A COMPARATIVE STUDY BETWEEN THREE ELECTRONIC LEAF WETNESS SENSORS AND A BETA-RAY GAUGE

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ABSTRACT

Leaf surface wetness duration time is an important agrometeorological parameter that determines fungal infections and spread of plant diseases. Surface wetness could also contribute to the reduction of transpiration and enhance pesticide effectiveness.

For these reasons, field and laboratory performances of commonly used electrical resistance (ER) sensors were compared with a beta-ray gauge (BRG). The BRG provided the most accurate measure of surface wetness duration which agreed favourably with visual observations since it uses a real leaf as a sensor. A commercially available electric grid sensor (Model 237, Campbell Scientific), which employs a hard epoxy-fibreglass board, was found to be accurate in the determination of wetness duration for tobacco but not for soybean leaves. A second cotton cloth ER sensor was found to record accurately wetness duration of dew and rain on soybean leaves. However, this sensor overestimated wetness duration on tobacco leaves. The data indicated that the choice of an ER sensor for best results depends on the density of the crop canopy. If accurate measurements of leaf surface wetness are critical it is suggested that the BRG system be used.

RESUME

La durée d'humectation d'un couvert végétale après une épisode de précipitation est un paramètre important en agrométéorologie, ce qui détermine les infections des champignons et la propagation des maladies des plantes. La durée d'humectation peut aussi contribuer à la réduction de la transpiration des plantes et ainsi améliorer l'efficacité des pesticides.

Pour ces raisons, le fonctionnement au laboratoire et sur le terrain de trois détecteurs de résistance électrique (RE) ont été comparé avec une jauge de rayons bêta (JRB). Le détecteur JRB fournissait la mesure la plus exacte de la durée d'humectation de la surface des feuilles, qui s'accordait bien avec des observations visuelles. Un des détecteurs construit d'une grille électrique et qui est disponible sur le marché, le modèle 237 de Campbell Scientific à Edmonton, Canada, emploie une surface de résine d'époxye et de fibres de verre. Ce détectuer est exact dans la détermination de la durée d'humectation pour les feuilles de tabac et non pas pour les feuilles de soja. Un autre détecteur RE qui lui utilise un morceau de tissu de cotton, a précisément enregistré la durée d'humectation sur les feuilles de soja, mais a surestimé la durée d'humectation sur les feuilles de tabac.

Pour obtenir de meilleur resultats, des données ont indiqué que le choix d'un detecteur RE est recommandé mais cela depend de l'épaisseur de la voûte des plantes. Pour des mesures précises de la durée d'humectation, il est recommandé d'utiliser le JRB.

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TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF FIGURES

FIGURE NUMBER Page

TABLE NUMBER

CHAPTER I: INTRODUCTION

A knowledge of certain agrometeorological parameters such as leaf temperature and leaf wetness duration time are useful in the field of crop disease forecasting. Leaf surface wetness arises from rain, dew or fog precipitates and in some cases may also be due to irrigation water of sprinklers that collects on leaf surfaces. Of these atmospheric precipitates, wetness from rain and dew has attracted considerable attention of plant pathologists and agricultural meteorologists.

The formation of dew on foliage surfaces originates from the processes of radiation and condensation. At night, and during clear sky and calm atmospheric conditions, heat from plant surfaces is radiated to space. This could cool the leaf to a temperature that is below the dew point. Water vapour suspended in relatively warm air aloft will then condense on cool plant surfaces. As the morning approaches, the dew will be evaporated due to incident radiant energy from the sun. When the sky remains cloudy and the atmosphere turbulent at night, dew does not form because the plant leaves may remain warm as the radiated thermal energy is reflected from the cloud cover and reabsorbed by foliage. Additionally, atmospheric turbulence will cause mixing and heat will be transported from the upper layers to the level of plant canopy and below. Thus, reabsorption of radiated energy by leaves and atmospheric mixing could prevent the surfaces from cooling off below the dew point during such nights, and suspended water vapour does not condense on plant surfaces to form dew.

Dew, rain, fog, and irrigated water are not the only sources of leaf wetness. Distillation of soil moisture and its deposition on plant surfaces also occurs. However, the process of distillation is distinguished from the process of dewfall (Monteith, 1957). Distillation is caused by water vapours from the relatively warm soil surface that condense on plant surfaces. In contrast, dewfall forms from the condensation of atmospheric water vapour. Weiss et al. (1989) concluded that the soil is the primary source of leaf wetness in semi-arid regions, since atmospheric humidity is generally low.

The presence of dew, rain or fog deposition on a leaf surface influences fungal and bacterial germination which may lead to infection and spread of plant disease (DeWeille, 1965). Therefore, leaf surface wetness duration time is an important and useful agrometeorological parameter for plant pathologists who are concerned about the propagation and the control of disease epidemics.

Leaf surface wetness may not be always harmful, however. In semi-arid regions, leaf surface wetness contributes to water conservation. As long as a leaf surface is wet. water loss due to transpiration is delayed. Evaporation from the soil surface is also delayed on occasions when the soil is wet from run-off of dew water from leaf surfaces. These effects cause suppression of evapotranspiration (Duvdevani, 1964; Baier, 1966) that results in water conservation, particularly, in marginal semi-arid agricultural regions of the world. In addition, surface wetness may provide leaf turgidity necessary for photosynthesis. There have been studies to indicate that leaf absorbs water through stomates and cuticles, and is a mechanism to provide water for semi-arid crops (Vaadia and Waisel, 1963).

Entomologists acknowledge that leaf surface wetness increases insect activity (McCoy et al, 1972). Pesticide effectiveness also increases if a water layer is present on leaf surfaces (NOAA, 1971). These observations show that there are indeed some beneficial effects of leaf surface wetness. However, the probability of a spread of plant disease may overwhelm any beneficial effects that leaf wetness may have.

The formation of free water on a leaf surface is essential for life cycle processes of plant pathogens. Pathogens such as downy mildews, cereal rust fungi, and apple scab fungi grow in presence of water (Wallin, 1963; Phillips, 1984). Availability of free water on leaf surfaces, during a critical time in the life cycle of the potato blight Phytophora infestans, is crucial in the germination of its spores and subsequent infection of leaves. It has been determined that sporulation of potato blight was meagre when relative humidity (RH) values were 95-97%. Profuse sporulation occurred when RH values exceeded 97%. Sporulation was maximized in presence of free water on a leaf surface (Wallin, 1963). In view of the importance of the leaf wetness parameter in agriculture and the prevalence of several measurement techniques, it was deemed necessary to determine the relative advantages and disadvantages of each technique.

The objectives of this comparative study were: 1) to analyze quantitative measurements of leaf surface wetness duration time by three electronic resistance (ER) sensors and the novel technique of beta-ray gauging (BRG) in a dew chamber of a laboratory, and 2) to compare the performances of these detectors in field crops of soybean and tobacco.

CHAPTER II: LITERATURE REVIEW

II.1 MECHANICAL SENSORS

Several leaf surface wetness detectors have been developed and used in the past. One of the early types of leaf wetness detectors, introduced 35 years ago, used a mere string as the sensing device. This was called the Dewit dew sensor. The Dewit dew sensor utilizes a degreased hemp string which responds to moisture by shrinking when wet and by returning to its original length when dried. This mechanical action moves an ink pen so that a trace of a wetting event is left on paper. It was found that this sensor had an error of less than one hour for the length of a dew episode for apple, potato, and carrot foliage, but not for onion leaves. The sensor considerably under or over-estimated the wetness duration time of onion leaves. Furthermore, wetness was found to be dependent on the age of leaves (Sutton et al., 1984).

Two more similar sensors utilizing fibres are the Hiltner dew meter and a chalk line type. The Hiltner dew meter utilized a horse hair as the sensing device and was based on the same principle as the Dewit dew detector (Wallin, 1963). A leaf wetness sensor devised by MacHardy and Sondej (1981) utilized a cotton chalk string attached to a contact plate that could make or break an electrical circuit as the string shrinks or stretches in response to moisture.

A different Taylor type sensor has been used to collect dew on a rotating glass turntable while a water-soluble pencil dissolves and leaves a time trace on the surface (Wallin, 1963; Schnelle et al., 1963).

One of the main problems associated with these mechanical types of sensors is that they are sensitive to wind. The introduction of wind dampeners to these sensors did not appreciably improve their performance in the field (Wallin, 1963). Moreover, with the string type detector there was an initial time-lag in detecting the onset of dew because of the fact that moisture must first be drawn into the fibres of the sensor to activate it (Sutton et al., 1984). Wallin (1967) observed that corrections must be made to the results obtained with these sensors due to errors introduced by the materials from which they have been constructed. The surfaces used for collecting dew also varied widely. Plastic, metal grids, ceramic disks, cotton, and wood surfaces were used.

However, the accuracy of results obtained by using the various mechanical sensors was limited.

II.2 ELECTRICAL RESISTANCE (ER) SENSORS

In general, there are two methods employed for determining leaf wetness. The first method depends on electrical or electronic devices to detect the formation of dew or rain on leaf surfaces. The second method is based on mathematical models along with the use of micrometeorological data collected from the surrounding environment. Modern methods of leaf surface wetness duration time measurements, however, utilize electrical or electronic principles. ER type sensors have been extensively tested in the laboratory and the field (Gillespie and Kidd, 1978; Getz, 1978 Barthakur, 1987). These sensors were found to be more reliable and easier to handle than their mechanical predecessors. Comparative studies of ER sensors have also been performed (Weiss and Hagen, 1983).

Basically, electrical leaf wetness sensors can be divided into two groups. The first group contains those sensors that are essentially "electrical leaves". These simulate a leaf surface with an electrical resistance grid that comprises the detection circuitry. The second group contains sensors that use an in vivo leaf, attached to the plant, as a detection surface.

II.2a Cotton Cloth Sensor

The first group of ER sensor employs an assembly of alternating wires woven on a rectangular frame of plastic or bakelite. A cloth is placed on the wire frame. Dew actually forms on the cloth, and wetting changes the resistance of wires. This type of sensor was employed in a comparative study by Wiess and Lukens (1981). In this study, the authors also attempted to place leaves of a bean plant (Phaseolus vulgaris L.) directly to the wire grid. Solid electrical contact between the grid and a leaf could not be achieved without either mechanically damaging the leaf or the small diameter wires. Wind damage to the detector occurred as the leaf fluttered.

Similar problems were encountered when a tobacco leaf was mounted on an ER sensor (Barthakur, 1985). Therefore, this method was deemed unsatisfactory. A piece of white cotton cloth replaced the actual leaf. Weiss and Lukens (1981) reported that the emissivity of a cotton cloth, (0.98) is equivalent to that of a leaf. In addition, a cloth is durable and simple to use compared to a leaf. Weiss and Lukens (1981) have observed that the entire cotton cloth is involved in moisture detection as diffusion of water wets the whole cloth. But in the case of a printed circuit board sensor, only one side of the printed circuit board surface is involved in moisture detection. Actual dew forms on both ventral and dorsal sides of leaves. A disadvantage of cotton cloth sensors is that dew usually forms as individual drops on waxy leaf surfaces. Evaporation rate of drops could be quite different from water evaporation from a cloth. This might introduce an error in the determination of wetness duration. However, tests in a dew chamber have revealed that the cotton cloth sensor is more sensitive to the detection of minute quantities of moisture that may not be visible to the naked eye without any magnification (Weiss, 1983). The ER sensor with a printed board, in this same study, did not respond to minute amounts of moisture (Weiss, 1983).

A laboratory study in a dew chamber (Barthakur, 1985) indicated that a cotton cloth ER sensor was unresponsive to either light dew or light drizzle. In this study, the novel technique of beta-ray gauging was used to detect the presence of water. Although the onset time between the cotton cloth sensor and a beta-ray gauge was found to be the same, the cotton cloth sensor gave leaf wetness duration times 27% shorter than those obtained from the BRG. The detection limit of the cotton cloth ER sensor was found to be lower than that of the BRG. The detection limit for the cotton cloth ER was 0.02 g of water per 9.6 cm^2 of sensing area; whereas the corresponding limit for the BRG showed twice this sensitivity. The BRG detected 0.01 g of water on a leaf surface. It was found that a cotton cloth ER sensor gave accurate and representative measurements when placed inside an alfalfa crop canopy (Weiss, 1981). But in a recent study by Weiss et al. (1989), it was found that the sensor's placement inside the canopy of the soybean did not provide meaningful leaf wetness measurements. It was found that the optimum position for this type of sensor was at the top of a soybean canopy. In the same study, it was observed that the sensor which showed the longest leaf wetness duration, was also the one that provided the most sensitivity to moisture detection. However, while the authors examined the field data of 1984 and 1985, it was revealed that although the cotton cloth ER sensor was sensitive to the onset of dew, the sensor recorded leaf wetness when the leaves were visibly dry. Weiss and Lukens (1981) described the same phenomenon in a previous study. They found on two separate occasions that the cotton cloth ER sensor indicated wetness when apparently no water droplets were present on leaf surfaces. The authors explained this inconsistency between visual and ER detection of moisture by attributing the discrepancy to the presence of a thin layer of water that was not visible on the leaf surface.

The basic problem could, however, be attributed to the difference in physical characteristics of foliage from a cotton cloth. The cotton cloth is made of a large number of fibres which act like capillary tubes. A large amount of energy is required to draw out the water in capillaries. One would expect the evaporation rates of water from a cotton cloth to be different from those on plane surfaces of leaves. There is also leaf surface roughness that may not exist in a cotton cloth. These factors must be kept in mind when interpreting wetness data obtained from ER sensors.

II.2b Printed Circuit Board (PCB) Sensor

The second type of ER sensor consists of an etched printed circuit board (PCB). This type of sensor has remained essentially similar in function and design since first tested by Davis and Hughes (1970). This sensor uses a printed circuit board where copper lines are directly etched on to the surface. The etchings are like interlocking fingers that are analogous to the wires on the cloth ER sensor that were described previously. The surface of the board on which dew forms simulates a real leaf surface.

Gillespie and Kidd (1978) compared a Dewit Leafwet recorder and a small (25 x 100 mm) PCB sensor deployed in an onion (Allium cepa L.) crop. The physical characteristics of the sensors were modified in two ways to mimic more precisely a leaf of an onion crop.

The first modification involved the use of different colours of latex paint applied to the sensor detecting surfaces. Latex paint was used to allow water to permeate to the copper fingers that lie underneath. The angle of deployment of the sensors in the crop was the second modification introduced in the measurements of wetness. Four shades of grey and a dark green colour were used to paint the sensor surfaces. It was found that as the colour of the paint darkened, the evaporation rate of water from the surface increased. The largest difference in evaporation rates was found between the dark green and white coloured sensors, where the dark green sensor dried 150 minutes ahead of the white sensor during overcast skies after rain events. Additionally, the near infrared absorbance of paint was found to be too high, which could result in a rapid increase in the evaporation rate of water. This would introduce inaccurate surface wetness duration times that may be substantially different from those of real leaves. However, it was noted that the high emissivity of non-metallized paint would allow for the accurate onset of dew formation during night time cooling periods (Gillespie and Kidd, 1978). The colour that best approximated the drying rate from onion leaves was a very light grey and an off-white shading. Although this modification may have some merits, Sutton et al. (1984), reported that some latex paints which contain surfactants, absorb moisture at high humidities. Thus, this effect might be another source of error in surface wetness measurements.

The deployment angle had a significant effect on the evaporation rate of water from the detectors. The two deployment angles used were 60° from the horizontal along the short axis and 20° along the long axis from the horizontal both pointing towards north. Differences in the drying rates were least for light or heavy dew that dried under sunny skies. But, for rain or heavy dew that dried under cloudy skies the time difference was larger and generally totalled 1.5 hours difference. The sensor angle did not affect the time of onset for dew. Gillespie and Kidd (1978) found that the average of the two deployment angles was used to obtain an approximation of real foliage duration times. When Gillespie and Kidd (1978) compared the error times of the two sensors they found the maximum error experienced between the PCB and the actual drying time of the crop was 27 minutes. But, the maximum error of the Dewit Leafwet recorder was established at 90 minutes which indicated the greater accuracy of the PCB sensor.

In a similar study conducted by Smith and Gilpatrick (1980), the performances of a Dewit and a Geneva wetness recorder were compared. The Geneva wetness recorder utilises the same PCB design as previously described. The sensors were installed at 1.5 m from the ground within an apple tree canopy, where leaf wetness events were to be recorded. On two separate occasions, the Dewit detector indicated leaf wetness duration an hour longer than the Geneva recorder. Two events were reversed and reported to have been recorded an hour longer for the Geneva than the Dewit recorder. A fifth wetness event was recorded identically for both sensors. The Geneva recorder responded to light misty rainfall sooner than the Dewit. This may be attributed to the time it takes for moisture to be absorbed into the hemp string of the mechanical Dewit leaf wetness sensor. Again, during the drying period, the moisture has to evaporate from the string which is expected to take a relatively long time. These factors reduce sensor accuracy on leaf wetness duration. It was observed that during calm atmospheric conditions the Dewit sensor was somewhat more accurate than the Geneva detector (Smith and Gilpatrick, 1980).

In a comparative study (Weiss and Lukens, 1981) between a cotton cloth ER and a PCB sensor, a persistent problem of Joule heating in the electronic circuit was found to be a significant factor that introduced error in the measurements. Heat build-up due to incident solar radiation on the electrical board enhanced the evaporation rate of water. In a subsequent study, Weiss and Hagen (1983) discovered another phenomenon that affected sensor behaviour. Their 1980 field data showed that the PCB sensor was significantly affected by the deposits of honeydew on the sensor surfaces left by insects living in the nearby vegetation. The sensor would give spurious wetness readings when the leaves were obviously dry. The hygroscopic nature of honeydew seemed to have attracted and absorbed moisture to the electrical grid which generated false signals of wetness events. However, honeydew did not seem to affect the cotton cloth ER sensor. The PCB sensor is also used routinely by the American National Weather Service. Weiss and Hagen (1983) have questioned the validity of the data obtained with this sensor as the standard instrument in view of the difficulties encountered.

II.3 SENSORS USING REAL LEAVES

The second category of electrical sensors are those that use real leaves as detection surfaces.

II.3a Microclip Sensor

The first type is an ER sensor which employs microclips attached directly to the leaf (Melching, 1974). The leaf acts as the resistance membrane between the wires, or microclips. The microclips have been evaluated on maize, wheat, and soybean leaves as well as on various tree and grass foliage (Melching, 1974). The sensor spacing, i.e. the distance between the microclips, could vary from 0.5 to 3.0 cm without significant effect on the recording system. The pressure developed by the microclips was approximately equivalent to 2.7 to 3.7 g weight. This was not sufficient to cause any damage to the leaf tissue. However, some of the limitations of the microclip type sensors have been pointed out by Sutton et al. (1984), where clips would respond to high RH before actual dew deposition took place. They observed that calibration against sensible dew was of paramount importance. In addition, these researchers reported that clip attachment had to be checked daily which was time-consuming and made the use of clips unsuitable for disease management purposes.

II.3b Beta-Ray Gauge (BRG) Sensor

A beta-ray gauge (BRG) technique (Bunnenburg and Kuhn, 1977; Barthakur, 1983) of detecting moisture on leaf surfaces was developed. This detection system uses an in vivo and attached leaf as the surface for the formation of dew and other atmospheric precipitates of rain and fog. As the BRG system uses a real leaf surface, wetness duration time obtained can be considered as realistic (Barthakur, 1985). A mature leaf is placed as an absorber within the space between a radioactive point source and a Geiger-Muller (G-M) detector. Radioactive particles (beta particles) are attenuated exponentially by a leaf and any water on its surface. A BRG system was first used by Bunnenberg and Kuhn (1977) for the detection of dew formation on soil surfaces. A beta-source was placed just under the soil surface and a solid-state silicon crystal detector was positioned over the source in the air. The soil acted as the condensing surface for the dew. Beta particles from a thallium-204 (^{204}Tl) source were determined to have the best properties for detection purposes (Bunnenburg and Kuhn, 1977).

The beta-ray gauge has certain advantages over other leaf surface wetness sensors. One advantage is that the water evaporation rate dependence on physical characteristics of surfaces, is eliminated. Another advantage is that the onset and termination of dew were more distinct for the beta-ray gauge than that of a Hiltner dew balance. The pen movement, due to wind, resulted in difficulty in reading dew onset and termination points accurately with a dew balance. Moreover, Bunnenberg and Kuhn (1977) have ascertained the accuracy of a BRG at 0.0012 mm of water thickness with a 95% probability (two-fold standard deviation).

Experiments were performed on leaves of tobacco (Nicotiana tabacum L.) in the field with a BRG (Barthakur, 1983). A collimated point source of beta-rays was positioned four cm above the leaf and the leaf was placed horizontally over a cylindrical G-M detector tube. A two mm gap was left between the leaf and the detector to ensure air movement. This prevented condensation on the detector mica window. Measured amounts of water were placed on the leaf surface in the laboratory, and the time to dry was measured by pen and ink recordings. When the leaf appeared to be dry, through visual observations, the BRG system still indicated leaf wetness. Leaf surface roughness may have been responsible for the discrepancy between visual and recorded wetness time.

In order to ascertain the accuracy of the beta-ray gauge a wet flat metal plate, simulating a leaf, was placed in a laminar air stream. Experimental results were then compared with the predicted ones by using a mass transfer relationship that was valid for the metal plate. A fair agreement between the experimental and the theoretical results showed the reliability of BRG as a water detecting device (Barthakur, 1983). Other dew chamber and field experiments indicated the superiority of BRG to other ER wetness sensors (Barthakur, 1985; 1987).

A comparative study between a cotton cloth ER sensor and a BRG in the laboratory demonstrated a 27% difference in wetness duration time. The cotton cloth ER sensor indicated a shorter wetness time than the tobacco leaf wetness of BRG. When a piece of cotton cloth 32.5 cm^2 in area and 0.023 cm in thickness was installed, the difference in wetness time was reduced to 12%. A thin cotton cloth of 0.012 cm thickness and mesh size of one mm further reduced the wetness difference time to 4.6%. A field experiment was carried out using an ER cotton cloth of 0.012 cm thickness and the BRG system on tobacco at a canopy height of 50 cm. The cotton cloth failed to respond to wetness under light drizzle or light dewfall. The BRG detected all wetness events regardless of the lightness of the dew. A comparative study between a cotton cloth sensor and a BRG in a dew chamber was conducted (Barthakur, 1987). Six repeated trials were performed with two ER cotton cloth thicknesses of 0.023 and 0.012 cm and three dew settings of light, moderate, and heavy. The BRG showed wetness duration times of 18.9% and 49.9% longer than the 0.023 and 0.012 cm cotton cloth thicknesses, respectively. Thus, the thickness and the texture of the cotton cloth are important in ER sensors to ensure accurate results. Weiss, in a personal communication, also emphasized the care that should be taken in selecting a cotton cloth in ER measurements of dew duration.

II.4 MATHEMATICAL MODEL APPROACH

Another approach for determining leaf wetness duration time is by using a mathematical model in conjunction with micrometeorological data (Monteith and Butler, 1979; Pedro and Gillespie, 1982; Weiss et al. 1989). Huband and Butler (1984) reported that a physical leaf surface wetness sensor is needed when a crop with a sparse canopy is of primary interest. If the canopy is dense or tall crops are under study, a mathematical model is appropriate to determine the wetness profile in a plant stand. Spatial variability between top and bottom of the canopy and sensor maintenance difficulties warrant the use of mathematical models.

The spatial variability problem in a dense canopy can be rectified (Huband and Butler, 1984). This is accomplished with a Davis-Hughes Vegetative Wetting System which consists of a number of ER sensors arranged in parallel. These are then installed from the top of the canopy to just above grass height (Getz, 1981) so that the entire stand is covered. This arrangement essentially eliminated the chance of missing surface wetness events throughout the canopy.

The use of micrometeorological data to estimate leaf wetness duration time falls into two groups; the first employs relative humidity records from field hygrothermographs (Lomas and Shashoua, 1970; Getz, 1981). Hygrothermograph readings set threshold values for relative humidity that allow calculation of daily duration of leaf wetness. Studies that employed this method, in general, proved unsuccessful, however. In a study performed by Lomas and Shashoua (1970), an attempt was made to correlate durations of leaf wetness of a Taylor type detector with relative humidity measurements that were set at a threshold greater than 85%. They found that leaf wetness duration times with threshold RH were underestimated and the predictive value of RH measurements was non-existent. Getz (1981) also arrived at the same conclusion. In his study four thresholds of relative humidity levels were evaluated, these were

>85%, >90%, >95%, and equal to 100%. It was found that no significant statistical relationship between measured hours of leaf wetness duration and the relative humidity thresholds could be established. Soil moisture, wind speed, and cloud cover need to be taken into account to accurately determine leaf wetness duration.

The second method requires comprehensive measurements of wind speed, relative humidity, leaf shading, global solar radiation and other meteorological parameters to predict leaf wetness times.

Pedro and Gillespie (1982) measured latent heat fluxes to and from a leaf and used an energy budget model to calculate dew duration times. They compared the predicted values from the model with the experimental surface wetness times using a ER sensor in the field. Calculated values of leaf dew duration for exposed and shaded corn and soybean leaves were examined. For 31 different dew events for exposed leaves, the calculated values differed by less than 30 minutes from the field measurements, except for two cases which differed by 45 and 135 minutes. Their investigations on shaded leaves for 23 different dew episodes showed an average difference of 60 minutes between predicted and measured dew duration times. The maximum time difference was found to be two hours. This large error was attributed to the use of diffuse solar radiation data in their model that were taken from outside the crop canopy.

In a comparative study, Weiss et al. (1989) made predictions of leaf wetness duration times by using a comprehensive, and mechanistic plant environment model. This model was called Cupid.

This model calculates dewfall length from leaf energy balance, leaf angles, and canopy layers. When vapour pressure of air exceeds the saturation vapour pressure, dew is assumed to have formed but an actual dew formation can also be modified by other micrometeorological parameters. Predicted values were compared with experimental results from two ER sensors.

The ER sensors employed in this study were with cotton cloths, and a real leaf on a grid wire network. The authors concluded that the Cupid model gave predictions of dew duration that were in excellent agreement with field measurements. The model was capable of differentiating wetness durations in various canopy layers as evidenced from agreements with simultaneous measurements by resistance grid sensors. Predictions of wetness duration from the comprehensive model were far superior to hygrothermograph readings of threshold RH.

CHAPTER III: MATERIALS AND METHODS

III.1 SENSOR DESCRIPTIONS

The present study involved a comparision between four different wetness sensors. Two widely used and commercially available ER sensors of leaf surface wetness were compared with the novel technique of a BRG that was developed in this laboratory. In addition, an ER grid sensor using a thin wooden surface was fabricated in an attempt to improve sensor performance.

I.1a Description of a BRG

There are three main components of our beta-ray gauge system. A thallium-204 (^{204}Tl) point source of 222 kBq activity was used as the radioisotope. This source emits only beta-rays with no emission of alpha particles or gamma rays. The maximum energy of the beta-rays from ^{204}Tl is 0.7634 MeV (1 eV = 1.6 x 10^{-19} J). An average energy of beta-particles is approximately 1/3 of the maximum energy. The half-life of ^{204}Tl is 3.77 years. The source was made to specifications by ICN Biochemicals, Inc., Costa Mesa, California, U.S.A. The point source was sealed in a plastic cylinder which partially collimated the beta-rays. ^{204}Tl was chosen because of its energy which is sufficient to go through a turgid leaf with a thick layer of water on its surface. The energy is not high enough to cause any damage to a leaf and the experimenter; the maximum range of beta-rays from this source is less than 25 cm in air.

Therefore, it is safe to operate the source without undertaking elaborate precautionary measures.

The second important component of the BRG system is a detector for beta-rays. A cylindrical Geiger-Muller (G-M) tube (Model LND 723, Nucleus, Oak Ridge, U.S.A.), which was 9.0 cm long and 3.5 cm in diameter, was used. The window was made of mica of mass thickness 1.4 mg/cm^2 through which beta-rays from the source could easily penetrate. The G-M detector was operated at 900 volts. An experimental leaf was placed over the window of the G-M tube which protected it from the elements.

A ratemeter (Model 443, Baird Atomic, Boston, U.S.A.) formed the third component of the BRG system. It supplied a high voltage to the G-M tube and simultaneously displayed counts per minute (CPM) on front panel of a ratemeter. The ratemeter is an analog instrument with an integrating circuit that allows it to display directly in CPM. The integrating circuit has a time-constant that could be varied from 10 s to a minute to change response time of the instrument. The ratemeter processed the millivolt (mV) signals from the G-M detector and was proportionational to the count rate. The ouput from the ratemeter was connected to a data logger. An in vivo and attached leaf was introduced as an absorber between the source and the G-M detector. A mature leaf was taken as a representative sample. At night most of the stomates are closed, and leaf turgidity is maintained. Dry-matter production for a mature leaf can be neglected as very small. Any change in absorber thickness, therefore, may be attributed to the formation of atmospheric precipitation. The absorber leaf was fixed with tapes to avoid fluttering and also to keep the geometry of the counting system constant. The distance between the source and the G-M tube was maintained at four cm (Fig 1).

The attenuation of beta-particles by matter follows a simple exponential law given by equation (1),

$$I = I_o \exp.(- uD) \quad . . . (1)$$

where I= count rate below a leaf and surface water (CPM).

I_o = count rate above the absorber (CPM).

u = effective mass absorption coefficient ($cm^2 \, g^{-1}$).

D = mass thickness of absorber ($g \, cm^{-2}$).

The Geiger-Muller tube and the rate meter used in the 1989 field experiments were replaced by a new and compact hand-held system. This portable system was called Radalert (Medicom, California, U.S.A.) and promised to be useful in wetness measurements. The Radalert unit was fitted inside a weatherproof foam-padded plastic housing. The output cable was passed through a small hole in the housing which was grommeted and siliconed so as to be water impermeable. A small wand was extended from the housing upon which the thallium-204 beta source was secured. A small 12 volt fan was installed under the housing so that cool air could be passed through the housing for ventilation, and thereby reduce heat build-up which could influence dew duration. On August 14, 1990, the Radalert unit developed a malfunctioning in its electronic circuit. The unit became unresponsive and was discontinued. Although the

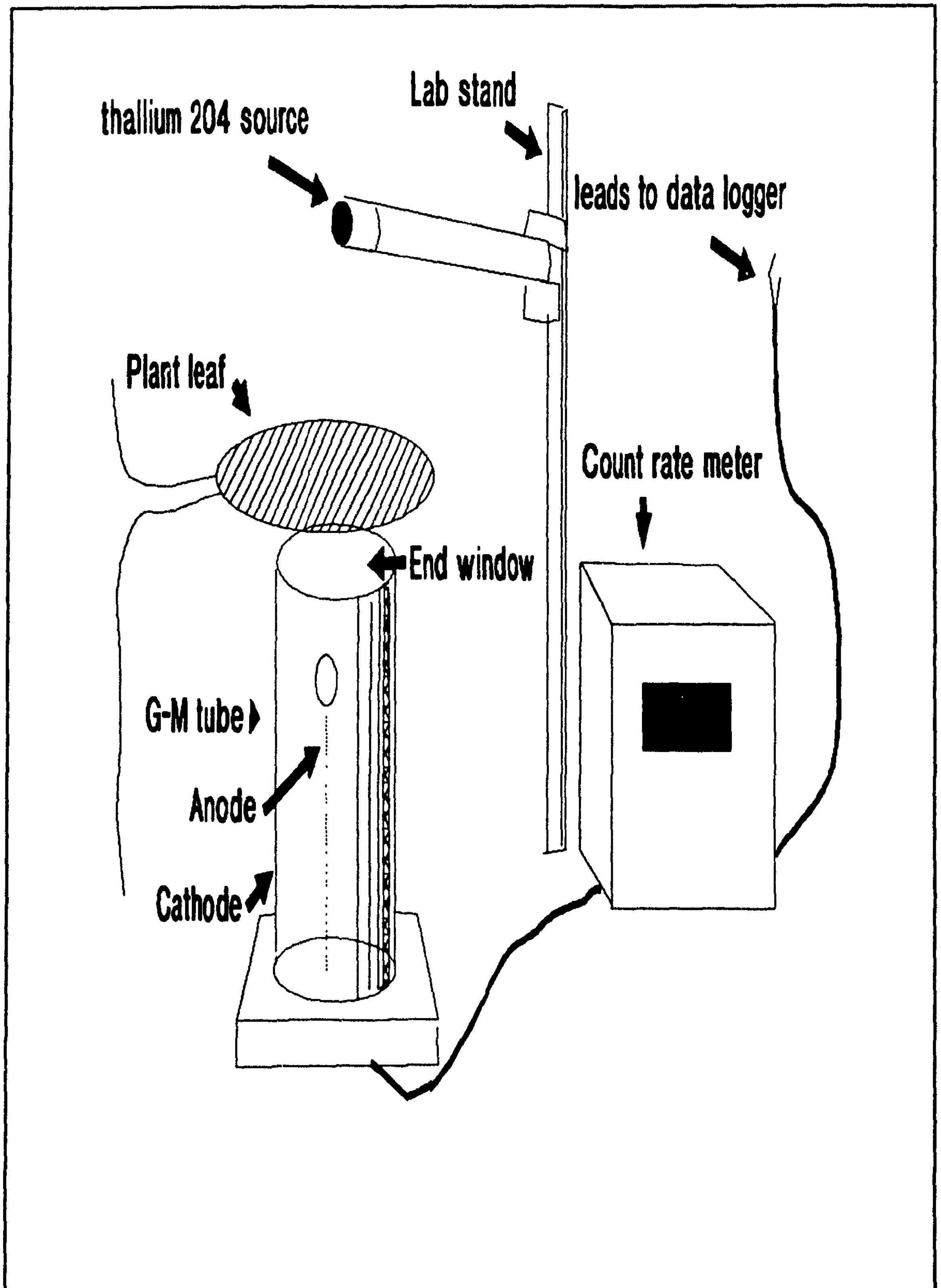

Fig. 1 BRG Sensor Layout

small unit was advantageous to use in the field, environmental conditions were perhaps too severe for it to function well. A rugged version of this unit need to be designed in the future. Thus, the BRG system that was used in 1989 field experiments was rei stalled.

III.1b Electrical Resistance Sensors

The three resistance sensors used in the present experiments operate on the same principle which is to allow a current to flow through an electrical grid when free water bridges over two wires carrying alternating current. This current is supplied by the data logger's excitation circuitry. When a wetting event, such as rain or dew is deposited on the sensor grid a voltage proportional to the amount of water on the grid will be recorded by the datalogger. When the sensor is dry there is no current flow through the grid, and hence no voltage signal is recorded by the data logger.

III.1bi Printed Circuit Board Sensor

The electric grid sensor employed in this study was purchased from Campbell Scientific Ltd, Edmonton, Canada (Model 237). The printed circuit board consisted of a hard epoxy-fibreglass board. The area was rectangular of dimensions 5.8 x 7.7 cm on which a grid network of gold coated copper lines were etched. These metal lines were interwoven so that a one mm gap existed between the adjacent fingers (Fig. 2a). Any two interspaced grids were attached to a two wire shielded cable which was connected to a data logger. The sensor used in all experimental settings was not treated with a coating of latex paint to increase sensitivity as suggested by Davis and Hughes (1970).

III.1bii Cotton Cloth Sensor

The cloth sensor used in this project was originally built to specifications in this laboratory as outlined by Weiss and Lukens (1981), and Weiss and Hagen (1983). The sensor consisted of a rigid rectangular frame on which an alternating network of 0.022 cm diameter galvanised wires were tightly woven. Each wire was passed through a plastic perforated board at each end and was electrically isolated from the adjacent wires. The frame was 5.0 cm wide and 6.5 cm long with two brass rods on the other sides to provide rigidity and to complete the rectangular sensing area.

Spacing between two adjacent wires was 0.5 cm. Steel wires were also used to provide strength to the sensing area. A modification involving the cotton cloth ER was made by interweaving a cloth between the wires. This method of cloth positioning was used to insure good electrical contact with the wire network when the cloth was wetted. This proved to be a good method of anchoring a cloth to the wire frame when wind was present (Fig. 2b). Previous studies found that the cloth had to be inspected daily due to damage done by small animals. The cloth was tied down to the frame to prevent wind removal (Weiss and Lukens, 1981).

III.biii Wood Sensor

The wood sensor ER was designed in this study to overcome some deficiencies in the printed circuit board sensor described earlier. A thin wooden board, 0.25 cm thick , 12.5 cm long, and 3.5 cm wide at the base was used as a support for the electrical grid network. The use of a wooden surface was also intended to minimize heat storage and heat build-up which occured with an epoxy-fibreglass board (Wiess and Lukens, 1981). The conducting wire used was the same 0.022 cm diameter galvanized steel employed on the cotton cloth ER sensor. The spacing between adjacent wires was 0.1 cm; this was to ensure a high degree of sensitivity to light dewfall. A layer of wax was melted onto the wood surface to simulate the waxy nature of experimental leaves (Fig. 2c).

III.2 AUXILIARY EQUIPMENT

A general description of the data logger settings and wire connections in the sensors used for field and laboratory experiments are given as follows. The data logger used was a Campbell Scientific Ltd, Edmonton, Canada, Model CR7. The CR7 has inputs for reading differential voltages which was used with the BRG. It also has inputs that read a single ended voltage for the electrical resistance sensors. In the latter case the data logger supplied an AC excitation voltage (5000 mV) to each electrical sensor. The alternating current does not polarize water molecules that collect on each sensor surface which prevented augmentation of evaporation rates. Shielded cables, 2.5 m long, were used

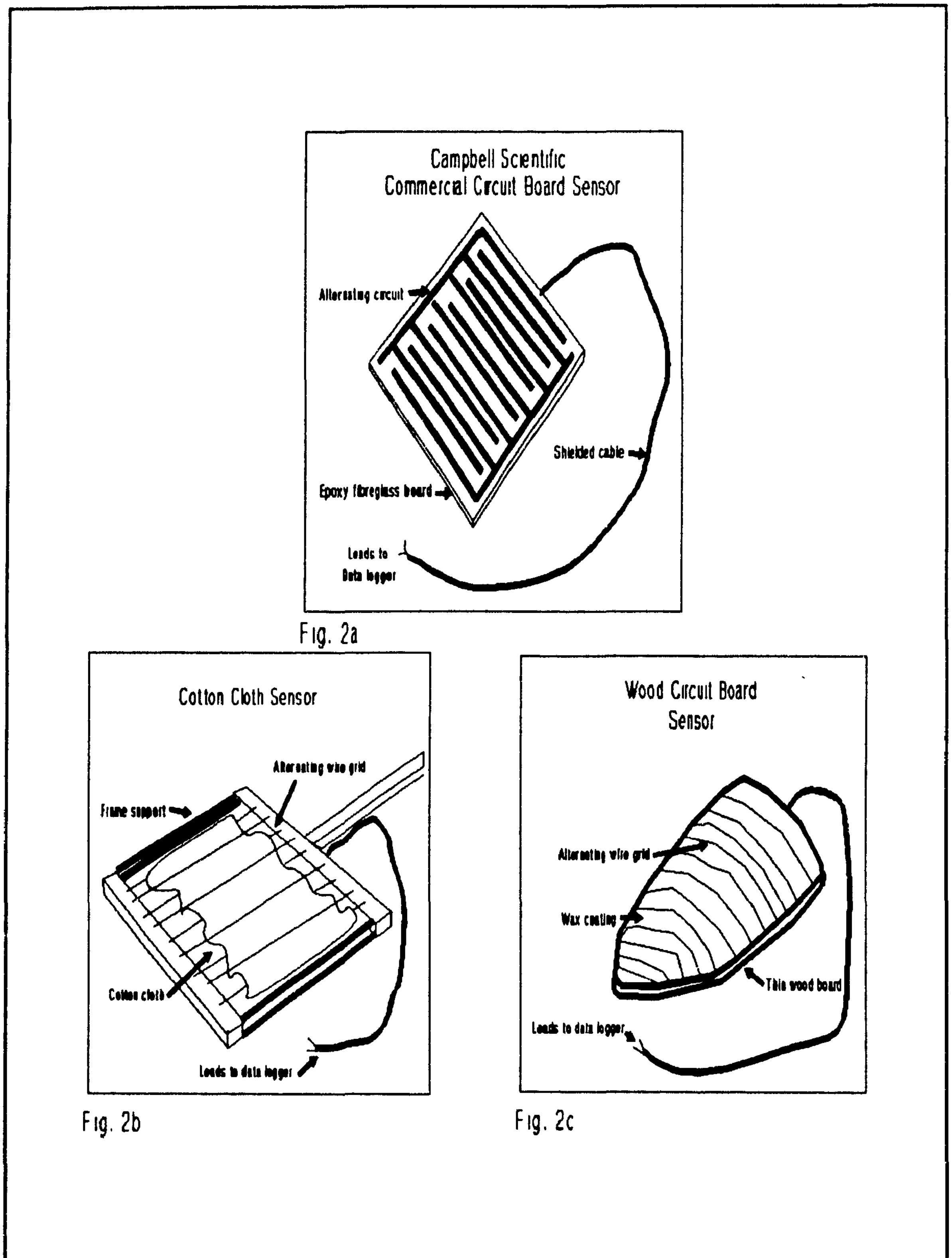

Fig. 2

Electrical Resistance Sensors

to attach the wood and cloth ER sensors to the data logger. Moreover, the sensor cables had resistors which matched with the cable resistance of the commercial sensors. This was to ensure that the output voltages of the three ER sensors were approximately the same. All electrical connections were sealed with Sykone silicone sealant and heat shrink tubing for insulation. The same connection sequence was used for both the dew chamber and field experiments.

The data logger was programmed to record a voltage reading for each sensor at every five minute time intervals. The times were recorded by minutes, hours, and Julian calender day. Data were recorded onto a standard cassette recorder. The data recorded on the cassette tape was processed through a computer via a Campbell Scientific CR21 interface box.

The field experiments were performed in late summers of 1989 and 1990. Late summer was selected to test the sensor performance since dew deposition on leaves was usually heavier than that which could be found in the early growing stages of the plants. However, early growing season will perhaps be equally important from a plant pathology point of view. A soybean crop was used during field experiments of 1989 to evaluate sensor performances. A tobacco crop was used in 1990 for the same purpose. A dew chamber experiment was carried out with soybean plants in 1989. A compact and relatively inexpensive beta-ray gauging system was developed for the 1990 field trials using a commercially available Geiger- Mueller detector. The potential use of the BRG sensor as a means to determine water and heat stresses was then evaluated as data patterns on these environmental stresses became evident.

III.3 TIME PERIOD

The installation of sensors and recording equipment for 1989 field trials began on August 18, 1989. Data recordings were terminated October 1, 1989, when soybean leaves senesced.

Field experiments of 1990 were initiated on August 3, 1990. As mentioned earlier, because of the malfunctioning Radalert unit all data collected upto August 14, 1990,were discarded. Data collection was then re-established August 14, 1990, and was finally ended on September 21 just before tobacco leaves turned yellow.

Laboratory experiments were performed throughout the winters of 1989 and 1990.

III.4 EXPERIMENTAL SITES

The experimental site for 1989 field trials was located at the Seed Farm research center of Macdonald College of McGill University. Leaf surface wetness sensors were installed in an experimental soybean crop 4.6 m from a farm road. A different site was selected for 1990 experiments on tobbacco. This site was located approximately 91.5 m further north from the original site in the seed farm and 30.5 m from the road (Fig. 3).

Laboratory experiments were conducted in a phytotron, Plant Science Department, Macdonald College. A Percival dew chamber (Model 50036, Boone, Iowa, U.S.A) was used to evaluate leaf wetness duration time of dewfall for the three ER sensors. The dimensions of the dew chamber were: 119 cm long, 59 cm wide, and 98 cm high.

III.5 PROCEDURE

It was necessary to protect the G-M detector from severe thunderstorms in the summer. The BRG system was used to monitor surface wetness continuously for 24 hours throughout the summer. Protection from mild weather was provided by the leaf itself. However, when the weather turned severe this protection was not enough. Several layers of water impermeable but thin plastic sheets were used to cover the mica window of the G-M detector. In a previous study a G-M detector was destroyed when water diffused through the mica window during a thunderstorm (Barthakur, 1985). Electrical connections were carefully sealed with silicone to prevent shorting of the wires from water.

An attached soybean leaf was placed over the G-M tube of the beta-ray gauge. The leaf was held fixed with tapes so that it would not flutter in the wind. The G-M tube was located at half the distance from the soil to the crop canopy. The ^{204}Tl source was adjusted on a laboratory stand so that the cylinder containing the source was tilted skyward 35° relative to the horizontal plane. This arrangement insured that water would not accumulate on the leaf beneath the source. Three electronic resistance grid sensors were then aligned in a North-South orientation with respect to the BRG.

Three ER sensors and the BRG were placed at a height of 0.5 m from the soil surface. All sensors were positioned so that their surfaces faced upwards to the sky. Leaves and branches were not allowed to overshadow the experimental leaves insuring radiation losses would be equal. To minimize water puddling on surfaces of the sensors these were tilted along their long and short axes (Gillespie, 1978). The long axis was tilted 15° with respect to the horizontal ground and oriented towards west; the short axis was also tilted 15° and oriented towards south.

Although the data logger recorded wetness information, additional weather data were also observed visually. These include meteorological sky conditions, dew, rain, and fog events. Visual observations were needed to test the performance of wetness sensors. Day and night time sky conditions were recorded as clear, cloudy, or rainy. Air temperature was noted as cold, cool, warm, or hot. Surface morphology of experimental leaves was examined. Any problem associated with the performance of auxiliary equipment such as the data logger and the tape recorder were also noted.

Electrical power was available in a nearby bench-mark climatological observatory across a farm road from the field plot. A small trench was dug across this road and a power cable was placed in it. Power to the data logger and the ratemeter of the BRG was supplied from this source.

For 1990 field trials three one m tall tabacco plants (Nicotiana tabacum L.) were planted near a meteorological instrument mast (Fig. 3). This was done so that use could be made

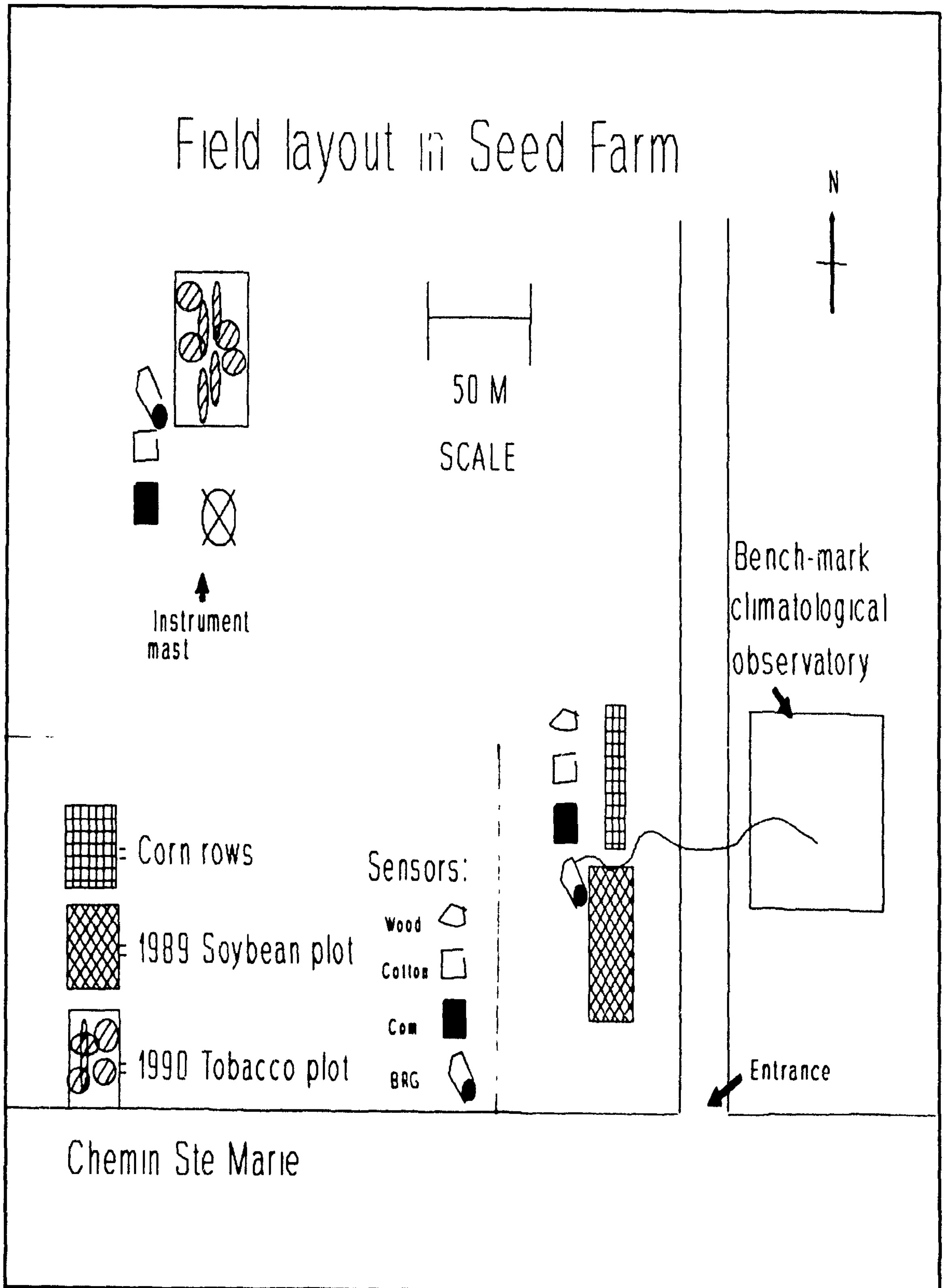

Fig. 3 **Field Layout 1989,1990**

of the CR10 data logger that had been installed there by the Department of Geography, McGill University. Four channels of the data logger were made available for this study. The ER sensors were aligned along the same north-south direction as in 1989. A tobacco leaf at 0.9 m height was used as the detecting surface for the BRG. The data logger's recordings were stored in ram memory and was accessed through a nine pin RS-232 port via a microcomputer. The data logger could hold approximately two weeks of stored data in memory and was self powered by internal batteries. The sensors and the plant leaves were visually inspected several times daily in order to establish surface wetness. Visual observations were compared with the BRG and ER sensors.

Dew chamber experiments were carried out as an additional test for the sensors. A dew chamber simulates dew formation as it occurs in nature under field conditions. The refrigerated inner wall of a dew chamber would act as equivalent to a clear night sky. The wall is cooled so that the long wave thermal radiation emitted by sensors and leaves would be absorbed into it. This would allow moisture in the air of the dew chamber to condense on the sensor surfaces as occurs in the atmosphere. The moisture in the dew chamber was supplied by a heated water bath under a grate that supported the sensors. The temperature in the water could be adjusted to provide for mild or heavy formation of dew. Lighting in the chamber was provided by incandescent and fluorescent bulbs.

The parameters of the dew chamber that could be adjusted were: refrigerator wall temperature, water bath temperature, and incandescent and fluorescent lightings. The air temperature was automatically regulated by the dew chamber and was kept constant.

For this experiment a potted soybean plant was used in conjunction with the beta-ray gauge. As usual a leaf was taped in position over the G-M tube's end window.

All four sensors were placed equidistantly at five cm from the inner refrigerated wall. The sensors and the potted soybean plant were placed on a metal grating 15 cm above the bottom of the dew chamber and five cm above the water bath. The dew chamber timer controls for water bath, wall temperature, and photoperiod were set to simulate a 24 hour day cycle. Dew formation commences at 18:00 hours when the water bath attains 25 °C; the refrigerated wall cools to the specific temperature setting required and the lighting is turned off. The dew chamber will then maintain this condition for 12 hours to simulate a clear night sky. Under these conditions dew formation occurs. In the morning the lights are turned on at 6:00 am, the water bath temperature decreased to 15 °C and the wall temperature increased to 25 °C. The air temperature approaches the wall temperature. These chamber settings remain for 12 hours until the next 24 hour cycle begins.

In order to achieve different dew duration times, the only setting that was adjusted was the wall temperature. This was set at four different temperature settings of -10 °C, -5 °C, 0 °C, and 10 °C. A different temperature setting continues for a 24 hour cycle.

III.6 DATA ANALYSIS PROCEDURE

Once all data were accumulated on the tape recorder for the 1989 field and laboratory testings, these were transferred to a computer. Data for the 1990 field trials were transferred directly to the computer memory. Data were transformed from binary to a data format, and eventually to a print format by means of Campbell Scientific Split program. The print file was then imported to Iotus 1-2-3 for analysis. Graphs of voltage versus time were created for each of the four sensors. From these graphs the elapsed time for each leaf wetness event was logged for later comparison. In general, the electrical resistance sensors would indicate a dry leaf surface state with a 0 mV reading. In the case of the wood sensor a dry state was approximately 80 mV. This was probably due to current flow across the wax surface. The resistance sensors would register a wet state with a voltage reading proportional to the amount of moisture present on the sensor surface. This was true until the sensor surface was completely saturated, then the voltage reading would remain unchanged at approximately 900 mV. The wet state of the BRG varied exponentially with the attenuation of the beta particles by the amount of water on a leaf surface. With maximum leaf surface saturation, the BRG registered a reading of 3 mV or approximately 3000 counts per minute (cpm). In the dry state the BRG registered 5.5 mV which was equivalent to a count rate of about 5000 cpm.

The data collected from the field was then sorted into three different moisture categories, dew, rain and fog. During the 1989 field experiments, August 18 to October 1, there were four dew episodes, seven rain events, and four fog events. Not all sensors managed to detect all events, however. The BRG sensor detected all events.

During the 1990 field trials, August 14 to September, 17 dew, and eight rain events were recorded. Two foggy conditions occurred at about the same time it was raining. For this reason, these fog situations were classified as rain events.

CHAPTER IV: RESULTS AND DISCUSSION

The analysis of data followed a procedure where all wetness events from the ER sensors were judged against corresponding results of the BRG system. Since there was a certain amount of difficulty experienced in ascertaining the exact starting and terminating points of a wetness event, a margin of error was established. ER sensor data could be resolved to within one hour of actual time of start and end points of specific wetness events. This is due to the uncertainty involved in reading time units from recording charts and data files. The one hour margin indicates the maximum allowable error and appears on data graphs as a "+". When an ER sensor has a reading that exceeds the "+", then this recording by the sensor is deemed to be inaccurate. The one hour margin of error is expressed as a percentage of BRG data.

In some cases, a "-" appears on a data graph. This indicates that for this particular event the sensor failed to detect any moisture. When a recording is not drawn on a graph and no symbol is present, this signifies that the particular sensor had a 0% difference from the BRG reading; the sensor had a perfect match with the BRG.

IV.1 LABORATORY EXPERIMENTS

Since a BRG employs an attached leaf as the condensing surface, detection of surface wetness is expected to be more realistic than other ER sensors that use physical leaf models of various materials. This was indicated by several researchers whose work was described in the literature review section of this thesis. For these reasons, BRG data were taken as references, and the responses of other ER sensors were evaluated accordingly.

Experiments in a dew chamber demonstrated the difference in behaviour between various sensors (Fig. 4). Duration time of dew was significantly longer as detected by the BRG than the ER sensors under identical conditions in the chamber. Four different conditions, ranging from heavy to mild dewfalls, were simulated by varying wall temperatures of the chamber from -10 to 10 °C. Accuracy of commercial and wood ER sensors improved with an increase in the amount of dewfall. Difference between the BRG and the commercial ER sensor decreased from 37.8% to 5% as dewfall increased from light to heavy. The wood ER sensor values decreased from 35.1% to 16.6% compared with the BRG under identical conditions. The cloth ER sensor showed only a slight trend towards this behaviour with differences decreasing from 89% to 79.9% for light to heavy dew. This tendency was also observed in a similar dew chamber study in which the difference between a BRG and a cotton cloth ER sensor decreased from 44.4% to 24.3% as dew formation increased from mild to heavy (Barthakur, 1987).

Thus, response of the commercial ER sensor were closest to

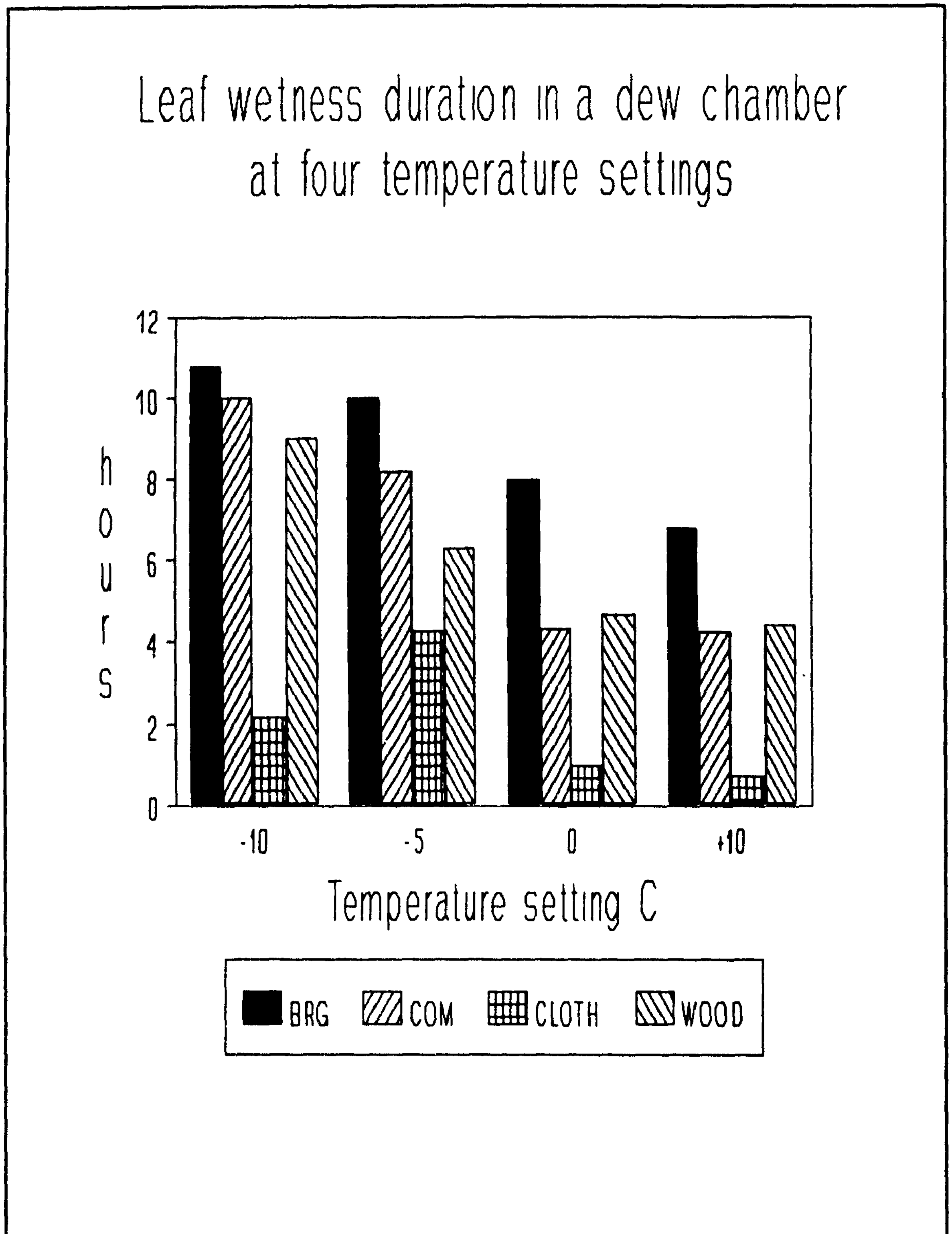

Fig. 4 Dew Chamber Results 1989

the BRG when dew was heavy; wood and commercial ER sensors responded almost equally when dew was light. The cotton cloth ER sensor showed the poorest response of all sensors tested. The commercial and wood ER sensors underestimated wetness duration on the average 26.7% and 32%, respectively, for all four artificially produced dewfalls. Dew duration lasted 78.5% less for the cloth sensor.

Two main reasons may be cited for unsatisfactory performance of the cloth ER sensor in the dew chamber. Firstly, fabric texture could influence distribution of water throughout the cloth by capillary action of fibres. On a real waxy leaf surface, dew water tends to form in spherical or cylindrical drops as a result of surface tension. Leclerc et al. (1985) found the shape of dew drops on soybean leaves to be cylindrical. Therefore, one would expect the rate of evaporation from individual drops to be quite different from a wet cloth. Moreover, small water droplets on a leaf surface could coalesce to form big water drops which would considerably alter the drying rates of leaves. Secondly, under heavy dewfall, a cloth could be saturated uniformly whereas individual drops may still remain on a real leaf surface. Again, this will produce different drying rates of surfaces. Although a cloth could be a convenient surface for wetness measurements and may simulate well a real leaf in emissivity characteristics, the physical nature of the cloth needs to be chosen carefully to represent realistically evaporation rate of water from a leaf surface.

The present results did not agree, with previous research.

A cloth ER sensor showed an average of 26.6% less in dew duration when compared with a BRG in a dew chamber (Barthakur, 1987). This compares favourably with present values of 26.7 and 32%, respectively, for the commercial and wood ER sensors. However, a 78.5% difference obtained for the cloth ER sensor in this study was high. This could be attributed to the physical properties of the cloth specimen used in the present experiments. It was found that when a cloth, 0.012 cm thick and a mesh size of one mm, was substituted for a 0.023 cm thick cloth, the average drying rates increased from 26.6% to 49.9% (Barthakur, 1987). Thus, it seems that cloth thickness and texture dramatically influence drying rates.

IV.2 FIELD EXPERIMENTS

IV.2a Wetness from Dew, 1989

Percentage differences in leaf surface wetness duration measurements between various ER sensors and the BRG are summarized in Table 1. Three kinds of atmospheric precipitates are included in this table. An important feature of these results is the relatively large variation in error in the measurements. Standard deviations ranged from ± 9.4 to ± 30.0% which indicate large errors involved in the individual measurements of wetness from a variety of atmospheric precipitates. Leaf surface wetness events due to dew

TABLE I

Percent difference of three ER sensors as compared with a BRG for 1989 field session.

Sensor	Preciptation	Percent difference				Missed
		high	low	Ave	± SD	
commercial	DEW	-28.9	-0.6	17.2	12.1	1
cloth	DEW	-50.0	1.1	23.8	19.2	0
wood	DEW	-54.5	5.8	28.2	21.0	0
commercial	RAIN	52.4	0.0	22.2	15.6	1
cloth	RAIN	30.2	2.5	15.9	10.8	1
wood	RAIN	-36.5	8.8	19.3	9.4	0
commercial	FOG	55.8	2.7	32.7	22.3	1
cloth	FOG	79.3	16.5	43.4	26.4	1+
wood	FOG	78.8	-13.0	35.8	30.0	1+

+ indicates failure to distinguish between three fog events.

- indicates an underestimate.

High represents the largest percent difference between the ER sensor and the BRG for a particular precipitation event.

Low represents the smallest percent difference between the ER sensor and the BRG for a particular precipitation event.

are presented in detail (Fig. 5). In general, ER sensors underestimated the actual dew length on soybean foliage compared with the BRG. Out of four separate dewfalls in 1989, only one event was recorded by the commercial ER sensor that can be considered as perfectly matched with the BRG. Two dewfall events were underestimated by -22.1 and -28.9%. The average percent difference in error (AE) from the BRG was 17.2% with a standard deviation (SD) of ± 12.1%. Moreover, the commercial sensor failed to record the second dewfall event.

The cloth ER sensor recorded two dewfall events that were within the margin of error. Two other events were underestimated by -33.8 and -50.0%. The AE of 23.8%, with a SD of ± 19.2%, was higher than that for the commercial sensor. The wood ER sensor measured two dewfall events which were within acceptable levels of accuracy from the BRG. Two events were recorded as underestimates with values ranging from -43.1 to -54.5%. The response of this sensor with an AE of 28.2 and a SD of ± 21.0% may be considered as unsatisfactory.

The relatively large differences exhibited by all ER sensors in estimating duration times on second and third dewfall events could be attributed to possible effects of cloud cover during these nights. For example, dew deposition began at 19:00 hours standard time for event three, but cloud covered the sky at about 23:00 hours which led to the complete evaporation of dew water from the surfaces of the sensors. However, the BRG continued to indicate the

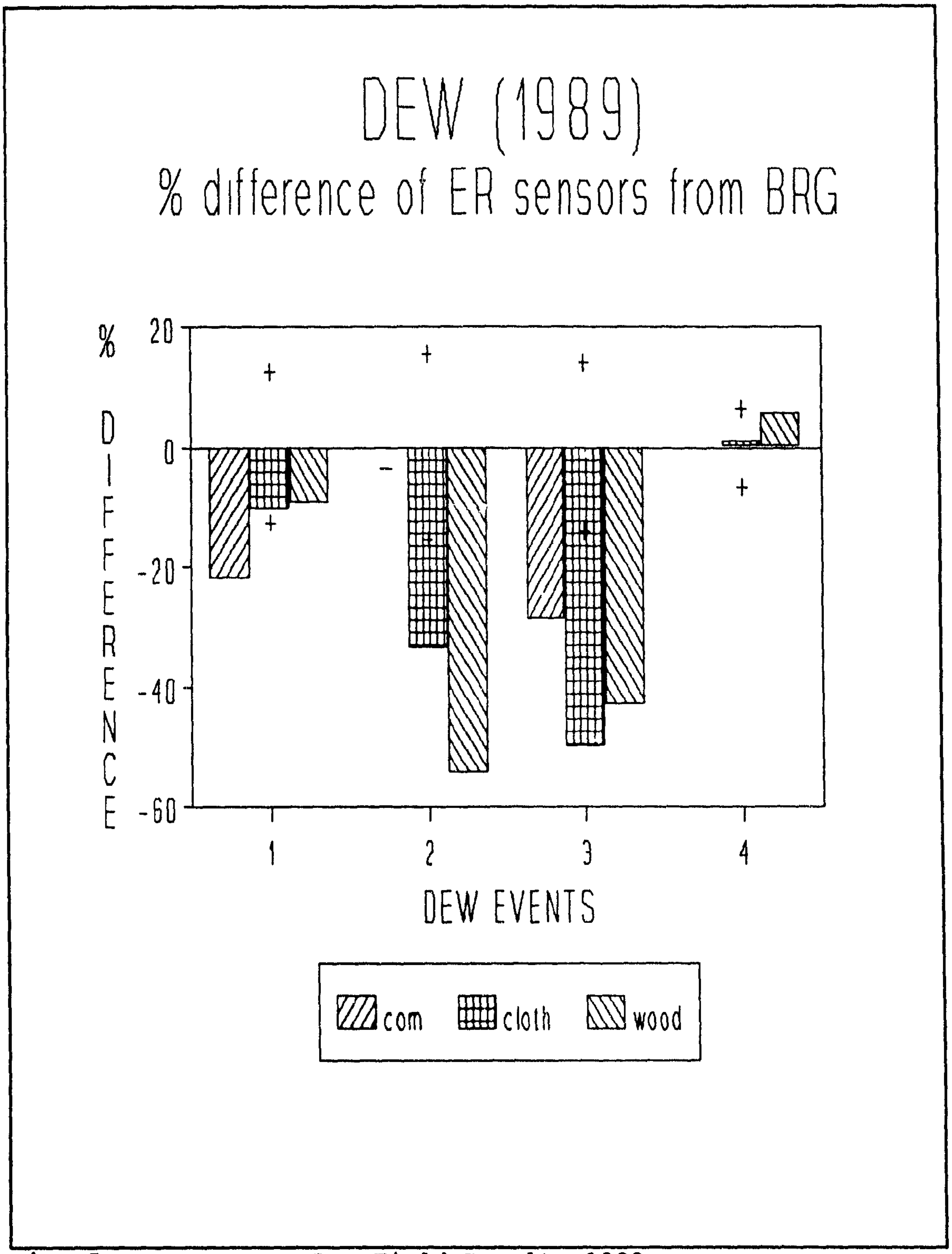

Fig. 5 Dew Field Results 1989

- sign denotes failure of sensor to record event.

presence of dew until 02:10 hours. A probable reason for the rapid evaporation of dew water on the detector surfaces was relatively small amount of dew formed during these nights. Heavy dew deposition normally occurred at approximately 03:00 hours.

All three ER sensors underestimated the length of time dew remained on soybean leaf surfaces. Leaf surface morphology of the soybean may affect moisture holding capacity which, in turn, will affect evaporation rates. Soybean leaves have long hair-like structures on their surfaces. These small hairs are vertically oriented when a surface is dry. When wetted the hairs assume horizontal orientation and water is trapped between them and the leaf surface. This was observed in a laboratory experiment with a microscope at 40X magnification. These long trichomes (hairs) may reduce mass transfer rates from a leaf surface to the atmosphere by smoothing the air flow over the leaf and thus reduce turbulence (Personal communication with Professor P.H. Schuepp, Department of Renewable Resources, Macdonald College). Dewfall events one and four showed presence of water on plant and sensor surfaces throughout the night. These surfaces dried in the morning by radiation from the sun. Dew water evaporated from surfaces of the ER sensors faster than from a real foliage. The ER sensors responded to dew termination depending upon their materials of construction. Dew water evaporation rate was much more rapid from the surface of the commercial sensor than either the cotton cloth or the wood sensor. Solar radiation is absorbed rapidly by the fibreglass-epoxy board and the metal elements of ER sensors.

Consequently, the heated surfaces led to an increased evaporation rate (Weiss and Lukens, 1981) of water.

For a soybean crop, the cloth ER sensor was found to perform satisfactorily Two dewfall events did not differ significantly from those of the BRG. The commercial ER sensor seemed to lack sensitivity to light dew as demonstrated by its failure to record the second dewfall event. This lack of sensitivity may have been caused by an insufficient amount of water to bridge the gap between two adjacent wires of the electrical grid on surface of the sensor. This was the primary reason for the recommendation of the application of latex paints on a printed circuit board surface (Gillespie and Kidd, 1978; Davis and Hughes, 1970) of an ER sensor.

The wood ER sensor performed adequately in detecting dew. But, it exhibited similar lack of sensitivity shown by the commercial sensor. This could be attributed to the similar design of the wood ER sensor as the commercial one. Basically, the shortcomings of the ER sensors could be traced to either the wire spacings or heat generation in the electric circuit and the substrate materials.

A leaf in a dense canopy of soybean dries slowly. Such a canopy acts as a shelter, and water evaporation from a surface is impeded due to protection offered by other neighbouring leaves. This essentially reduces mass transfer rates of water from forced convection. Since the cotton cloth ER sensor also required a longer time to dry than the commercial sensor, a good choice for this canopy would be a cloth ER sensor.

IV.2b Wetness from Rain, 1989

Leaf surface wetness from rain was detected by the ER sensors somewhat more accurately than was the case for dewfalls (Table 1). Performance in detecting rain varied with sensors (Fig. 6). Both positive and negative differences were observed when compared with the BRG. This was in contrast with dewfall detection where differences were mostly negative (Fig. 4).

The commercial sensor recorded only two of seven rain events within an acceptable level of accuracy. One rainfall event (number six) matched perfectly with the BRG. Two rainfall events were recorded as overestimates and two rainfall events were underestimates. The ranges for the over and underestimates were 23.6% to 17.1% and -23.5% to -16.5%, respectively. The seventh rainfall event was not detected by this sensor. The AE value was 22.2% with a SD of ± 15.6%.

The cotton cloth ER sensor performed somewhat more satisfactorily than the commercial sensor in detecting wetness duration from rain. Three accurate readings were scored. Three times this sensor overestimated wetness duration by 12.2% to 30.2%. The AE was 15.9% with a SD of ± 10.8%. One rainfall event was not detected.

The wood ER sensor did not perform as well although it had one perfect score. Three rainfall events were overestimated by 8.8 to 36.5%. Three events were rated as underestimates by the wood

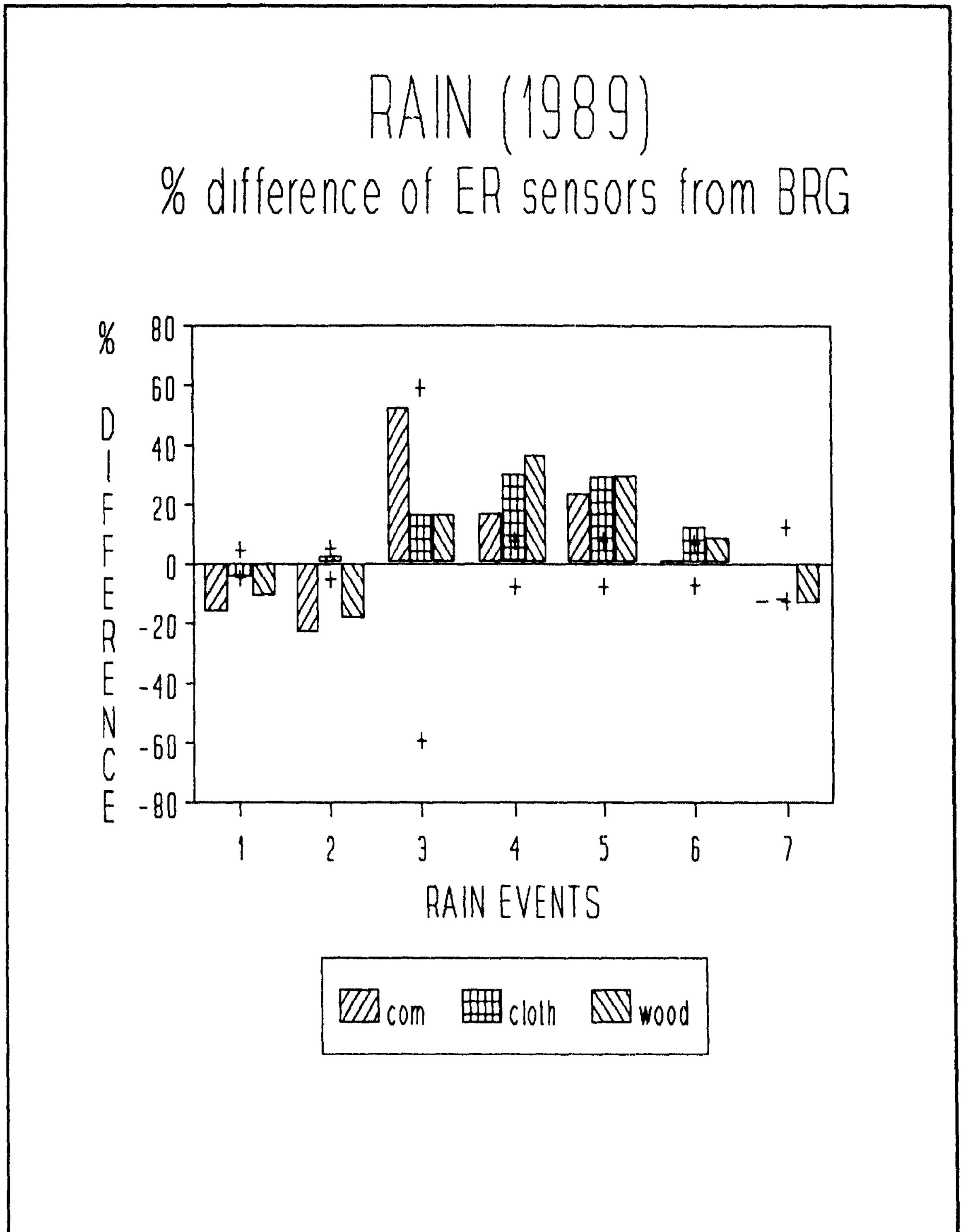

Fig. 6 Rain Field Results 1989

- sign denotes sensor did not record event sensor, and these values ranged from -11.2% to -18.7%. It was interesting to note that this sensor recorded rainfall event seven which the other two ER sensors failed to detect. This rain was categorized as a very light drizzle. The BRG record showed the drizzle initiation at 10:55 and termination at 18:55. The wood ER sensor showed the beginning and end of this drizzle at 11:30 and 18:25, respectively.

IV.2c Wetness from Fog, 1989

Fog is difficult to differentiate from light drizzle. Occurrences of fog were obtained from meteorological forecasting from Dorval airport which is about 15 kilometres from the experimental site. Fog detection was most inaccurate for cloth and wood ER sensors (Table 1; Fig. 7). The cloth sensor gave the poorest results, it recorded one event with an underestimate of -34.4% and another event with an overestimate of 16.5%. Events three, four, and five were overestimated by 79.3%. The cloth had the highest AE of 43.4% with a SD of ± 26.4%.

The wood ER sensor performed unsatisfactorily in fog detection. It had one result within the margin of error and two overestimates; one of 15.2% and the other of 78.7% for the events three, four, and five. The AE was 35.8% with a SD of ± 30%. Moreover, these sensors failed to distinguish between three separate but contiguous fog events number three, four, and five so that the duration time recorded by these sensors was the cumulative of three individual events and the wetness duration time

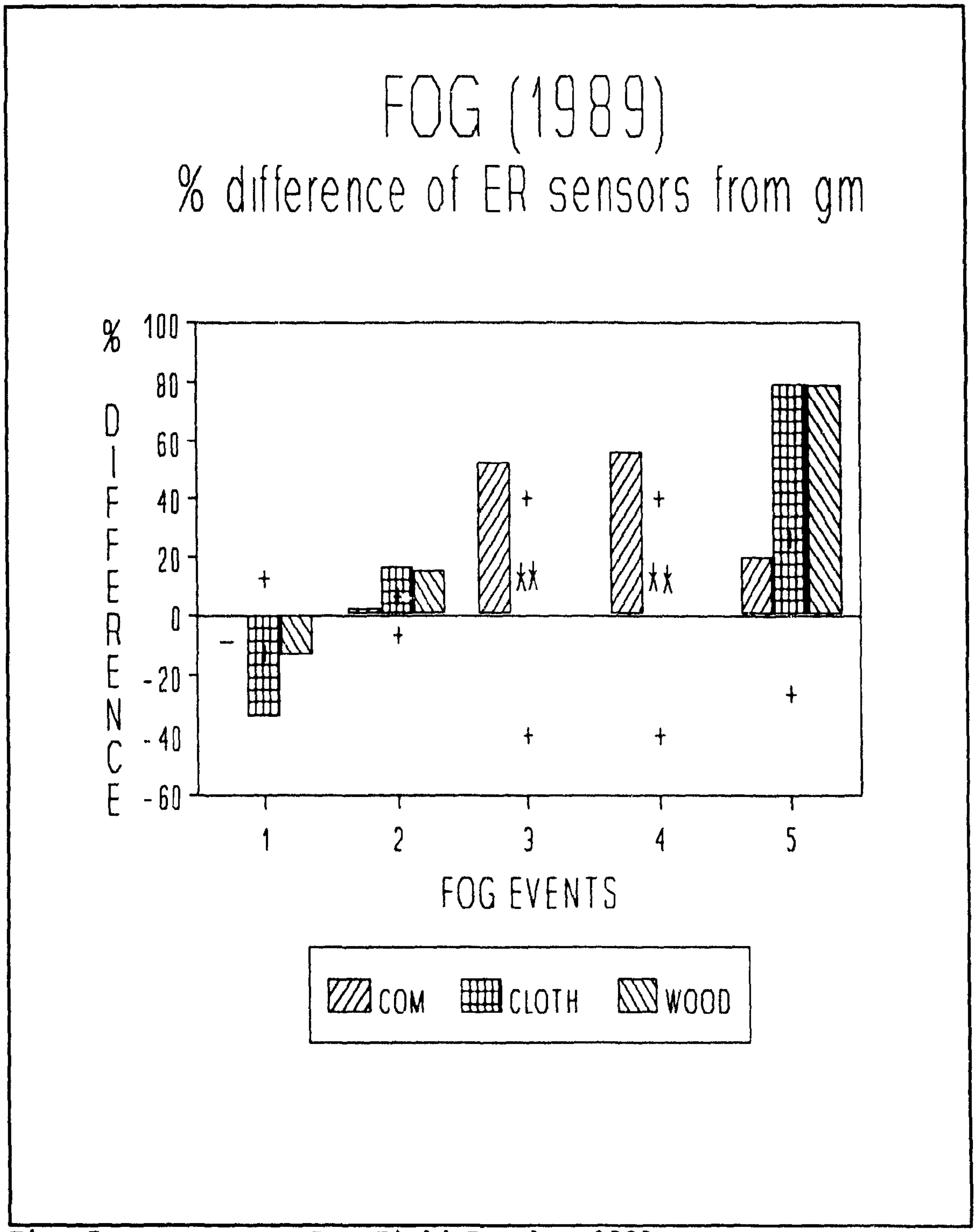

Fig. 7 Fog Field Results 1989

- sign denotes failure of sensor to record event.
* sign denotes sensor failed to separate this event from other events.

had to be considered as resulted from one single event (Fig. 7). Temporal resolution of atmospheric precipitations are important since surface wetness duration parameter appears as an exponent in a power law relationship of infection efficiency models used by plant pathologists. An example of this is the Richards model used by Lalancette et al. (1988). Any error in wetness duration may result in inaccurate predictions of infection intensity of plant disease from mathematical models. Thus, the wood sensor may be considered as unsatisfactory on this basis.

The commercial sensor performed fairly well in detecting wetness duration from fogs. However, it did not register one fog precipitate. Values for the two overestimates were not as high as the ones associated with the two other ER sensors. Two wetness events fell within the margin of error. The overestimate values were 52.4 and 55.9%, respectively. This could be attributed to the fact that the second and the third fog events were of short duration which resulted in the high percentage differences. The AE for this sensor was 32.7% with a SD of ± 22.3%.

IV.2d Wetness from Dew, 1990

Deviations in leaf surface wetness duration from BRG data and as measured by ER sensors for tobacco plants are summarized in Table 2. The 1990 field data showed considerable improvement

TABLE II

Percent difference of two ER sensors as compared with a BRG for the 1990 field session.

Sensor	Preciptation	Percent difference				Missed
		high	low	Ave	± SD	
commercial	DEW	17.2	0.0	5.9	5.2	0
cloth	DEW	17.2	2.3	6.2	4.4	0
commercial	RAIN	57.9	1.6	24.6	18.5	0
cloth	RAIN	60.9	3.1	35.2	22.5	0

High represents the largest percent difference between the ER sensor and the BRG for a particular precipitation event.

Low represents the smallest percent difference between the ER sensor and the BRG for a particular precipitation event.

from those of 1989 results. For 1990 data there were no missing events reported by the ER sensors for either dew or rain. Only two sensors were used, as previously mentioned, and these were the commercial and cotton cloth sensors. The wood sensor did not work well in the 1989 field session. The wax coating had deteriorated to the point where the sensor was not functioning reliably. For this reason, this sensor was excluded for 1990 field trials.

Detailed results of wetness duration measurements from dew by ER sensors are shown in Fig. 8. The 1990 data contrasted sharply with the results on soybean crop of 1989 field study. This was in conformity with the conclusions of Huband and Butler (1984) who stated that plant height and sparse canopy contributed to accurate wetness duration measurements by ER sensors. Difference in leaf size may also have affected wetness duration measurements. Tobacco leaves are several times larger in area than an average soybean leaf. Heat and mass transfer rates are substantially different from large compared with small leaves. Thus, the fixed size of ER sensors do not represent the actual heat and mass transfer characteristics of real leaves of various sizes and shapes.

Generally, the results given by both sensors for dew events were overestimates and most of these deviations were due to the extended dew drying times. But in several cases, for example, event numbers 2, 3, 5, 7, 8, 11, 12, 13, 15, and 16, the deviations were due to ER sensors detecting the onset of dew before the BRG. The average ER sensor response was 39 minutes faster than the BRG.

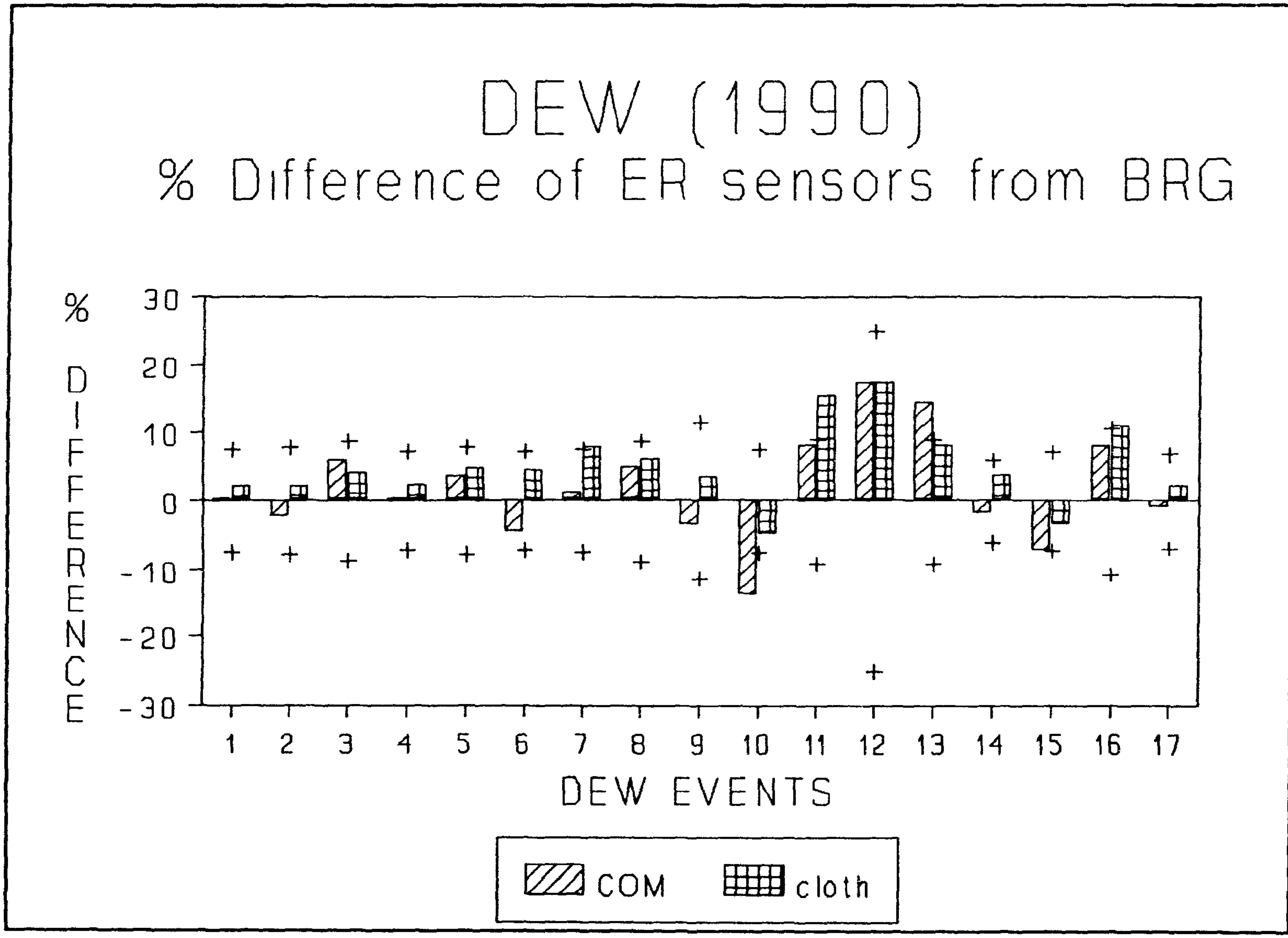

Fig. 8 Dew Field Results 1990

There could be many possible explanations for this. ER sensors may respond to high relative humidity of the atmosphere. Surface of a sensor may be conducive to condensation of water vapour. The BRG may have a slow response if dew drops are widely scattered on leaf surfaces. None of these possible explanations could be identified as the cause for the fast response of the ER sensors. However, visual observations did indicate absence of surface moisture while the ER sensors showed wetness.

For dewfall events 12, 13, and 16, cloud cover delayed the onset of dew by several hours past the normal dewfall time of approximately 19:00 hours (SD ± 1 hour).

The commercial type ER sensor responded to 15 events that were within the acceptable range; two of these readings were exactly the same as the BRG. One dew event reading underestimated the dew length by -13.9%, and one overestimated dew length by 14.3% over the BRG. The AE was 5.9% with a SD of ± 5.2%.

Event number 10 was one of the dewfalls for which the commercial sensor failed to give an accurate reading. The effects of cloud cover hampered sensor response that was similar to the ones observed during the 1989 field testing session.

The results of the cloth sensor were not quite as good as that of the commercial sensor. Fourteen out of 17 dew events were within the margin of error, and three dew duration events were deviated from 8.1 to 15.4%. The AE was not as low as that for the commercial sensor, and was found to be 6.2% with a SD of ± 4.4%.

This data showed that the commercial sensor excelled in wetness measurements from this precipitation category with a lower AE and 15 accurate readings. The 1990 data established the superiority of the commercial over the cloth ER sensor.

IV.2e Wetness from Rain, 1990

Leaf surface wetness from rain water for 1990 are shown in Fig. 9. No improvement in the performance of ER sensors over 1989 data could be discerned. Measurements of rain water duration on leaf surfaces were as inaccurate as they had been in the 1989 field session. As in the 1989 field session, the sensors tended to overestimate actual dew duration times. However, there was a tendency for the sensors to provide more accurate results when a rain event was long followed by sensor drying by the sun. When a rain was of short duration and foliage and sensor surfaces dried under cloudy skies, results were nearly always inaccurate.

The commercial sensor was only able to measure four out of eight rain events within the margin of error. Three events were overestimated by 57.9 to 17.8%. One event was underestimated by -29.0%. The AE was 24.6% and a SD of $\pm$ 18.5% which was significantly higher than what was found with respect to dew wetness. In case of the cloth sensor, the results were even more unsatisfactory. Only two out of eight events were accurate enough to fall within the margin of error. Five rain events were overestimated by 7.1 to 60.9%. The cloth and the commercial sensors agreed on one occasion in underestimating wetness duration by -

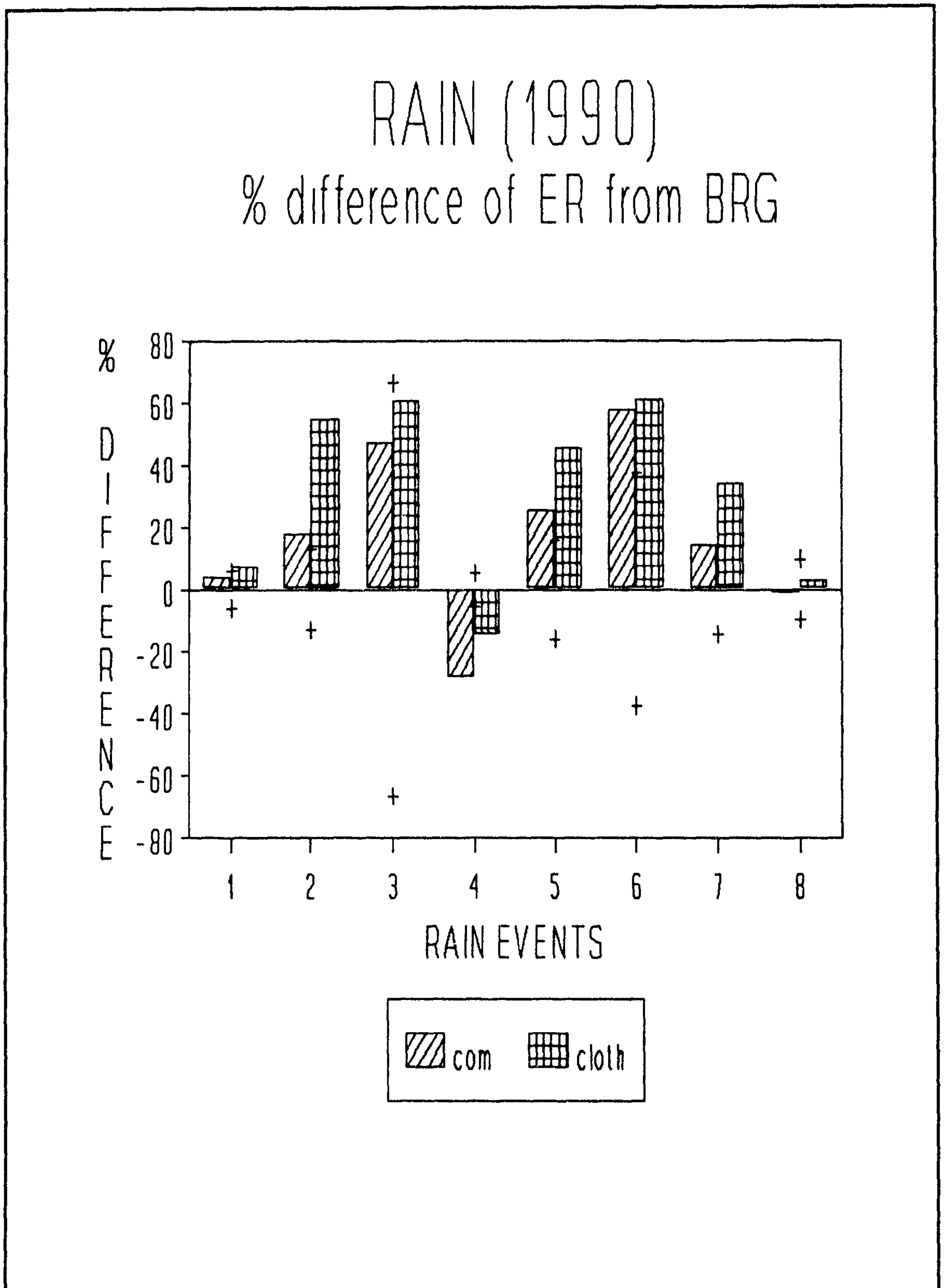

Fig. 9 Rain Field Results 1990

14.9%. The AE was 35.2% with a SD of ± 22.5%. These results again showed the commercial sensor to be superior.

The range of deviations from BRG data are very large. However, there were occasions when ER sensors provided comparative values, whereas at other times the deviations were too large to be acceptable. The rain data also indicated that the commercial is superior to the cloth ER sensor. It was noted that none of the precipitations were left undetected by the sensors in 1990.

IV.3 COMPARISON ON DEW WETNESS

The functioning of the ER sensors in detecting dew in a soybean crop in 1989 and tobacco plants in 1990 were not similar. In general, most dew events recorded in 1989 by the ER sensors underestimated the actual dew length obtained with the BRG. In 1990 this trend was reversed and the ER sensors overestimated the actual time over the BRG recordings on tobacco plants. The thick canopy of the soybean crop must have contributed to an average drying time which was attained at 10:27 AM with a SD of ± 19 minutes. Monteith (1957) reported that a dense and high canopy accumulates more dew than relatively open canopies. A few plants provided a sparse canopy for tobacco in 1990. Leaf surfaces were observed to be dry at 9:20 AM (local time) with a SD of ± 88 minutes. However, the ER sensors did not show as great a variation in drying times when moved from one crop to the other. These averages did not include extra lengthening in dew duration arising from cloud cover in the mornings. The ER sensors indicated that drying time was dependent on the materials from which they were constructed. Canopy thickness, leaf hair structures, leaf size are not taken into account in the determinations of surface drying times. These factors are inherently included in the BRG detecting device.

IV.4 COMPARISON ON RAIN WETNESS

The accuracy in the determinations of leaf wetness duration times due to rain was not as good as dew for all ER sensors both in 1989 and 1990 field sessions. The average error for the commercial, cloth, and wood ER sensors in 1989 field experiments was 22.2, 15.9, and 19.3%, respectively, and most values tended to overestimate actual drying times (Table 1). This compares favourably with 1990 field trial results. The commercial and cloth ER sensors showed average errors of 14.7, and 21.0%, respectively (Table 2). The cotton cloth ER sensor results were closer to the BRG estimates in the soybean canopy than the commercial sensor. Conversely, the commercial ER sensor provided closer results for tobacco plants than the cotton cloth ER sensor.

IV.5 COMPARISON ON FOG WETNESS

Since fogs could not be differentiated from rains in 1990, both events were classified as rain. Therefore, no comparison could be made with respect to fog precipitates in 1989.

IV.6 DATA MANAGEMENT

The CR10 data logger with built-in memory capabilities was vastly more reliable and easier to use than the CR7 data logger equipped with a cassette tape recorder which often malfunctioned. On numerous occasions, solar heat was found to cause the tape to expand. This made it extremely difficult to restore data. Fifty percent of data from the 1989 field session could not be restored from the CR7 cassette. Shielding the instrument from solar radiation had only limited success.

IV.7 COST COMPARISON

The commercial ER sensor, available from Campbell Scientific Ltd., Edmonton, Canada, approximately costs $90.00. This cost does not include any accesory electronics that is needed to record data. The cost of the cotton cloth ER sensor, when assembled in the laboratory, should not exceed $35.00. The cheapest is the wood ER sensor which can be assembled for under $10.00. Unfortunately, this sensor did not work as well as expected. The BRG system is considerably more sensitive, and is expensive. The cost of the thallium source is approximately $50.00. An ordinary G-M tube costs about $100.00; a ratemeter approximately $300.00. However, a ratemeter is not absolutely required if an independent high voltage power supply is available. The miniaturized version that was used (Radalert) in the 1990 field testing session had a total cost of $400.00 that did not include the beta-ray source. A data logger is not necessary for a wetness sensor. However, if a data collecting system is used for ER sensors, it will cost from $1000.00 to $2000.00, depending on models CR7 or CR10 (Campbell Scientific) data loggers. If a simple Rustrak chart recorder is used, the cost can be substantially reduced to less than $100.00 for each sensor including the BRG. This cost comparison shows that the price of each sensor is competitive, although the BRG system could be more expensive if a sophisticated ratemeter is bought.

IV.8 STOMATAL DYNAMICS AND PLANT WATER STRESS

An interesting aspect of this project that was observed during the analysis of the BRG's data was that significant counting rate fluctuations were occurring from late morning to mid afternoon. This effect was observed during this time interval when the sky was clear, and sunny and the air hot. As mentioned before, beta-ray attenuation in the BRG is due to an accumulation of water in the form of dew, rain or fog on the surface of a leaf. Obviously, during daylight hours on these days the leaves were dry. On examining the graphs of temperature and count rates versus time an important relationship emerged between counting rates and time (Fig. 10). As temperature increased the counting rates decreased during the morning hours. In the afternoon when temperature increased, counting rates increased. This indicated that the plants were physiologically responding to water and /or heat stresses. It was possible that stomatal closure had occurred due to stresses imposed upon the plant (Heath and Orchard, 1957; Jordan and Ritchie, 1971 Osonubi and Davis, 1980) and water vapour that would normally be transpired was stored within the leaf's mesophyll cells which in effect was causing a concentration of water to build-up in the leaf's tissue. This will create an increase in the mass thickness of leaves and decrease counting rates. Although this was not the main thrust of this research, future work should be concentrated in using the BRG system in studying stomatal dynamics as a function of temperature and moisture stress in the field.

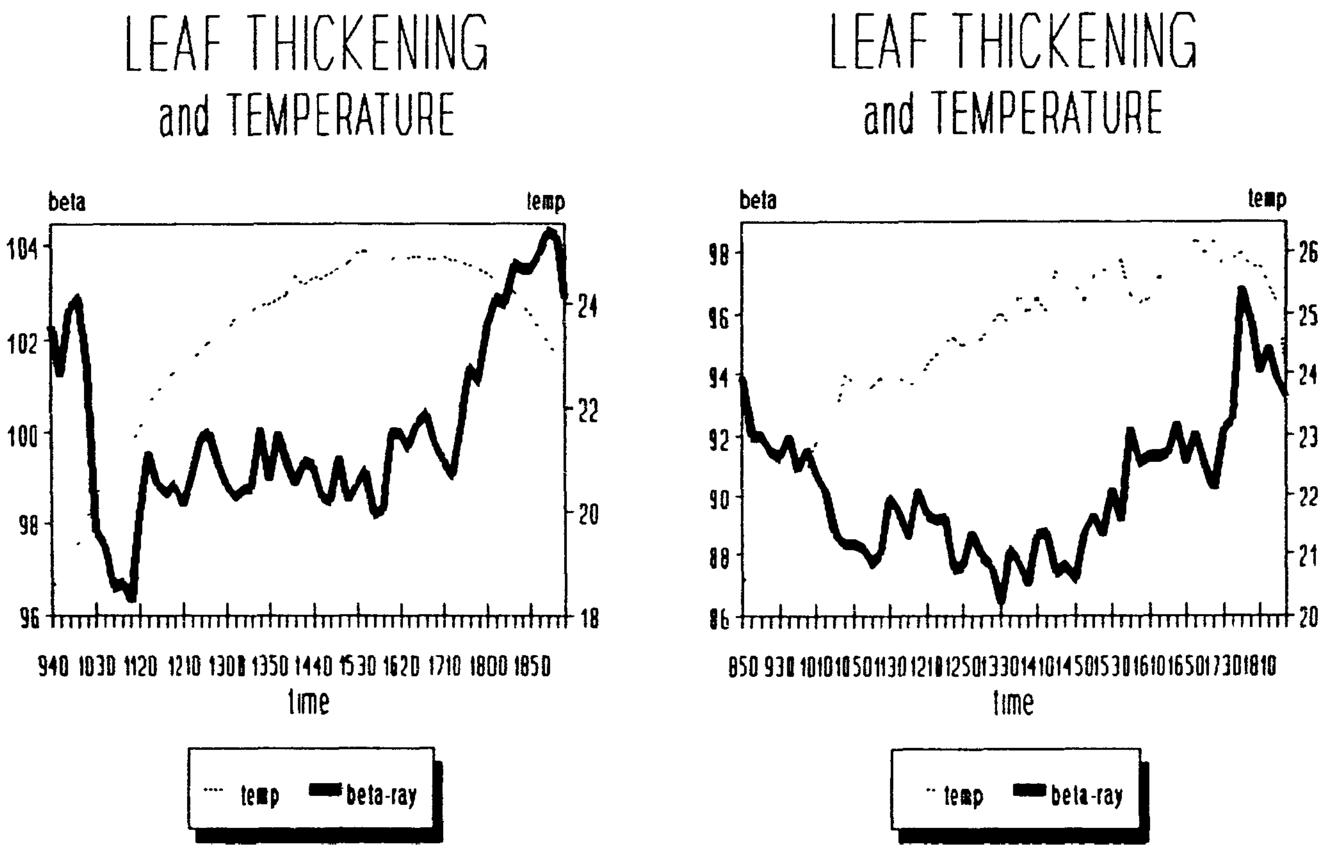

Fig. 10 Leaf Thickening and Temperature

CHAPTER V: CONCLUSIONS

Dew chamber experiments showed the commercial ER sensor to provide the best results on leaf surface wetness as compared to the BRG. Discrepancy between the BRG and ER sensors of cotton cloth and wood was found to be the largest. Onset of dew formation was detected within 15 minutes of the BRG by all ER sensors. However, ER sensors did not agree among themselves on dew termination time in the dew chamber. When dewfall was light, the cotton ER cloth sensor did not respond. Heat generation in the circuit board of ER sensors could have also contributed to errors of wetness measurements.

Field experiments showed that the cotton cloth ER sensor provided satisfactory results on wetness from dew and rain in a dense soybean canopy. Wetness from fog was measured adeptly by the commercial ER sensor. The wood ER sensor was judged to be unsatisfactory for wetness measurements. The commercial ER sensor would be appropriate for a sparse tobacco crop. For the detection of all moisture categories the BRG system is highly satisfactory since a live leaf is used as the condensing surface.

Choice of a most suitable ER sensor for leaf surface wetness measurements depends on several factors. Atmospheric precipitations of various kinds that cause leaf surface wetness play an important role in the selection of a right sensor. The microclimate of the surrounding environment, canopy density, and leaf morphology are also important factors to be considered in the selection process. When comparing ER sensors in order to determine the most suitable detector, considerations should be given to both its successes and failures to measure leaf surface wetness. Obviously, if a sensor fails to record certain precipitation events, this can be discarded as unreliable; since accurate determinations of leaf surface wetness duration times are important in plant pathology. Another criterion that can be used to judge the performance of a particular sensor is to establish the extent to which it deviates from actual wetness duration.

Cost is also an important factor by which a sensor is selected. Although a BRG system is relatively more expensive, ER sensors used in conjunction with dataloggers are not less expensive. If accuracy of wetness detection can be sacrificed to a certain extent, an ER sensor may be chosen. This is especially true if a series of ER sensors are needed throughtout the canopy. However, under those circumstances where accuracy of surface wetness measurements are crucial, a BRG system is recommended.

V.1 DIRECTION OF FUTURE RESEARCH

Future research should involve improving the BRG system so that it could be more suitable for field work. During the field trials of the present project, considerable amounts of sealant had to be used in order to protect the G-M tube from severe weather. Portability of the instrument should be of major concern. In this respect, miniaturization of the BRG system for field applications would be of considerable value. Possible use of solid-state silicon crystals as detectors should also be explored in order to increase sensitivity of the BRG even further.

As mentioned earlier, potential of using a BRG system in investigating stomatal dynamics as a function of temperature and moisture stress also exist. Investment in a BRG system may be worthwhile if plant moisture stress along with leaf surface wetness could be monitored by the same instrument. Future research should, therefore, be concentrated in evaluating a BRG system if it could fulfil the dual task just described.

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