This extension to the domain theory is an improvement on the theory of Everett (4) but is more complicated in use. The formulation by Enderby (3) is even more difficult to apply. An attempt to analyze the data from Caribou silt loam on the basis of Enderby's formulation was inconclusive because the data obtained was neither sufficient nor of the right kind (11). Enderby's theory depends on the use of secondary scanning loops. Even though the present extensions involved both sets of scanning curves to set it up, it would be possible to use a computer to store the necessary information to use the theory for prediction of additional scanning curves relating water content and pressure head.

This theory may offer an explanation for the discrepancy between the results of earlier work (10, 11, 13) and those of Poulovassilis (7, 8) and Talsma (9). In the earlier work (10, 11, 13) involving nonequilibrium nonsteady flow there was a significant pore blockage effect whereas Poulovassilis and Talsma using equilibrium (7, 9) and steady flow (8) found the independent domain theory worked without taking account of pore interactions. Certainly differences can be measured between unsteady and steady-state flow (12). It would appear that unsteady flow would prevail in natural conditions during rainfall infiltration and the early phases of redistribution.

An extension of the domain concepts to allow interaction has successfully explained the nature of the primary wetting and drying scanning curves of five materials ranging from glass beads to clay loam. The curves indicating the significance of pore interaction appeared dependent only on one variable, the water content, and could be used for additional predictions of scanning curves in the water content-pressure head relationship.

ACKNOWLEDGMENT

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Measuring Soil Matric Potential *in situ* by Sensing Heat Dissipation within a Porous Body: II. Experimental Results[1]

C. J. PHENE, S. L. RAWLINS, AND G. J. HOFFMAN[2]

ABSTRACT

A sensor described previously to measure the matric potential of soil water *in situ* was tested in soil-plant systems. Experiments were performed in the laboratory in a controlled environment and in the field. In the field, temperatures obtained by the sensor were used to predict optimum time for measurement to avoid error caused by diurnal temperature drift in the soil. The error caused by temperature drift was eliminated completely by using two matched diode sensors and taking a temperature difference measurement.

The accuracy of the matric potential sensor proved to be as good as or better than that of other techniques used to measure matric potential. Sensors with high sensitivity in the 0 to −2 bar matric potential range had an accuracy of ±0.2 bar. The accuracy decreased progressively to ±1 bar at a matric potential of −10 bars.

Additional Key Words for Indexing: soil water, psychrometer, salinity sensors, matric potential sensor.

In part I, Phene, Hoffman, and Rawlins (1971) described and gave details for constructing a sensor that measures the matric potential component of soil water potential *in situ*. Here we evaluate the performance of the instrument in terms of four criteria essential to its usefulness in the laboratory and in the field.

These criteria are:

1) The sensor should measure matric potential more accurately or more simply than other available sensors.

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[1] Contribution from the US Salinity Laboratory, SWC, ARS, USDA, P. O. Box 672, Riverside, Calif. 92502, and a part of the senior author's Ph.D. thesis, University of California, Riverside. Received Sept. 14, 1970. Approved Dec. 1, 1970.

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2) It should respond quickly to changes in matric potential.

3) It should remain stable with time.

4) It should measure matric potential independently of soil temperature fluctuations.

PROCEDURE

Experiment 1

In the first experiment, two matric potential sensors were used in a controlled environment to test their accuracy, stability, and response time. The matric potential sensor readings were compared with readings from the combination sensor developed by Ingvalson et al. (1970). This combination sensor, a combined thermocouple psychrometer and salinity sensor, estimates matric potential as the difference between water potential measured by the thermocouple psychrometer and osmotic potential measured by the salinity sensor with an accuracy of about ±0.5 bar.

Figure 1, a cross-sectional photograph of the soil column after the experiment, shows the relative position of three of the four sensors. The lower matric potential sensor, not shown in the photograph, was located to the left of the upper matric potential sensor. The soil column, 29 cm in diameter and 26 cm deep, was packed uniformly with Indio clay loam. Matric potential sensors and combination sensors were installed at 6- and 12-cm depths. The porous body of the upper matric potential sensor was the ceramic material described in Table 1, Part I (Phene et al., 1971). The porous body of the lower matric potential sensor was Castone.[3] The soil column was then installed in the microchamber described by Hoffman, Phene, and Rawlins (1969). On December 24, 1969, 12 red kidney bean seeds (*Phaseolus Vulgaris* L.) were planted at a depth of 1 cm from the soil surface. The soil was saturated from the top by irrigating with 7.6 liters of quarter-strength Hoagland solution. On January 6, 1970, 2 liters of quarter-strength Hoagland solution were added to the column. Five subsequent irrigations used quarter-strength Hoagland solution to which sufficient NaCl and $CaCl_2$ had been added to lower its osmotic potential to −1 bar and adjust its sodium adsorption ratio (US Salinity Laboratory Staff, 1954) to 3.1. The electrical conductivity of the solution was 3.1 mmhos/cm.

During the experiment, the temperature of the environmental chamber was 25 ± 0.2C, the relative humidity was 60 ± 1%, and the CO_2 concentration was 400 ± 10 ppm. The photoperiod was 14 hr with a light intensity of 4.4 mw/cm^2 at the top of the chamber.

The output of each of the combination sensors was read manually several times a day. A data acquisition system automatically recorded the output of each of the matric potential sensors every 2 hr. The matric potential sensors were calibrated before and after the experiment by the method described in Part I (Phene et al., 1971).

Experiment 2

To determine the accuracy, stability, and response time of the sensor over a wider range of matric potentials, a second experiment was performed in the same microchamber with a mature tobacco plant (*Nicotiana tabacum* L., cv. Coker) growing in a Pachappa sandy loam soil. The porous body of the matric potential sensor was gypsum. The matric potential was permitted to drop two or three times lower in this experiment than in Experiment 1.

A soil thermocouple psychrometer (Rawlins and Dalton, 1967) and a salinity sensor (Richards, 1966) were installed in separate locations 10 cm below the soil surface and midway between the plant stem and the edge of the soil column. The matric potential sensor was installed 2 cm below the soil surface, midway between the plant stem and the edge of the soil container, and opposite the thermocouple psychrometer.

Because the matric potential sensor with a gypsum porous body loses most of its water between 0 and −1 bar, its accuracy in this range is ±0.2 bar. Below −1 bar, the accuracy decreased progressively to ±1.0 bar at −3 bars, after which the accuracy remained constant to −10 bars. The soil column was irrigated with 300 ml of water on August 1 and 6. On August 10, it was irrigated with 300 ml of solution, adjusted to −3 bars osmotic potential by addition of sodium chloride. Measurements and calculations were performed as in Experiment 1.

Experiment 3

Next, the accuracy, stability, and response time of the sensor were tested in a Pachappa sandy loam field plot on which a mature crop of alfalfa (*Medicago sativa* L.) was growing. A matric potential sensor was installed at the 35-cm depth to test how well it met the four criteria in the field. The porous body of the sensor was a mixture of ground ceramic and Castone referred to as Mix 1 in Fig. 7, Part I (Phene et al., 1971). Most of its sensitivity was between 0 and −6 bars. The accuracy of this sensor determined during calibration was ±0.2 bar between 0 and −3 bars matric potential, decreasing to ±1 bar below −3 bars.

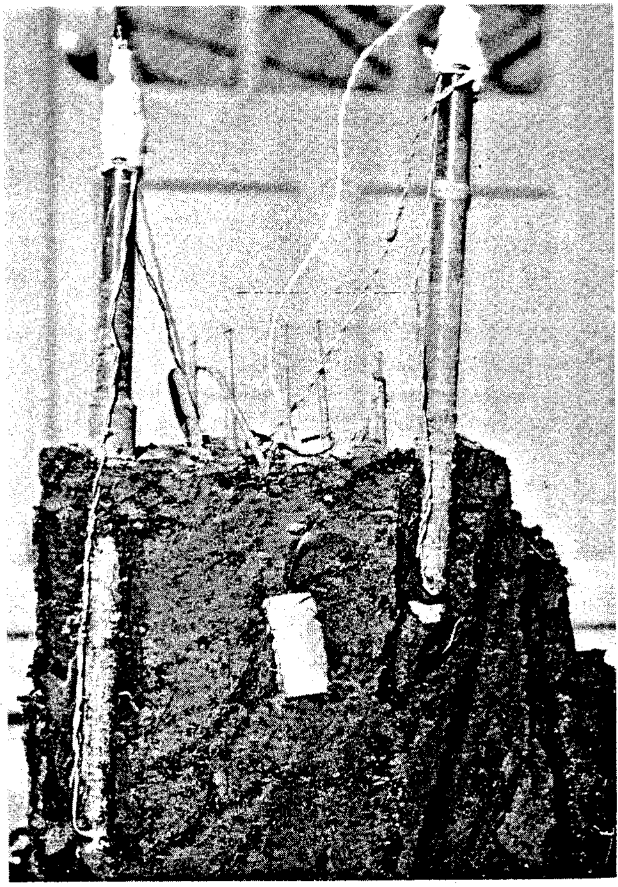

Fig. 1—Soil column cross-section showing two combination sensors (Ingvalson et al., 1970) and our matric potential sensor (*center*) at the 6-cm depth.

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[3] Castone is a casting material used mainly in dental work; it is manufactured by Ransom and Randolph Co., Toledo, Ohio. The citation of particular products or companies is for the convenience of the reader and does not imply any endorsement, guarantee, or preferential treatment of the USDA or its agents.

Salinity sensors and thermocouple psychrometers were also installed in the plot at both 25- and 35-cm depths. Water potential measured by the thermocouple psychrometer and osmotic potential measured by the salinity sensors were recorded daily during daylight hours. As in Experiment 2, readings were compared with those of thermocouple psychrometers and salinity sensors.

The sensor was calibrated in a pressure plate following the method outlined in Part I (Phene et al., 1971). To insure that no drift took place in calibration, as required by criterion 3, the matric potential sensor was calibrated before and after the experiment as in Experiment 1.

To determine whether the diurnal variations encountered in the field were actually due to the instruments or the soil, a matric potential sensor and a psychrometer were installed in a sealed container filled with similar soil at the same water content and buried in the same field plot at the same depth.

A data acquisition system recorded matric potential sensor data every hour. The recording equipment was located approximately 110 m from the field plot. To measure the effect of long leads, a matric potential sensor was placed in a constant temperature bath and several measurements were taken with leads 5, 110, and 220 m long.

Soil temperature was measured with the matric potential sensor, and the data were used to select the time for making matric potential measurements when soil temperature change was least.

Matric potential was calculated directly from the data acquisition system tape by a computer, using a third-order equation to approximate the calibration curve of the sensor. This method of data conversion allowed measurements to be processed rapidly with an error of 0.5 bar or less.

Experiment 4

In Part I (Phene et al., 1971), we discussed the possibility of eliminating the error caused by the temperature fluctuation in the soil by replacing the resistor R_3 in the bridge with a diode whose characteristics would match the matric potential sensor diode. This experiment was performed with two matched diodes to test how well the modified sensor would eliminate the temperature dependence and meet the fourth criterion.

To subject the matched diode to the same thermal changes as the diode in the matric potential sensor, they were cast in the same materials. To minimize the change of heater resistance with temperature, we used constantan wire for the matric potential sensor heater. The modified matric potential sensor was placed in a column of Pachappa sandy loam soil equilibrated at −0.1 bar matric potential. The column was then placed in a water bath, the temperature of which was cycled between 9 and 25C at a maximum rate of 1.8C/hr. Matric potential and temperature measurements were taken automatically every 2 hr with a data acquisition system.

RESULTS AND DISCUSSION

Experiment 1

Figure 2 compares the matric potentials measured by the combination sensors and the matric potential sensors. The matric potential sensor readings are the average of midnight and noon readings. The water and osmotic potentials measured by the combination sensors are the average of two or three measurements taken manually during the day. The matric potentials reported for the combination sensors are the differences between water and osmotic potential readings. In making this comparison, we realized that the matric potential measurement could be in error because of spatial variation in salt and water contents of the soil or errors in the combination sensor readings. During calibration, the matric potential sensor at the 12-cm depth was accurate to ±0.2 bar between 0 and −2 bars, the the range in which most of the measurements were made. The sensor at the 6-cm depth had an accuracy of ±0.3 bar between 0 and −6 bars because of a slightly different sensor matrix. Figure 2 shows that at the 6-cm depth the difference between the combination sensor readings and the matric potential sensor readings was 0.3 bar or less, while at the 12-cm depth, the difference never exceeded 0.8 bar for the duration of the experiment.

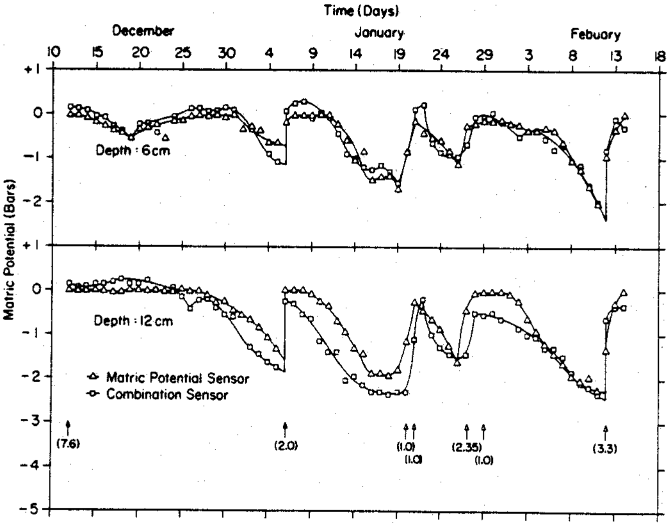

Fig. 2—Matric potentials at the 6- and 12-cm depths in an Indio clay loam soil column. Filled arrows indicate nonsaline irrigations; open arrows indicate saline solution irrigations. Volume of irrigation is given in liters.

To meet the second criterion, matric potential readings should stay in phase with readings from the thermocouple psychrometer. The thermocouple psychrometer responds rapidly because it requires movement of water vapor only. The other two sensors depend on movement of the soil solution, a slower process. Figure 2 shows no difference in response time large enough to cause problems in interpretation of the data. The sensors remained in phase with each other when plotted on a daily basis. When the data were plotted at 2-hr intervals, the matric potential measurements show a diurnal cycle of about ±0.2 bar for 1½ days preceding the irrigation, but show no diurnal cycle for 3 days after the irrigation. The reason for this is not entirely clear, but it is possible that at a low matric potential, diurnal variations in transpiration rate caused measurable variation of matric potential. Richards (1949) and Rice (1969) have reported this phenomenon.

To evaluate the stability of the sensor, calibration curves were obtained by identical techniques immediately before and after the experiment. The difference in the means of the points varied between 2 and 3μv and the maximum difference in standard deviation never exceeded 2 μv. This is within the accuracy of the measurements, indicating there was no significant drift for 5 months when the matric potential sensor was used continuously.

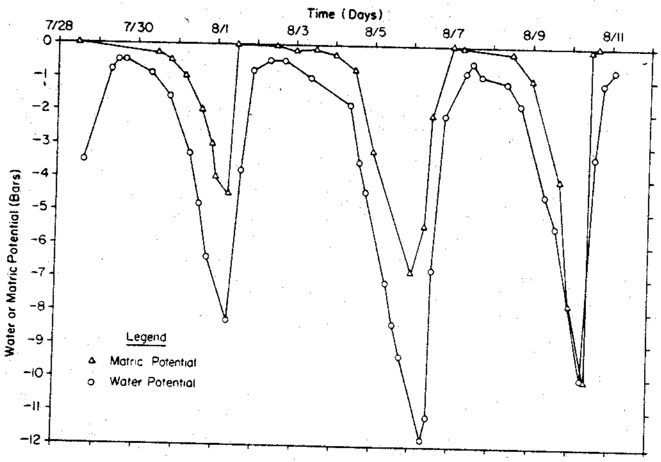

Fig. 3—Matric and water potentials in a Pachappa sandy loam soil column.

Experiment 2

In this experiment, the matric potential was lowered to a minimum of −10 bars. The data are shown in Fig. 3. The salinity sensor readings, which showed the osmotic potential to be nearly constant at about −1 ± 0.5 bar, are not included in the figure.

Since the three sensors were not at the same depth, we did not expect the sum of the matric and osmotic potentials to equal the water potential precisely. Following an irrigation, the matric potential sensor detected the wetting front first, reflecting a high matric potential before the wetting front reached the psychrometer. Examination of the column after the experiment showed the greatest root concentration to be near the center of the column and closer to the thermocouple psychrometer than to the matric potential sensor. It is possible that, because the psychrometer was near the greatest concentration of roots, the water potential started to decrease first; a simultaneous decrease in hydraulic conductivity could have resulted in the difference in matric potential at the two depths on August 1 and 6. Since we expected some difference in the measurements because of the location of the sensors, we cannot evaluate the precise accuracy of the sensor, but the data of Fig. 3 indicate the maximum error to be 4 bars when the total potential was −12 bars.

Figure 3 shows that the matric potential sensor stayed in phase with the thermocouple psychrometer and promptly returned to zero potential after each irrigation.

Experiment 3

This field experiment tested the matric potential sensor for all four criteria. In determining the effect of long leads, the mean output of the bridge and its standard deviation were calculated to be 1.033 ± 0.006 mv for leads 5 m long and 1.034 ± 0.008 mv for leads 220 m long. Thus, the long leads, when placed between the bridge and the data acquisition system, did not affect the results significantly.

Figure 4 shows some of the data collected over a 3-month period for a matric potential sensor and two thermocouple psychrometers. Because the salinity sensor showed a fairly constant osmotic potential varying between −0.5 and −0.75 bar during the entire irrigation cycle, osmotic potentials are not shown in the figure.

In spite of this difference in location and of the fact that the measurements were not taken at the same time, the readings made with the matric potential sensor agreed within 0.5 bar with the calculated values obtained by subtracting the osmotic potential from the water potential, except for the measurements made between April 30 and May 14. Values recorded between April 30 and May 14 are slightly in error because of a drift in voltage of the heater power source. Figure 4 shows that the matric potential sensor responded rapidly and in the expected direction to an irrigation on June 10 and to harvests on April 15, May 13, and June 9. It also responded rapidly to rains on May 3, 4, 5, and 6, although the sensitivity had been decreased because of the circuit malfunction mentioned

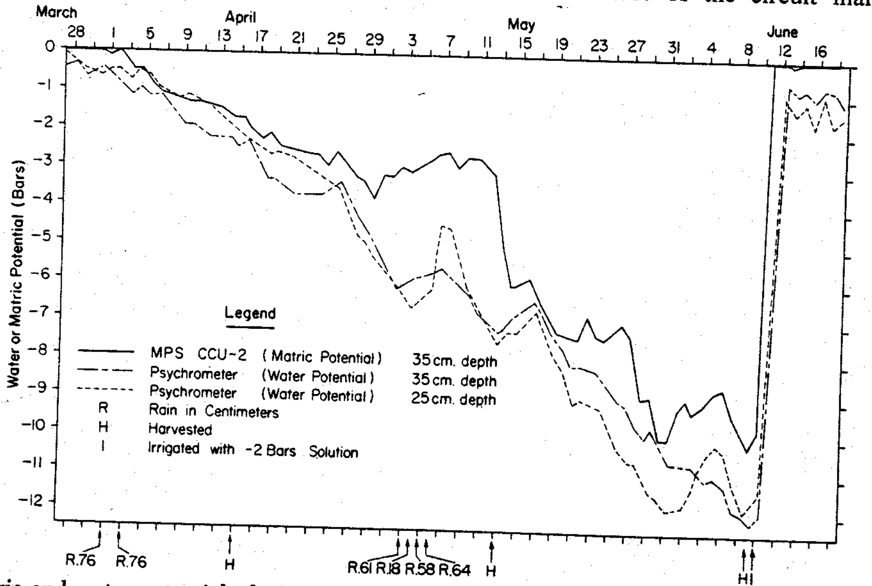

Fig. 4—Change in matric and water potentials during an irrigation cycle in a field plot containing Pachappa sandy loam soil.

above. For clarity, air and soil temperature are not reported on Fig. 4 although they were recorded continuously. Some of the increases in water potential correspond exactly to a decrease in evapotranspiration demand caused by either a cloudy sky or a lowering of air temperature, or both.

Criterion 4 requires the sensor to measure matric potential independently of soil temperature fluctuations. Since soil temperature cycles sinusoidally with time, the sensor will satisfy the first three criteria only if criterion 4 is satisfied first. At high matric potentials where the sensor sensitivity is large, small temperature changes do not cause significant errors. But, as the soil dries, the sensitivity of the sensor decreases and small temperature changes cause significant errors. To minimize this error, the time of the measurement was shifted to coincide with that of minimum soil temperature change. From March 27 to May 21, 2:00 am readings were plotted, while from May 22 to June 19, the measurements plotted were those coinciding with minimum temperature drift, which did not always occur at 2:00 am. When matric potentials were recorded at the time of minimum temperature drift, temperature fluctuations caused no significant error, and criterion 4 was satisfied.

In evaluating the accuracy of the sensor, one should remember that although the psychrometer and the matric potential sensor were installed at the same depth, they were 15 cm apart. Some of the difference between water potential and matric potential could also be attributed to diurnal variations of matric potential. These diurnal variations of matric potential were measured independently with the matric potential sensor and the psychrometer. When the matric potential sensor and the psychrometer were installed in a sealed container filled with the same soil and the container was placed in the plot at the same depth as the other sensors, no diurnal variation of matric potential in the container occurred. Meanwhile, measurements of matric potential under the same condition in the soil showed an apparent diurnal cycling of 0.6 bar. Since the diurnal cycling in the plot increased when the alfalfa was harvested, water removal by the plants was not the cause. This suggests that the water movement in the soil profile might be caused by a temperature gradient. Water potential measurements, obtained in the afternoon, followed matric potential measurements by about 12 hr, so that errors caused by diurnal variation could have been significant.

Richards (1949) reported that field tensiometer data are subject to a diurnal variation, with a lowering in potential in the afternoon when the transpiration load is greater. This diurnal change is greatest at shallow depths and is even observable in the absence of moisture extraction by plant roots, as observed after the alfalfa was harvested. This diurnal effect, he suggested, can be minimized by taking the reading at the time of day when temperature change is at a minimum. Rice (1969) recently reported similar findings obtained using recording tensiometers in the root zone of Bermudagrass (*Cynodon dactylon* (L.) Pers.). For precise comparison of the psychrometer and matric potential sensor data, the measurements should have been taken at the same time.

In testing the stability of the calibration with time, we found that differences in the calibration curves made before and after the experiment were within the accuracy of measurement. Thus, no measurable drift in calibration occurred.

Experiment 4

This experiment tested the modified matric potential sensor's dependence on temperature fluctuations. If the two diodes are subjected to the same thermal regime, the diode replacing R_3 acts as a reference and masks out any temperature drift occurring. When the temperature was cycled, the matric potential measurement remained within 0.1 bar. Similar results were obtained when the matric potential sensor was placed in the field and measurements were taken every 2 hr. Thus, when the sensor is used in this manner, the temperature dependence is eliminated.

CONCLUSIONS

The matric potential measured by the heat dissipation sensor agreed with that calculated by subtracting the osmotic potential from the soil water potential within an accuracy of ±0.5 bar.

The matric potential sensor at the 12-cm depth responded to an irrigation in less than 2 hr.

The calibration of the sensor was stable within ±0.5 bar for 5 months of continuous usage.

The accuracy of the measurement in a temperature controlled environment was ±0.2 bar, making the sensor a valuable instrument for research. The matric potential measurement was found to be accurate within 0.1 bar when the sensor was temperature compensated with a matched diode cast in a block of the same material and the temperature was changed 15.2C at a rate 1.8C/hr.

The sensor was found suitable for remote operation with a data acquisition system, making feasible large, complex field experiments and the use of computers to interpret many data in a short time.

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