychrometers is the temperature dependence of the measured voltage and water potential relationship. The calibration models, incorporating temperature dependence, of Savage et al. (1981a,c), Brown and Bartos (1982) and Savage et al. (1982) are applicable to conditions where temperature is accurately controlled. Consequently, for field conditions, the calculation of statistical confidence limits for measured water potentials is not possible. Recently, however, a calibration model applicable to leaf psychrometers used in field conditions has been proposed (Savage, 1982; Savage and Cass, 1983a; Savage et al., 1983a). One source of error in field studies is sample and sensing junction temperature gradients (zero offsets). However, leaf psychrometer zero offsets may be substantially reduced by adhering to the precautions of Savage et al. (1983d) or Turner et al. (1983). In the case of soil psychrometers, Wiebe and Brown (1979) investigated temperature gradient effects on in situ psychrometer measurements of soil water potential (Section VII.C).

It has been proposed that the relationship between T vs $(V - V_o)/\psi$, where V_o is the measured output voltage corresponding to a water potential of 0 kPa, is linear (Savage et al., 1983a). The relationship may be determined for a number of water potential values, the data grouped and the slope S and intercept I determined where $T = I + S(V - V_o)/\psi$. Hence, for a given measured voltage V corresponding to an unknown leaf water potential, ψ,

$$\psi = S(V - V_o)/(T - I). \tag{2}$$

In practice, the parameter V_o would have to be determined prior to determining the voltage-water potential relationship. There is some evidence indicating that V_o is temperature independent (Calissendorff and Gardner, 1972). The square of relative error in water potential, $\sigma(\psi)/\psi$, may be computed from the sum of squares of $\sigma(S)/S$, $\sigma(V')/V'$, $\sigma(T)/(T - I)$ and $\sigma(I)/(T - I)$, the error in S, V', T and I respectively (Savage et al., 1983a), where $V' = V - V_o$. The subcomponent errors may be calculated given $\sigma(S)$ and $\sigma(I)$, which are determined by the calibration (linear) relationship of T on $(V - V_o)/\psi$, and $\sigma(V')$, which is determined by the actual field measurements and $\sigma(T)$, which is assumed to be ±0.25 °C. An expression for $\sigma(V')/V'$ has been presented by Savage (1982):

$$\sigma(V')/V' = [((0.015\ dV + 0.0147\ T\ dV)/10.4)^2 + (0.05\ V')^2]^{\frac{1}{2}} \tag{3}$$

where the first term was obtained by Brown and Bartos (1982) for screen-caged thermocouple psychrometers and the latter by Savage (1982) for leaf psychrometers, assuming that field voltages may be measured to within 0.05 µV. The subcomponent errors and total error in water potential for a given thermocouple psychrometer is shown for a range of temperatures (Table II). Of note is the increase in $\sigma(I)/(T - I)$ and $\sigma(T)/(T - I)$ as T approaches I, generally a negative quantity (Table II). The value of I ranged between about -23 and -8 °C for data from the literature (Table II). In general, $\sigma(S)$ and $\sigma(I)/(T - I)$ contribute significantly to the overall error (Table II). Assuming that zero offsets are small, calibration errors contribute significantly to the error in water potential measurement; hence the need for accurate calibration.

B. DEWPOINT TECHNIQUE

Neumann and Thurtell (1972) introduced a technique for measuring the dewpoint temperature depression in a small sealed cavity adjacent to a leaf or soil surface. These authors showed that the chamber relative humidity can be calculated by measurement of the dewpoint temperature T_{dp} and hygrometer temperature T. Hence the Kelvin equation may be applied to determine the water potential ψ.

Consider a hypothetical thermojunction whose temperature is determined only by latent heat energy transfer, that is, evaporation and condensation. If the junction is covered with water and is at a temperature $T_j > T_{dp}$, then water will evaporate from the junction until $T_j = T_{dp}$ (Wescor, undated). If $T_j < T_{dp}$, then water will condense onto the junction, again until $T_j = T_{dp}$. If heat energy transfer is _via_ latent heat only, then T_j will converge on T_{dp} (Campbell _et al._, 1973). Measurements by this technique should be relatively independent of the wetting characteristics of the junction and the size and shape of the water droplet formed on the junction (Neumann and Thurtell, 1972).

1. Setting of the Dewpoint Cooling Coefficient

In order to use a hygrometer in the dewpoint mode, it is necessary to eliminate the effects of all forms of heat energy transfer other than latent energy. This is achieved using a dry atmosphere in the hygrometer chamber and setting the cooling coefficient II (Campbell _et al._, 1973) to give a constant voltage output. Under these conditions, II = II_o. An analysis of variance by Savage (1982) indicated significant differences, for a given dewpoint hygrometer, in II_o as a function of the stationary voltage and voltage range used. There were also significant II_o differences between hygrometer types (Merrill leaf cutter hygrometers, Wescor leaf, soil, and chamber hygrometers). It is recommended that only the "0 TO 100" µV range be used and that the cooling coefficient be defined as that corresponding to a stationary voltage of 25 µV for 2 minutes (Savage _et al._, 1981b; Savage, 1982).

2. Temperature Dependence of the Dewpoint Cooling Coefficient

Slope and intercept differences in the II_o vs T relationship between hygrometers are significant and probably arise from differences in the electrical resistance between hygrometers. As a result of these differences, Savage _et al._ (1981a,b) and Savage (1982) determined II_o as a function of the _in situ_ temperature range for each dewpoint hygrometer, but found this to be time-consuming. Instead, II_o may be corrected for temperature using:

$$II_o = II_o(T_o) + 0.7\ (T - 25) \qquad (4)$$

where II_o is the cooling coefficient at temperature T, and $II_o(T_o)$ is the value at temperature T_o greater than 20 °C. Wescor (undated) suggest a value of 25 °C for T_o. This relationship (Eq. 4) is not particularly accurate below 15 °C, and Savage et al. (1981b) recommend accurate determination of II_o at low temperatures.

3. Dewpoint Hygrometer Calibration

The dry atmosphere necessary for the determination of the dewpoint coefficent, is substituted by a piece of filter paper saturated with salt solution of known concentration. The voltage-water potential relationship should be determined for each hygrometer as there appears to be considerable variability between hygrometers (Durand-Campero and Wiebe, 1981). Other workers have also calibrated dewpoint hygrometers individually (Baughn, 1974; Savage et al., 1981b, 1982). The dewpoint calibration relationship is not as temperature dependent as the psychrometric (Section V.F), so that there is little increase in measurement accuracy if they are calibrated over a range of temperatures. Savage et al. (1982) presented a method for temperature correcting dewpoint hygrometer calibration slopes.

Although the dewpoint technique is less temperature dependent, there is variability between individual units (Baughn, 1974; Durand-Campero and Wiebe, 1981; Savage et al., 1981a), suggesting that the technique is not independent of junction (dry and wet) characteristics. This variability necessitates individual calibration for accurate measurement of water potential. Comparison of theoretical with empirical calibration curve slopes for a number of dewpoint hygrometers at different temperatures indicated that these instruments need only be calibrated at, eg. 25 °C, if the calibration slopes are corrected for temperature (Savage et al., 1982). These workers used the following equation to calculate the dewpoint hygrometer calibration slope, $S_d(c)$ (kPa/µV), at any temperature T:

$$S_d(c) = -S_d(T_o)\times 10^3 / [S_d(\text{theory};\ T_o)(6.30211 + 0.04462\ T)] \qquad (5)$$

where $S_d(T_o)$ is the empirical slope at temperature T_o and $S_d(\text{theory};\ T_o)$ is the calibration slope at temperature T_o calculated by setting $T = T_o$ in the equation:

$$S_d(\text{theory; } T) = -1000/[6.30211 + 0.04462\ T]. \tag{6}$$

A comparison between $S_d(c)$, based on $S_d(T_o)$ where T_o = 25 °C, and the empirically measured values at the same temperature yielded mean differences of ± 1 %. The magnitude of the error, relative to the measured value at that temperature, never exceeded 4 %.

4. Calculation of Error in Water Potential Measurements Using Dewpoint Hygrometers

A method for the estimation of the standard error in measured water potential, as a function of T, for hygrometers employed in the dewpoint mode has been proposed (Savage, 1982; Savage and Cass, 1983a; Savage *et al.*, 1983a). The approach employed is conceptually similar to the error analysis for the psychrometric technique (Section IV.A.2). Five main sources of error were identified:

a. calibration error at temperature T;
b. error due to predicting the value of the calibration slope at temperature $T = T_o$;
c. error due to incorrectly setting the dewpoint cooling coefficient II at a value II_o;
d. error in dewpoint voltage measurement;
e. error in temperature measurement.

Savage *et al.* (1983a) developed suitable mathematical expressions for each error term. The error arising from an incorrect setting of II_o has a number of subcomponents and is the major component of the total error in measured water potential. This error is determined by the multiplicative factor $K_p/S_d - 1$ where K_p and S_d are the respective psychrometric and dewpoint values for the slope of the voltage water potential curve for a given temperature T. Savage *et al.* (1983a) found that

$$K_p/S_d = A(T - I)^B \tag{7}$$

where A and B are empirical constants. This relationship indicates the interrelationship between the psychrometric and dewpoint techniques *via* the parameter I. At low temperatures, T approaches I (Table II) with resultant increase in K_p/S_d (Eq. 7) and hence the major component of the total error increases (Table III). Therefore at low temperatures, the dewpoint technique has little advantage over the psychrometric technique in terms of measurement error. In particular, the dewpoint error is more sensitive to zero drift error as it affects the dewpoint voltage V_d directly as well as indirectly _via_ a change in correct setting of the dewpoint coefficient value.

All parameters required for the application of the model of Savage _et al._ (1983a) should be known _a priori_ in order to compute the error value associated with a measured water potential value. The model has been applied to leaf hygrometer measurements but is also valid for screen-cage soil hygrometer measurements.

C. RECALIBRATION OF THERMOCOUPLE HYGROMETERS

Field use of screen-caged thermocouple psychrometers for soil water potential measurement has been discussed by Brown and Johnston (1976). Contamination of the thermocouple sensing junction during field use may necessitate recalibration of the hygrometer at some stage, either during use or at the end of the experiment. A decision on the recalibration of a given thermocouple hygrometer should be based on the outcome of a statistical test. In the case of a given thermocouple psychrometer, the original regression line was constructed by plotting T vs $(V - V_o)/\psi$ (Eq. 2). Approximate confidence (Snedecor and Cochran, 1980) limits for this linear relationship may be obtained from:

$$e(V'/\psi) + (t\ S_{y.x}/S)[1 + 1/n + e(V'/\psi)/(\mathrm{sum}(V'/\psi - e(V'/\psi))^2)]^{\frac{1}{2}}, \qquad (8)$$

where $e(V'/\psi)$ is the estimated V'/ψ value at temperature T (using the regression line equation), t is the Student's t value with n - 2 degrees of freedom, n is the number of data points of the regression line, $S_{y.x}$ is the standard error of T on V'/ψ for the regression line, and S is the slope value (Eq. 2). It is then relatively easy to determine whether or not the V'/ψ value for the new data point lies within the confidence interval calculated using Eq. (2), for a given temperature T. If not, the psychrometer should be fully recalibrated. Similar calculations can be performed to determine whether or not the dewpoint hygrometer calibration curve slope or the relationship between the dewpoint cooling coefficient (II_o) and temperature T, for a given dewpoint hygrometer, has altered since the last calibration process.

V. LEAF WATER POTENTIAL MEASUREMENTS

A. TEMPERATURE EFFECTS AND HYGROMETER INSULATION

A major problem associated with the field use of thermocouple leaf hygrometers is fluctuating thermal gradients within the apparatus under variable radiation and wind conditions. These cause temperature differences, between the measuring thermojunction and the leaf surface, which preclude an acceptable level of precision in the water potential determination. In order to damp rapid temperature fluctuations and reduce internal temperature gradients, Neumann and Thurtell (1972) placed a 12 mm layer of styrofoam insulation covered with aluminized mylar tape around their hygrometer. Hoffman and Rawlins (1972) placed a 25 mm layer of styrofoam on their units. Campbell and Campbell (1974) designed a hygrometer, similar to that of Neumann and Thurtell (1972), that covered both leaf surfaces (unlike that of Hoffman and Rawlins, 1972). This hygrometer, constructed from aluminium, covered an area of less than 3 cm^2 and less than 1 cm^2 of leaf was sealed in the chamber. The high thermal conductivity of aluminium ensures that leaf and chamber air temperature are nearly the same. In a field experiment, Brown and Tanner (1981) were able to reduce zero offsets, a measure of hygrometer temperature gradients, to less than 0.3 µV in magnitude using a 10 mm layer of styrofoam insulation covered with heavy aluminium foil which was painted white. White however will not reflect radiation of wavelengths greater than about 700 nm. Pallas et al. (1979) used leaf hygrometers in the field with small aluminium umbrellas to minimize thermal gradients. With this shading, they found that zero offsets were less than 1 µV in magnitude. If the umbrellas are too small, they need continual repositioning as the sun alters its position, but if too large, they shade a greater area of the leaf. Savage et al. (1983d) covered all surfaces of the hygrometer aluminium housing with thermal insulation (Scotch mount tape, 4009 by 3M, Industrial Tape Div.). A layer of about 12 mm of insulation material was applied to the top and bottom of the housing and about 6 mm to all sides except the non-slit side (side A of Fig. 2a). This arrangement minimized leaf shading, covering only 6 cm^2 of the leaf. The insulation material was covered with highly reflective aluminium foil. In cases when the abaxial leaf surface faced upwards, which resulted in exposure of the hygrometer lead wire to incoming solar radiation, they taped aluminium foil over the wire in order to reduce heat conduction to the hygrometer piston (Fig. 2b). Turner et al. (1983) modified their hygrometers "by replacing the aluminium block of rectangular cross section with a cylindrical block of similar material and size which could be more easily insulated."

In a field experiment, Savage et al. (1983d) measured zero offsets of between -0.1 and 0.6 µV for leaf hygrometers. Maximum values occurred when direct solar radiation entered the slit area, striking the hygrometer piston. Direct shorting of the binding posts of the hygrometer microvoltmeter using a short piece of copper wire indicated meter zero offsets that ranged between 0.1 to 0.2 µV. Measured zero offsets should therefore be reduced by this amount (G. S. Campbell, 1983, pers. comm.).

Savage et al. (1983d) noted that their aluminium and thermal insulation tended to accumulate static charge causing large zero offset voltages, which could be confused with large leaf and sensing junction temperature differences. They dissipated the charge accumulation by connecting the hygrometer earth lead wire to their chart recorder earth connection.

B. MODIFICATION OF THE LEAF ENVIRONMENT BY LEAF HYGROMETERS

Hygrometric techniques have become the standard method for water potential measurement (Boyer, 1966; Ike et al., 1978). The basic premise of in situ leaf water potential measurements is that the energy of water in equilibrium with the attached leaf gives a measure of that in the conducting elements of the stem xylem (Slatyer, 1966, 1967 p 153). If only a part of the leaf is enclosed by the hygrometer, it is assumed that the leaf water potential of the enclosed area is in equilibrium with the more or less unchanged water potential of the rest of the leaf (Slavik, 1974 p 63). Enclosing segments of leaves substantially modifies the leaf environment, possibly altering stomatal aperture, transpiration and water potential. It is likely that the local water potential will be that of the veins which traverse the leaf area covered by the hygrometer. This may differ from the water potential in the mesophyll or substomatal cavity. For this reason, the area of the leaf surface enclosed by the hygrometer should be as small as possible (Squire *et al.*, 1981). Since each stomate acts independently of all others (Lange *et al.*, 1971), covering part of the leaf should not affect the stomates of the uncovered leaf portion. Boyer (1972b) states that the thermocouple psychrometer probably indicates a spatial average for leaf tissue which implies that cells which are well below the tissue surface contribute to the net vapor flux density at the sensing thermojunction.

Some of the early workers enclosed whole leaves in their attempts at measuring lea water potential *in situ* (Lambert and van Schilfgaarde, 1965; Lang and Barrs, 1965 Manohar, 1966a,b,c). This interferes with normal transpiration, and therefore probabl changes the water potential of the leaf. Using dewpoint hygrometers that covered 25 cm^2 of the leaf (Table I), Neumann *et al.* (1973) claimed that their water potential measurements were not significantly different from values measured in adjacent exposed portions of wheat and sunflower. Their hygrometer covered most of the soybean leaflet and the measured value probably represented the water potential at the point where the petiolules of the three leaflets connected. Other workers used leaf hygrometers that covered a smaller fraction of the total leaf area: Hoffman and Splinter (1968a) used a unit that covered 2.9 cm^2 of the leaf; the silver foil hygrometer of Hoffman and Rawlins (1972) covered about 1.4 cm^2 of only one side of the leaf; the double-sided unit of Campbell and Campbell (1974) covered about 3 cm^2. Heat of respiration errors were overcome by heat-sinking the leaf. The unit of Campbell and Campbell (1974) was designed to achieve rapid uniform thermal equilibrium. Other, smaller designs, do not achieve this goal (Wiebe and Prosser, 1977; Savage *et al.*, 1983d).

C. EFFECTS OF CUTICULAR RESISTANCE ON MEASURED LEAF WATER POTENTIAL

Cuticular resistance to water vapor diffusion between the substomatal cavity and the sensing junction is a problem unique to leaf hygrometry. This resistance is not encountered in soil or solution hygrometry (Savage *et al.*, 1983c). Rawlins (1964) suggested that if vapor diffusion between the sample and the chamber air is obstructed by a barrier such as the leaf epidermis, observations of water potential can be in error as a result of non-equilibrium between the sample and the chamber air if either sources or sinks for water vapor are present in the chamber. However, Barrs (1965a,b) found good agreement between data collected using a Spanner psychrometer and a wet-loop psychrometer and argued that cuticular resistance did not cause error in the wet-loop device. Within the dark hygrometer chamber, the carbon dioxide concentration may be high so that the diffusion resistance of the cuticle-stomate system may delay equilibrium.

Zanstra and Hagenzieker (1977) found that leaf diffusion resistance may lower <u>in situ</u> water potential values obtained using silver-foil psychrometers claiming that this was not the case if the instruments were employed in the dewpoint mode, but presented no data in support of their claim.

Peck (1969) appears to be the first worker to have suggested that one method of reducing the equilibrium time would be to "slash" the leaf sample. He cautioned that excessive use of such a treatment would affect the water potential of plant tissue by the release of cell turgor pressure. Neumann and Thurtell (1972) were the first workers to actually attempt to reduce leaf cuticle resistance by dissolving the cuticle with xylene (Table I). Leaves treated in this way and left in hygrometers for periods of up to a week showed no visible damage in the treated area when the hygrometers were reopened. Neumann <u>et al</u>. (1974) compared water potentials measured using two hygrometers placed 100 mm apart on opposite sides of the midrib of a maize leaf, one pre-treated with xylene and the other pre-abraded with a razor blade. They found that potentials measured after these pre-treatments differed slightly over their range of measurements (> -800 kPa), particularly in their dry range.

As an alternative method for reducing the leaf diffusion resistance, Brown and Mc Donough (1977) used a thermocouple psychrometer, sealed on the abaxial leaf surface, with a cavity through the lower portion of the psychrometer which allowed radiation on to the adaxial leaf surface. Illumination of the hygrometer cavity section was first performed by Neumann and Thurtell (1972) who constructed a glass hygrometer so that the enclosed leaf section could be illuminated to open the stomates. They found rapid equilibration between the substomatal and hygrometer cavities was achieved. Both these techniques, however, enhanced the temperature gradients between the leaf and the hygrometer sensing junction, thereby introducing large errors into the measured values (see Section III).

Various other methods of reducing the leaf diffusion resistance have been used: scratching the leaf area with a razor blade (Richter, 1978); rubbing the leaf, using a cotton bud and a slurry composed of non-ionic detergent and carborundum 600 which consists of 40 µm particles (Brown and Tanner, 1981); gently rubbing the leaf with a mixture of detergent and #800 emery grit (Baughn and Tanner, 1976) or #600 emery grit (Ike et al., 1978); rubbing the leaf gently for 30 or 60 s with the index finger and a cotton cloth previously dipped in a slurry of distilled water, non-ionic detergent and carborundum 400 (60 µm particles) or 600 (40 µm particles) grit or calcined aluminium oxide sieved through a 75 µm sieve (Savage, 1982; Savage et al., 1983c); carefully rubbing the epidermis exposed to the hygrometer chamber with 500 (50 µm particles) grit carborundum (Turner et al., 1983). All these techniques scarify the epidermal cuticle, allowing increased water vapor diffusion. The type of abrasive, if used, and the method employed to apply it will depend on the nature of the leaf.

In a field experiment, Savage et al. (1983c) compared different abrasion treatments by sealing pairs of psychrometers on either side of the midrib of Citrus jambhiri plants. They found that the severity of abrasion affected the shape of the output voltage curve from the thermocouple psychrometer and that this shape may be used to indicate whether or not leaf diffusive resistance is affecting the measured water potential. They also obtained scanning electron micrographs of leaf areas abraded using cotton bud abrasion, 30 s (light) and 60 s (intensive light) abrasion and a coarse abrasion. The 30 and 60 s abrasion treatments resulted in greater surface damage than cotton bud abrasion. The 60 s treatment gave best comparison with pressure chamber measurements over the water potential range 0 to -3 000 kPa. Coarse abrasion produced fewer surface scratches but isolated cavities were observed where the epidermal layer was exposed (Fig. 3). Savage et al. (1983c) also measured the diffusive resistance of the abraded and adjacent unabraded areas under dark conditions. Intensive light abrasion reduced this resistance from 65.1 to 11.1 s/cm for a moderately stressed plant with a leaf water potential of -1 600 kPa.

The time required for vapor in the hygrometer cavity to reach equilibrium with that in the substomatal cavity depends on the state of the stomata prior to sealing the hygrometer against the leaf. In the case of well watered citrus plants, this time can be less than 15 min on cloudless days (Savage, 1982, unpublished data) but as large as 60 min under laboratory lighting conditions for abraded leaves (Savage et al., 1983c). H. H. Wiebe (1982, pers. comm.) suggested that if the chamber area of the hygrometer cavity were slightly increased, the amount of water condensing on the junction would not be a limiting factor affecting measured water potentials. Since the resistance of leaf tissue to cede water to the thermocouple junction is likely to increase in plants subjected to variable drying periods, Durand-Campero and Wiebe (1981) (in a controlled environment experiment) used longer cooling periods to obtain leaf psychrometric measurements of plants under water stress.

D. PRACTICAL FIELD ASPECTS

There are a number of details that have to be adhered to when using thermocouple leaf hygrometers for field water potential measurements. Some of these, namely leaf abrasion and isothermality, have already been mentioned (Sections V.A and V.C respectively). Another important aspect is cleanliness of the hygrometer cavity. The effects of contaminants on the thermocouple junction include reduction of voltage sensitivity to water potential as well as an increased difficulty in "plateau" identification in the case of the psychrometric method. Campbell (1972) discussed these problems and devised a simple test for chamber and sensing junction contamination.

Material, used to seal the hygrometer to the leaf surface, that has entered the hygrometer chamber should be removed using a toothpick or washing in petrol (petroleum). Following this, the hygrometer cavity is immersed in boiling distilled water, immediately washed in acetone and 4 mol/kg ammonium hydroxide (Campbell and Campbell, 1974; Savage *et al.*, 1983d), and finally cleaned with a jet of steam (H.H. Wiebe 1982, pers. comm.). Some commercially available hygrometers are difficult to clean as they have a protective screen covering the sensing thermojunction. A beeswax-lanolin mixture can be used to seal the hygrometer piston against the leaf (Campbell and Campbell, 1974). The relative amount of each constituent determines the rheological properties of the mixture. One of these properties, the temperature at which the mixture softens (T_s in °C) is related to the volume ratio of lanolin to beeswax (R) by the approximate relationship: $R = 20.76 - 0.43 T_s$ (Savage *et al.*, 1983d). Generally, a mixture that has a softening temperature 2 °C greater than the expected daily maximum block temperature should be used. Savage *et al.* (1983d) found that this mixture did not penetrate into the leaf tissue of *C. jambhiri* over a period of a week where maximum temperatures exceeded 35 °C. However, this mixture (and apiezon vacuum greases) did penetrate papaya and avocado leaves within hours after sealing the hygrometer against the leaf. In such cases a Parafilm (trade name) ring, which is solid below 50 °C, may be used as an alternative sealant (Brown and McDonough, 1977).

Various other materials have been used for sealing hygrometers to leaves: silicon stopcock grease (Lambert and van Schilfgaarde, 1965); apiezon Q vacuum grease (Lang and Barrs, 1965); two epoxy components mixed and applied during the dough stage to the psychrometer tip (Hoffman and Splinter, 1968a); water proof adhesive and petroleum jelly mixture (Calissendorff and Gardner, 1972); silver-impregnated, water-based conductive coating (Hoffman and Rawlins, 1972); apiezon M grease (Neumann and Thurtell, 1972); a Parafilm gasket lightly coated on both surfaces with petrolatum (Wiebe and Prosser, 1977); anhydrous glue for applying silver foil psychrometers to one side of the leaf (Zanstra and Hagenzieker, 1977); lanolin (Pallas and Michel, 1978); 90 % lanolin and 10 % beeswax (Pallas <u>et al</u>., 1979); 40 % paraffin wax and 60 % lanolin (Brown and Tanner, 1981); 50 % paraffin wax and 50 % anhydrous lanolin (Turner <u>et al</u>., 1983).

Sudden temperature changes within the measurement system and spurious voltage fluctuations in the electronic circuitry are serious problems in field experiments (Brown and Tanner, 1981). These fluctuations can be reduced or eliminated by covering the hygrometer lid with aluminium foil tape and the inside of the lid with styrofoam (Savage <u>et al</u>., 1983d). The hinged cover of the meter should not be opened fully whenever wires are connected or the function switch operated, thus preventing direct radiation from entering the unit. Conduction of heat along the hygrometer lead wires to the meter was reduced by mounting a polystyrene block covered with aluminium foil tape to the side of the meter. This eliminated the apparent temperature gradients and fluctuating zero offsets.

Wind may cause the seal between leaf and hygrometer to be broken. To avoid this, Savage <u>et al</u>. (1983d) secured the stem or branch to the metal rod supporting the thermocouple hygrometer. The leaf angle of soybean changes as water stress increases and it is necessary to occasionally alter the position of the hygrometer to accommodate these movements (Oosterhuis <u>et al</u>., 1983). The leaves of succulent plants often become thinner and may slip out of the hygrometer on drying (Durand-Campero and Wiebe, 1981). These workers mounted the hygrometers on neighbouring leaves whenever this occurred.

In windy conditions, droplets of dew may enter the hygrometer slit, resulting in large temperature differences between leaf and hygrometer sensing junctions causing large zero drift errors. Savage et al. (1983d) could not obtain accurate pre-dawn leaf water potential measurements under such conditions. Their first measurements on any day commenced after 09h00 when all dew had evaporated.

E. VALIDITY OF HYGROMETER WATER POTENTIAL MEASUREMENTS

With the development of hygrometry came the need to compare measured potential values with a suitable standard technique, usually the Scholander pressure chamber (Scholander et al., 1965). The premise of such comparisons (summarised in Table IV) is that the leaf hygrometer should not influence the water potential of the leaf at the point of measurement. In the field, a variety of factors may effect the measured water potential: the temperature dependence of the psychrometric or dewpoint techniques, sealing the hygrometer against the leaf, temperature gradients, percentage of the leaf shaded by the hygrometer and inadequate calibration procedures. Furthermore, leaf abrasion may be too severe, resulting in measured water potential being influenced by the osmotic potential of the cell fluid. Alternatively, abrasion may not have reduced the leaf diffusive resistance sufficiently for the hygrometric technique employed.

Using the dewpoint technique in a controlled evironment experiment, Ike et al. (1978) showed that some of the variation between pressure chamber and dewpoint hygrometer water potential measurements in cassava can be accounted for by the length of petiole outside the pressure chamber. This illustrates one of the many factors that can affect xylem water potential measurements and hence the relationship between comparative measurements. Furthermore, different leaves are often used when comparing measurements. Different leaves may have different potentials due to spatial variation (Ritchie and Hinckley, 1975). Other problems associated with xylem potential measurements include the use of too high a pressure increase rate instead of a rate between 10 to 20 kPa/s (Brown and Tanner, 1981) and inadequate covering of the selected leaf to reduce dessication (Turner and Long, 1980).

The relationship between xylem and water hygrometric potential, for various laboratory or field studies, is shown in Table IV. Of note is that six studies were peformed in the field (with a correlation coefficient greater than 0.9) of which three utilized the psychrometric technique. Included in this table are comparisons of total water potential for whole and excised leaves, using thermocouple hygrometers (Boyer (1968) used an isopiestic psychrometer). Also included is a comparison of dewpoint and psychrometric measurements using two types of commercially available thermocouple hygrometers (Durand-Campero and Wiebe, 1981). Many of the species used by Turner *et al*. (1983) showed a linear relationship between total (psychrometric) and xylem water potential measurements. However, the *in situ* psychrometers underestimated the leaf water potential in the *Helianthus* species at low water potentials and overestimated the water potential in *G. hirsutum* and *C. avellana* (Table IV). The degree of over-estimation was shown to result from water potential differences across the leaf. They concluded that *in situ* psychrometers require calibration against pressure chamber measurements before psychrometer measurements can be used as an absolute measure of leaf water potential. These workers used similar abrasion treatments for all species.

In a field experiment, Brown and Tanner (1981) found that xylem and total (dewpoint) water potential measurements on alfalfa compared favourably. They used the same leaf in their measurement comparisons. However, when sampling comparisons were made on different plants, the water potential measured using the hygrometer was always greater than that measured using the pressure chamber. They claimed that this was due to the hygrometer covering one leaflet of the alfalfa leaf and decreasing leaf transpiration. Their hygrometer covered 9 cm^2 of the leaf.

Using the psychrometric technique in a field situation, Savage *et al*. (1983d) found no difference between xylem and total (psychrometric) water potential measurements for potted *C. jambhiri* trees for total leaf water potentials greater than -3 000 kPa. These workers used different leaves for these comparisons. Oosterhuis *et al*. (1983) found that *in situ* psychrometers overestimated the leaf water potential in their field study using soybeans. They did not attempt to abrade the soybean leaf surface so that their psychrometer measurements may have been affected by high leaf diffusive resistances.

Wiebe and Prosser (1977) found that the silver foil hygrometers of Hoffman and Rawlins (1972) yielded more variable water potential data compared to the pressure chamber or the leaf hygrometer of Campbell and Campbell (1974). These workers presumed that this was because of the lower temperature uniformity in the silver foil hygrometer system and larger zero offset values. These units were also more difficult to seal to leaves, for long periods of time.

Some workers compared leaf and soil water potential measurements by allowing plants to equilibrate under dark conditions for at least 8 h. The hypothesis of such comparisons is that the leaf water potential should approach the soil water potential, assuming that evapotranspiration is small (Brunini and Thurtell, 1982). These workers found that the difference in water potential (dewpoint technique) observed between leaf and soil after the plant had been left several hours in the dark, appeared to be related to uneven moisture distribution in the pots used. Furthermore, the plant appeared to be responding to the average soil water potential. Using thermocouple psychrometers in a growth chamber experiment, Brown and McDonough (1974) found that soil and leaf water potential never reached equality even when their plants (Populus tremuloides Michx.) were under little stress.

F. COMPARISON OF PSYCHROMETRIC AND DEWPOINT TECHNIQUES

The advantages of the dewpoint technique compared to the psychrometric are (Neumann and Thurtell, 1972):

a. dewpoint measurements are relatively independent of the wetting characteristics of the thermocouple junction as well as the size and shape of the water droplet formed on the junction;

b. in the dewpoint mode, no net water exchange occurs at the wet junction, allowing the measurement to be made without disturbing the vapor equilibrium in the chamber;

c. the dewpoint calibration relationship has a larger sensitivity (-270 compared to -143 kPa/μV at 25 °C for the psychrometric method (Savage et al., 1981a);

d. the temperature sensitivity of the dewpoint calibration is smaller (0.85 compared to 10.14 kPa/(μV °C) (Savage, 1982);

e. in a temperature gradient, the temperature difference between the sample and the vapor in the chamber theoretically does not influence the measurement since the vapor pressure in the chamber is determined by the temperature of the sample and the dewpoint temperature is dependent on this vapor pressure only.

However, water potentials measured using the dewpoint technique are critically dependent on the magnitude of the cooling coefficient, particularly at low temperatures. In a controlled environment experiment, Durand-Cappero and [illegible] found that an

Campero

plant water deficit increased, the cooling coefficient for in situ leaf hygrometers required downward adjustment by 1, 2 µV or greater to ensure that the sensing thermojunction maintained the dewpoint temperature. This suggests that changes in the cooling coefficient are necessary when the thermocouple is wet, compared to when it is dry.

Contrary to the opinion of Neumann and Thurtell (1972), the dewpoint technique appears to be dependent on thermocouple junction characteristics (Section IV.B.3). Variability between individual dewpoint hygrometer units is reflected in differences in the value of the dewpoint cooling coefficient (Savage et al., 1982) and the voltage-water potential calibration curve (Durand-Campero and Wiebe, 1981). In the case of leaf water potential measurements, these workers concluded that under conditions of high leaf resistance and small sampling area, the dewpoint method is preferable to the psychrometric for measurements of total leaf water potential. They found that in such cases, psychrometric measurements overestimate the leaf water potential and overestimation becomes progressively greater at high leaf diffusive resistances. These workers did not abrade leaf surfaces (Table IV).

Using perforated metal plates of known resistance between the evaporating surface (filter paper discs) and sensing junction, H. H. Wiebe (1983, pers. comm.) found that:

a. an increase in diffusion resistance above about 10 s/cm caused the psychrometric voltage to increase (with corresponding water potential decrease);

b. an increase in diffusion resistance above about 5 s/cm caused the dewpoint voltage to increase (with corresponding water potential decrease);

c. dewpoint measurements appeared to be more variable than the corresponding psychrometric measurements for a given diffusion resistance.

Wiebe's data therefore indicates that the dewpoint technique is more sensitive to diffusion resistance compared to the psychrometric technique. The resistance values measured by Savage et al. (1983c) following abrasion of citrus leaves were just greater than 11 s/cm under completely dark conditions. They obtained excellent field correspondence between xylem and psychrometric water potential which is confirmation of the resistance limit value (10 s/cm) obtained by Wiebe. Neumann and Thurtell (1972) were unable to measure leaf resistances for Zea mays plants placed in a laboratory. Following treatment of a leaf with xylene, leaf resistance decreased to 2 to 3 s/cm. Miller ([illegible]) also reamples from the literature where workers had obtained satisfactory water potential measurements (psychrometric technique) using leaf material with cuticular resistance values greater than 20 s/cm.

G. SENSITIVITY OF THERMOCOUPLE HYGROMETERS

The use of thermocouple hygrometers for continuous monitoring of in situ leaf water potential is an aspect of field hygrometry that has not yet received much attention (Savage and Cass, 1983b). Hygrometer sensitivity is of importance in such applications. Lambert and van Schilfgaarde (1965) thought that their psychrometer could respond to changes in psychrometric water potential to within 5 min but chose a time interval of 20 min between measurements. They maintained that there was a time lag between dynamic changes in water potential of the test leaf and the psychrometer output. Hoffman (1966, cited by Hoffman and Splinter, 1968b), calculated this lag to be about 10 s for tabacco if the stomates were open but greater if the stomates were closed. Assuming little water absorption within the psychrometer cavity, Peck (1969) obtained an expression for the equilibrium time:

$$(r_\ell V/A)\ \ln[(RT/\bar{V}_w \delta)(h_i - h_s)]. \tag{9}$$

r_ℓ is the leaf resistance to water vapor diffusion, V the psychrometer volume, A the sample surface area (within the chamber), R the universal gas constant, T the chamber temperature, $\bar{V}_w$ the partial molar volume of water, δ the desired difference between chamber and sample water potential, h_s the sample relative humidity and h_i the initial chamber relative humidity (prior to sealing). Peck (1969) calculated that for r_ℓ = 1 000 s/cm, a leaf psychrometer with V/A = 30 mm, T = 20 ^{o}C, δ = 50 kPa, h_s = 50 %, and h_i = 99.36 %, the equilibrium time is greater than 60 min. According to this theory, commercially available Wescor hygrometers have equilibrium time values less than 10 s, assuming r_ℓ = 10 s/cm, V/A = 1 mm and δ = 10 kPa.

Campbell and Campbell (1974) found that the in situ leaf dewpoint hygrometer appeared to respond to plant water potential changes in less than 30 min. In a laboratory experiment, Baughn and Tanner (1976) monitored changes in dewpoint hygrometer water potential, caused by excising a test leaf, with a sensitivity of a few minutes. Boyer (1972a) altered the water potential of a salt solution sealed in a thermocouple psychrometer cavity by injecting a salt solution of different concentration. He found that the psychrometer (isopiestic technique) reacted to the change in water potential with a time constant of 30 s (the time required to respond to 63 % of the water potential change). Boyer's technique did not separate psychrometer responses from the delay in attaining the new water potential arising from the finite but unknown mixing rate of the added salt solution. Turner et al. (1983) investigated the response of in situ leaf psychrometers to changes in leaf hydration in a controlled environment. They concluded that in situ psychrometers are suitable for measuring dynamic changes in total leaf water potentials since the instruments were sensitive to water potential changes occurring every 7 min.

In a field experiment, Savage and Cass (1983b) measured psychrometric water potential changes before and 1 min after excision of citrus leaves. Simultaneous xylem and total water potential measurements were performed on adjacent leaves prior to the time of excision and then on the psychrometer leaf about 2 min after excision. Their data indicate that within the first 2 min after excision, these measurements were linearly correlated (r = 0.97). For uncovered leaves they measured total (psychrometric) water potential decreases of 250 to 700 kPa in 1 min after excision for high evaporative demand conditions. Their results showed that the thermocouple psychrometer can be used as a dynamic and non-destructive field technique for monitoring total water potential. In a related experiment, they measured an increase in C. jambhiri water potential within 15 s after petiole excision or parallel or longitudinal midrib incision. Such increases ranged between 20 to 80 kPa (average of 50 kPa) and were noted in light and dark conditions, but persisted for longer time periods in the latter case (Savage et al., 1983b).

VI. WATER POTENTIAL MEASUREMENT IN TREES, STEMS AND ROOTS

A. WATER POTENTIAL MEASUREMENT IN TREES

Wiebe et al. (1970) used miniature (20 mm long) porous cup psychrometers to measure water potentials of trees under field conditions that included variable temperatures. All [illegible] were installed at heights of 1 to 2 m above ground in juniper, elm, Russian olive and maple trees. Trunk installations were as follows: holes were drilled through the bark to a depth of about 10 mm under the cambium. Branch installations were made in the angle between two branches (at least 20 mm in diameter). Each hole containing a psychrometer was immediately covered with an asphalt compound or grafting wax to prevent drying. These workers used polyurethane foam in sheets and as a spray to insulate the stem in the vicinity of the implanted psychrometer and thus reduce temperature changes caused by intermittent direct sunlight. To test the reliability of the tree water potential measurements, Wiebe et al. (1970) simultaneously determined twig and leaf water potentials using other methods and psychrometric soil water potential measurements. The highest water potentials were recorded in the soil installations, and in each case decreased progressively up to tree trunk to the branches and leaves. When transpiration was reduced, at night or on a rainy day, the water potential of the twigs and branches increased, and the overall gradient decreased. The data obtained from the implanted stem psychrometers were always in good agreement with data obtained from pressure chamber and laboratory psychrometer chamber measurements when adjusted for the gradient through the trees. Leaf water potential determinations never gave higher values than the twig water potential determinations with the pressure chamber.

B. STEM WATER POTENTIAL MEASUREMENTS

Michel (1977) has pointed out that knowledge of root permeability to water movement was limited by lack of continuous records of water potential at the base of an intact plant stem. To overcome this deficiency, Michel (1977) and Pallas and Michel (1978) devised a technique for attaching dewpoint hygrometers to the secondary xylem vessels at the base of plant hypocotyls. Some difficulty was encountered during measurements because of thermocouple contamination by fungal growth and temperature gradients (Michel, 1979). In spite of these problems, continuous monitoring of water potential was achieved for soybean (Michel 1975, 1977) and peanuts (Pallas and Michel, 1978; Pallas et al., 1979). In a controlled environment experiment, Pallas and Michel (1978) compared results from hygrometers attached to the leaves and stem of peanut plants. These workers found that within 30 min after illuminating their controlled environment, the stem dewpoint hygrometers could detect the beginning of an oscillation in stem water potential. By contrast, only one of their four leaf dewpoint hygrometers detected any oscillation in leaf water potential. They found that the amplitudes of cycles in stem water potential detected were several hundreds of a kilopascal greater than those detected by the leaf hygrometer. Their study indicated that leaf hygrometers on peanut and soybean leaves with intact cuticles were less sensitive to dynamic changes in the plants water potential than embedded stem hygrometers. When the plant's water potential changes were not rapid, leaf hygrometer measurements agreed closely with stem hygrometer measurements.

C. ROOT WATER POTENTIAL MEASUREMENTS

Measurement techniques used in root water uptake experiments prior to 1977 have been reviewed by (Herkelrath <u>et</u> <u>al</u>., 1977). Since then, field measurements of root water potential have been performed (Nnyamah and Black, 1977a,b; Nnyamah <u>et</u> <u>al</u>., 1978), using the dewpoint technique. Root hygrometers were installed by exposing the root, removing all soil. A slanting incision was made into the root xylem tissue and extended to form a lip. The exposed inner surface was lined with dry gypsum powder, a porous cup soil hygrometer was placed axially against the xylem beneath the lip and sealed by three layers of electrician tape and a coating of Dow Corning 781 silicone rubber. Soil was replaced around the root and 24 h were allowed for equilibration (Nnyamah and Black, 1977a). As a check on the performance of the root hygrometers, root xylem pressure potential was measured using the pressure chamber apparatus (Table IV). The roots were 1.5 to 2 mm in diameter and 150 mm long at a depth of 150 to 200 mm. These workers concluded that their technique of measuring root water potential had some advantages over other techniques reported in the literature because measurements were made directly and continuously in the path of water movement (Nnyamah <u>et</u> <u>al</u>., 1978). Brunini (1979), cited by Brunini and Thurtell (1982), also measured root water potential directly using dewpoint hygrometers.

VII. SOIL HYGROMETERS

A. CONSTRUCTION

The materials used for construction of the soil hygrometer and the shape, arrangement of components and lead wire gauge diameter affects the performance of the instrument. At present, these factors are the subject of considerable research and no clear optimal specifications have yet emerged. The consequences that arise from hygrometer construction are discussed in Section VII.C.

Soil hygrometer sensors for <u>in situ</u> measurement of water potential have been constructed from a variety of materials. The basic elements of a soil hygrometer consist of a body into which the lead wire pass and which attach to the thermocouple sensing junction. This junction is enclosed and protected by a porous barrier which allows water vapor equilibration between the thermocouple cavity and soil.

The body of the hygrometer is usually constructed from a teflon plug and coated with epoxy (Hoffman and Splinter, 1968a; Brown, 1970; Wiebe <u>et al</u>., 1971) or inserted into an acrylic (Rawlins and Dalton, 1967) or metal body. Various metals have been used for this purpose including brass (Campbell, 1979), copper (McAneney <u>et al</u>., 1979; Brunini and Thurtell, 1982) and stainless steel (some commercial models). Copper heat sinks have been employed in the body for thermal stability (Rawlins and Dalton, 1967).

The interior of the thermocouple chamber should be constructed from material that does not adsorb large quantities of water. Campbell (1972) investigated the adsorption properties of a range of materials and found vaseline to adsorb least water, followed by brass, stainless steel, nickle, polythene, teflon and paraffin wax. Tygon, axle grease and rubber cement were found to be unsuitable. Some users coated the interior of the hygrometer chamber with resolidified wax just prior to use (Baughn, 1974; McAneney <u>et al</u>., 1979).

The porous barrier between the thermocouple cavity and the soil serves to protect the sensor from contamination and provides an equilibration path for water vapor. Materials used for construction include ceramic (Rawlins and Dalton, 1967) which usually has an air entry pressure of about 100 kPa, but McAneney <u>et al</u>. (1979) used a ceramic plug with an air entry pressure of 1500 kPa. Ingvalson <u>et al</u>. (1970) incorporated a 1500 kPa plug in a 100 kPa ceramic bulb for measuring both osmotic and water potential. Lang (1968) was the first to replace the ceramic bulb with a cylindrical stainless steel wire mesh cage (100 mesh). Brown (1970) used a stainless steel mesh number of 200 with openings of 74 µm. Brown and Collins (1980) designed a double screen cage (inner 400 mesh, outer 200 mesh) to improve protection against contamination of the thermojunction by soil. The thermocouple was also provided with an additional copper lead to measure temperature at the junction. Brunini and Thurtell (1982) introduced the use of a porous silver membrane with an air entry pressure of 1500 kPa.

The shape of soil hygrometers varies from porous spherical ceramic bulbs to cylindrical ceramic or stainless steel mesh cups or solid cylindrical bodies with porous end windows (Wiebe et al., 1977). Porous disc-shaped units have also been designed (Campbell, 1979; Brunini and Thurtell, 1982).

The diffusion resistance of the ceramic barrier will effect the response time of the hygrometer. Rawlins and Dalton (1967) calculated the conductivity required to maintain a potential difference of less than 10 kPa between the thermocouple cavity and the soil and concluded that it was about one-sixth the conductivity of ceramic with an air entry pressure of 100 kPa.

Brown (1970) investigated the water vapor equilibrium time for junctions that were enclosed in ceramic cups, stainless steel mesh and a bare junction. The bare junction reached vapor equilibrium in about the same time (20 min) as temperature, but the screen-cage required 33 min and the ceramic cup 170 min. Extended periods of time in soil would tend to reduce the conductivity of the ceramic cup more than steel mesh owing to microbial growth in the finer ceramic pores (about 3 µm) compared to the coarser mesh apertures (about 74 µm).

McAneney et al. (1979), using a 1500 kPa ceramic plug, did not identify vapor diffusion resistance of their instruments as a major limitation. However, they did conclude that their sensor was unsuitable for monitoring rapid changes in osmotic potential because of the high diffusion resistance of the ceramic to solutes. A similar limitation may apply to diffusion of water vapor. Brunini and Thurtell (1982) replaced the ceramic cup with a silver membrane with an air entry pressure of 1500 kPa and determined that the solute equilibration time of their device was 2 h as opposed to the equilibration time of 23 h required by McAneney et al. (1979).

Poor contact between soil and hygrometer porous barrier may contribute to diffusion resistance. Coarse-grained soils, which have a preponderence of particles in the 200 to 2000 µm diameter class, generally offer a large resistance to liquid flow across the soil-ceramic interface because of the limited number of liquid films that actually touch the ceramic surface. This contact resistance has been identified with tensiometer response

(Towner, 1980), but it is likely to be greater in hygrometry where measurements are made at lower potentials than tensiometry. Merrill and Rawlins (1972) drew attention to the possibility of a high contact resistance developing in swelling soils as shrinkage causes soil to be drawn away from the hygrometer. Ceramic cups are likely to be more adversely affected than steel mesh cylinders because of the difference in the mode of operation between these materials. Ceramic cups are in liquid contact with soil water and the surface where measurements are made is the interior of the cup. Screen cages, however, probably have a lesser liquid conducting role and the recessing surface is probably the soil-water interface against the mesh.

B. CALIBRATION

The procedures for calibration of soil hygrometers follow the general method discussed in Section IV. However, certain details of the procedure differ from leaf hygrometer calibration because of the presence of large and persistent, temperature gradients in soil and because soil hygrometers cannot be calibrated <u>in situ</u>. For this reason, meticulous attention to the temperature dependence of the calibration sensitivity is necessary. In addition the chamber geometry during calibration must be identical to that of the <u>in situ</u> geometry.

Soil hygrometers may be calibrated in the psychrometric or dewpoint mode. There appear to be certain advantages in selecting the dewpoint mode (Section V. E), but few rigorous comparisons have been conducted to confirm this. However, Nnyamah and Black (1977a) found that dewpoint and psychrometer measurements of water potential in the field were comparable to within 30 kPa over the range -1200 to -300 kPa.

Calibration of screen-caged and ceramic hygrometers differs because the evaporation surface of the former is at the screen and soil-water interface system and at the interior of the ceramic surface for the latter. The ceramic cup acts as a continuation of the soil pore system and must be in liquid equilibrium with the soil water. For this reason, the wet-bulb depression can be assumed to be the difference in temperature between the inner ceramic surface temperature and the wet-bulb temperature (Campbell, 1979).

Brown (1970) described the calibration of screen cage psychrometers using small test tubes lined with filter paper, and saturated with the calibrating solution. The sensor is placed so as to be surrounded by filter paper, the test tube sealed with a rubber stopper and immersed in a constant temperature water bath. Subsequently, Brown and Collins (1980) introduced a stainless steel chamber that could be sealed using rubber O-rings with a small cavity that could be entirely lined with filter paper. The chambers are immersed in an isothermal water bath with about 350 mm of lead wire to prevent heat energy flow along the wires from reaching the chambers. Brown and Collins' (1980) describe a double mesh screen-cage hygrometer (inner 400- and outer 200-mesh stainless steel screen) that could be immersed in salt solution for calibration purposes.

Ceramic cup hygrometers are usually calibrated by immersion of the hygrometer in a small container of calibrating colution which is the placed in an isothermal waterbath (Wiebe _et al._, 1971). Two concentrically arranged glass test tubes have also been used to facilitate good thermal contact between bath and calibrating solution (Oster _et al._, 1969). Wheeler _et al._ (1972) found that immersion of psychrometers in salt solutions resulted in leakage of salt into the sensor chamber causing about 30 % of the units to malfunction. Greater success was obtained by using alternate methods such as a vibrating bath which splashed calibrating solution onto the exterior of the ceramic bulb. After calibrating, the sensors should be thoroughly washed in several changes of deionised water.

Neither of these techniques simulate the geometry surrounding the hygrometer when in position in the soil. The error which this introduces is not known but is generally assumed to be negligible. In some cases, only the thermocouple junction was calibrated in ceramic cups permanently affixed in calibrating chambers and then transferred to different ceramic cups for placement in soil. This practice was, however, identified as a possible source of error in psychrometric water potential measurement because it displaced the calibration intercept (Rawlins and Dalton, 1967).

C. TEMPERATURE EFFECTS

Fluctuating temperatures are a major source of error in the measurement of the wet-bulb depression. If the dry-bulb temperature is not equal to the sample temperature (ceramic surface or soil-water-screen interface), this would represent an error in measurement of the temperature difference between the wet-bulb and the sample. This error is proportional to the difference between internal instrument zero and the voltage measured when both sensing and reference junctions are dry (zero offset voltage).

Because temperature gradients are an unavoidable feature of soil hygrometry, it is necessary to adopt precautions to reduce the associated measurement errors. At present it is thought that this reduction may be achieved by either using high thermal conductivity materials for construction (Neumann and Thurtell, 1972; Campbell, 1979) and/or by careful attention to design so that vapor and heat flow paths are identical (Rawlins and Dalton, 1967; Wiebe _et al._, 1977).

Other hygrometer modifications such as double junction thermocouples (Hsieh and Hungate, 1970) and two thermocouples of opposite polarity (Hsieh and Hungate, 1970; Calissendorff and Gardner, 1971; McAneney _et al._, 1979) have not served to solve the problem of measurement errors in temperature gradients, although they may have served other purposes (Wiebe _et al._, 1977).

Early hygrometers were very sensitive to temperature gradients and precise temperature control was necessary (±0.001 °C). Introduction of a spherical ceramic cup by Rawlins and Dalton (1967) followed by the many subsequent modifications, improved but did not eliminate temperature sensitivity. Further intensive research on the effect of soil hygrometer design on temperature gradient errors has been conducted by Wiebe _et al._ (1977), Campbell (1979) and Wiebe and Brown (1979).

Wiebe _et al._ (1977) used several types of hygrometers in their investigation (spherical and cylindrical ceramic, stainless steel mesh and stainless steel with a mesh end window). The design which was least sensitive to temperature gradients was a stainless steel mesh cylinder with the thermocouple located near the distal end of the chamber. Campbell (1979) tested several brass hygrometers with ceramic barriers for thermal stability in temperature gradients of 0.05 to 0.1 °C/mm. Errors in measuring the temperature at the sensing junction were negligible compared to measurement of wet-bulb depression. The design that gave the lowest temperature gradient error was a symmetrical, small brass hygrometer with a symmetrical ceramic side-window.

In order to ensure that the dry junction temperature is equal to that of the ceramic surface, the thermocouple sensing junction must be symmetrically placed in relation to the surface of the ceramic. In addition, heat conduction along the thermocouple wires to the junction must be minimal. The spherical design of Rawlins and Dalton (1967) approached this ideal, while Wiebe et al. (1977) were able to demonstrate that some of the cylindrical cup psychrometers also approached this ideal. Campbell (1979) showed that the junction temperature could be maintained at chamber air temperature by ensuring that the length of the thermocouple was at least 3 mm, if wire diameter of 25 µm was used.

Campbell (1979) indicated that an additional source of error arising from temperature gradients is drift in the zero setting amplifier circuit. This can arise from changes in thermal voltages at contacts or within the microvoltmeter and from changes in the reference junction temperature during cooling, as may happen when there is significant flux of heat energy along connecting wires.

Campbell (1979) concluded that zero offset values and temperature differences between the evaporating (ceramic) surface and the sensing junction were minimised by constructing the hygrometer body from materials with a high thermal conductivity (brass, stainless steel, aluminium). The largest errors in water potential measurement arose from the effect of the hygrometer on the water and heat flow patterns in a temperature gradient. This manifests itself as a change in soil water potential adjacent to the hygrometer. With the use of suitable materials and a symmetrical design, Campbell (1979) showed that it was possible to minimise the perturbation of water and heat flow and reduce zero offset values to one-tenth and measurement variability to one-third that for a commercial ceramic hygrometer.

Wiebe et al. (1979) showed that variability in measurements from several types of hygrometer was minimised by reducing the size of the hygrometer and by using non-metallic materials for construction. This conclusion differs from that of Campbell (1979) who identified clear advantages in using matallic hygrometers to reduce the temperature gradient within the hygrometer chamber. Wiebe and Brown (1979) showed that while metal hygrometers reduced temperature gradients within the hygrometer, gradients in soil outside the hygrometer were very much steeper. These steep gradients appear to enhance water vapor flux in the vicinity of the hygrometer. The movement of water vapor and accumulation or loss of liquid water at the surface and within the chamber of the hygrometer introduces further error in measurement. Wiebe and Brown (1979) found that cylindrical, metal hygrometers with a metal screen end-window trapped large amounts of water in soil adjacent to the outer surfaces, as well as inside the hygrometer. The reason for this, is that the pathways for heat and vapor flow are not identical. Smaller, ceramic hygrometers which bridge a smaller total temperature change in the temperature gradient, caused less perturbation to the pattern of water movement. Hygrometers that provide the best coincidence of heat and vapor pathways as well as low temperature gradient in the hygrometer body appear to be screen cage units. However neither Campbell (1979) nor Wiebe and Brown (1979) tested these units.

D. FIELD MEASUREMENTS

Relatively few comprehensive field measurements of water potential have been conducted. Where field measurements have been carried out, few precautions have been adopted to reduce the effects of temperature gradients and water condensation on hygrometers. No attempts appear to have been made to assess the errors arising from these effects.

The first successful attempt to use hygrometry for large-scale soil water potential measurement was carried out by Rawlins et al. (1968), using the spherical ceramic psychrometer of Rawlins and Dalton (1967). Measurements were carried out in a large acrylic container wrapped in aluminium foil and placed in a greenhouse. Hoffman and Splinter (1968b), Lang (1968) and Herkelrath et al. (1977) performed similar measurements in controlled environments in which temperature was kept constant.

Merrill and Rawlins (1972) described the long term use of a large number of psychrometers for monitoring soil water potential in the root zone of field plots irrigated with saline water. Psychrometers were initially installed vertically but Merrill and Rawlins (1972) observed that the diurnal variation on psychrometer output could be reduced by horizontal placement of the sensors. Furthermore, 50 to 100 mm of lead wire adjacent to the psychrometer was placed horizontally. Wiebe and Brown (1979) also suggested that water potential measured could be obtained when the surface net radiation is low (that is, near sunset or sunrise) ensuring that zero offsets are a minimum.

Merrill and Rawlins (1972) measured soil temperatures which were used to correct for the temperature dependence of the thermocouple output. A well-designed and constructed automatic data scanning system was used. A distance of over 100 m between the field experiment and the data loggers necessitated several special precautions to achieve the desired level of precision in the measurements. Two types of psychrometer were used, a laboratory-constructed ceramic type containing several grams of [illegible] to act as a heat sink and a commercial ceramic type without a heat sink. The former sensors showed smaller diurnal variation in output, possibly because the presence of the heat sinks promoted better thermal stability. However, the commercial psychrometers displayed greater calibration stability. Any deterioration in calibration sensitivity could be restored by washing the thermocouple junction in hot 10 % alcoholic KOH solution.

Moore and Caldwell (1972) constructed soil sensors by mounting psychrometers in stainless steel tubes which were perforated at the level of the sensor. These were installed by driving them to the required depth. Other hygrometers were installed using the conventional technique of the time, that is by forming an access hole by driving a metal rod to the required depth, inserting the psychrometer vertically and back-filling with soil. Temperature gradients were large, for example, about 0.13 °C/mm at the 150 to 300 mm depth interval and fluctuations of 1 000 to 2 000 kPa were observed in the water potential measured under those conditions. Wheeler et al. (1972) used the latter technique to install psychrometers in the field but encased the lead wires in polyethylene tubing. Easter and Sosebee (1974) used teflon end window double junction psychrometers to monitor soil water potential in two field plots, one irrigated to monitor a water potential of -100 kPa, the other not irrigated. Results of the study are obscure but temperature gradient and water vapor flux error were probably very large. It was the experience gained by these and other pioneering efforts that revealed the magnitude of error arising from field temperature gradients.

Brown and Johnston (1976) report on the durability of end window psychrometers during extended periods of field use (2 to 40 months). Generally the changes in calibration sensitivity during these periods was small (< 5 %) and little evidence of thermocouple junction damage was observed.

The only case in which the dewpoint mode has been used in the field was reported by Nnyamah and Black (1977a,b). The sensors used were Wescor Pt 51-10 ceramic hygrometers calibrated in both dewpoint and psychrometric modes, with mean dewpoint sensitivity of -133 kPa/μV (at 25 °C) and 3 % coefficient of variation amongst thirty hygrometers. The hygrometers were installed in the field by excavating trenches to depths as great as 750 mm, and driving a 9 mm steel rod 300 mm horizontally into the walls of the trenches at various intervals down the profile. Hygrometers were inserted into the apertures thus formed, presumably soil was repacked around the leads and the trenches were sequentially refilled at 100 mm intervals. The stated advantages of this method are that the hygrometers are inserted into undisturbed soil and the lead wires are oriented perpendicular to the temperature gradient. Nnyamah and Black (1977a) do not mention taking any precautions to ensure that the plane of the thermocouple was placed horizontally. The hygrometers performed well over a period of three months with only one unit in thirty malfunctioning during this time. Soil water potential values obtained in the field using the hygrometers were compared with similar values obtained from neutron water meter measurements and direct sampling in conjunction with a laboratory-determined water retention curve. Over the range -1200 to -200 kPa, agreement was linear and within 30 kPa with r = 0.99 (Table IV). Similar results were obtained from comparison of field-measured dewpoint and psychrometric water potential. This suggests that temperature gradients were not a serious problem in their field experiments and that there does not appear to be any particular advantage in the dewpoint mode as is suggested by the lower temperature sensitivity of this technique. In addition to these comparisons, these workers were able to measure simultaneous soil water potentials and root xylem potential of Douglas fir trees over a period of 2 months. Features of this comparison were that root xylem potential was always lower than soil water potential and the former responded more rapidly to rainfall. Although, Nnyamah and Black (1977a) interpreted this as uptake of water by roots close to the surface, before water had penetrated to the depth of measurement, the possiblity that the equilibration time of the ceramic hygrometer could have lagged root uptake of water cannot be excluded. Nnyamah and Black (1977b) reported the use of field hygrometers, tensiometers and a neutron water meter for characterising the unsaturated hydraulic conductivity of soil over the range 0.001 to 10 mm/day. Using this information, together with computed evapotranspiration rates (Bowen ratio/energy balance method), they were able to measure the flux of water through their field site. This experiment represents the most sophisticated use of soil hygrometers in the field recorded thus far.

In summary, the essential requirements for successful field soil hygrometry must include the following precautions to minimise the effects of fluctuating diurnal temperatures and temperature gradients:

a. hygrometer size: the size of the hygrometer must be small in order to a smaller temperature gradient and facilitate flux of water vapor through the chamber (Wiebe and Brown, 1979);

b. hygrometer shape: the geometry must be concentric with the thermocouple sensor centrally or distally located in the chamber (Rawlins and Dalton, 1967; Campbell, 1972; Wiebe <u>et</u> <u>al</u>., 1977);

c. thermocouple junction: single junction, allowing temperature measurement along the sensor (Wiebe <u>et</u> <u>al</u>., 1977), junction length at least 3 mm long and constructed of fine wire (25 µm diameter) to reduce flux of heat from the body of the hygrometer to the junction (Campbell, 1972);

d. construction material: controversy exists concerning the material for construction of the body of the hygrometer (Campbell, 1972; Wiebe and Brown, 1979) but from available evidence it appears that the optimal material is low conductivity material for the body and a cylindrical stainless steel mesh. Ceramic cups, although they appear suitable, may have sufficiently high diffusion resistance to limit their usefulness in soil;

e. field placement: hygrometers should be installed in undisturbed soil with as much lead wire buried horizontally as possible (Merrill and Rawlins, 1972). The plane of the thermocouple junction should be orientated at right angles to the temperature gradient (Wiebe <u>et</u> <u>al</u>., 1977);

f. measurement times: measurements could be performed at times of day when the soil heat energy flux is close to zero (R. B. Briscoe, 1981, pers. comm.), with resultant zero offsets being comparatively small. In practice, such times are around sunset and sunrise. With the use of microprocessor systems (Briscoe and Tippetts, 1982), such measurements are practical, on a day to day basis.

VIII. SUMMARY AND CONCLUSIONS

The accuracy of non-destructive soil and leaf water potential measurements using thermocouple hygrometers is dictated by the calibration method. In the case of leaf hygrometers used in the field, it is best to calibrate units under cloudless and calm field conditions ensuring that there are virtually no thermal gradients within the instrument. At present, it is not possible to accurately calibrate soil hygrometers in the field.

In the case of leaf water potential measurements, the cuticular resistance may introduce measurement errors in both psychrometric and dewpoint methods. The [illegible] abrasion used, if necessary, is determined by the cuticular resistance of the leaf. There is some evidence indicating that both psychrometric and dewpoint techniques may be affected by cuticular resistance. Available evidence suggests that the former is affected if resistances are greater than about 15 s/cm and the latter if greater than about 10 s/cm. *In situ* field comparisons with pressure chamber measurements are presented for a whole range of crops. Practical aspects associated with such hygrometric measurements are detailed for both leaf and soil water potential.

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FIGURE CAPTIONS

Fig. 1. Measured thermocouple psychrometer output voltage as a function of time (20 s cooling time and water potential of -1757 kPa at 25 °C). After Savage *et al.* (1981a); published with permission from publishers.

FIG. 2. Diagrammatic representation of an *in situ* leaf psychrometer covered with thermal insulation and reflective aluminium foil. Four layers of insulation material (each 3 mm thick) at the base of the psychrometer were used with two layers on all sides to minimize leaf shading (except the non-slit side which had three layers). Total shaded area of the leaf was at least 8 % of the total leaf area.

(a) Cut-away view showing the narrow bore plastic tube and brass securing screw;

(b) Aluminium foil cover over the piston top and lead outlet.

After Savage *et al.*, 1983d; published with permission from publishers.

FIG. 3. Scanning electron micrographs of an abraded *C. jambhiri* leaf surface area. There are a few surface scratches due to the non-angular nature of the carborundum powder used for abrasion. However, abrasion ruptured the cuticle and walls of occasional epidermal cells, exposing cell lumina which appear as empty cavities on the micrographs. These would be filled with cell sap in living leaves.