Evaluation of Soil Moisture Sensors

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Abstract. This study evaluated the measurement accuracy and repeatability of the EC-5 and 5TM soil volumetric water content (SVWC) sensors, MPS-2 and 200SS soil water potential (SWP) sensors, and 200TS soil temperature sensor. Six 183cm x 183cm x 71cm wooden compartments were built inside a greenhouse, and each compartment was filled with one type of soil from the Mississippi Delta. Sixty-six sensors with 18 data loggers were installed in the soil compartments to measure SVWC, SWP, and soil temperature. Soil samples were periodically collected from the compartments to determine SWVC using gravimetric method. SVWC measured by the sensor was compared with that determined by the gravimetric method. SVWC readings of the sensors have a linear correlation with the gravimetric SVWC (r^2=0.82). The correlation was used to calibrate the sensor readings. The SVWC and SWP sensors were capable of detecting general trend of soil moisture changes. However, their measurements varied significantly among the sensors and were influenced by soil property. To obtain accurate absolute soil moisture measurements, the sensors require soil-specific calibration. The 5TM, MPS-2, and 200TS sensors performed well in soil temperature measurement test. Individual temperature readings of those sensors were very close to the mean of all sensor readings.

Keywords. Soil moisture sensor, irrigation, soil water potential, soil water content, soil temperature

INTRODUCTION

Irrigation scheduling determines the time and amount of water to apply. Irrigation scheduling methods may be classified into three main categories: weather-based methods, soil moisture-based methods, and plant-based methods. Weather-based methods schedule irrigation based on the amount of water lost by plant evapotranspiration (ET) and the amount of effective rainfall and irrigation water entering into the plant root zone. Soil-based methods measure soil moisture levels in the plant root zone and apply water if there is water shortage for plants. Plant-based methods directly detect plant responses to water stress and initialize irrigation as plants indicate suffering from water stress.

Soil moisture sensors have been widely used to measure soil moisture status and determine supplementary water requirements by crops. Various types of sensing devices have been developed and made commercially available for water management applications in recent years. Evaluations have shown that each type of sensing device has its advantages and shortcomings in terms of accuracy, reliability, and cost (Basinger et al., 2003; Chanzy et al., 1998; Evett and Parkin, 2005; Seyfried and Murdock, 2004; Yao et al., 2004). The neutron probe has been shown to be a reliable tool for determining soil water content. However, its use of radioactive source requires special licensing and training for operation and has restricted its application in recent years. Meanwhile, electromagnetic (EM) sensors, such as electrical capacitance and resistance type sensors, and time-domain reflectometer (TDR) devices have been rapidly developed and widely adopted for soil water measurement (Dukes and Scholberg, 2004; Fares and Alva, 2000; Miranda et al., 2005; Seyfried and Murdock, 2001; Vellidis et al., 2008). Yoder et al. (1997) tested 23 soil water sensors representing eight sensor types, including neutron probe, electrical capacitance sensors, electrical resistance sensors, TDR devices, and heat dissipation sensors with carefully controlled soil water contents. Measurement errors of the volumetric water content of the soil were determined for each sensor. The results indicated that the capacitance sensors had the best performance in the study. Leib et al. (2003) evaluated soil moisture sensors of several different brands and types under identical operating conditions in the field for three years. They found that most sensors were able to follow the general trends of soil water or potential changes during the growing season, but that actual measured values varied significantly between sensors and calibrated neutron probe measurements. It was suggested that a soil specific calibration of each sensor was necessary to obtain high accuracy in the measurements. Evett et al. (2006) compared several EM sensors with a neutron moisture meter in measuring water content of three soils. It was found that all EM sensing devices under test were sensitive to soil temperature differences. Similar to the suggestion by Leib et al. (2003), the authors recommended that all of the EM sensing devices would require separate calibrations for different soil horizons. Previous research indicated that the EM sensors were inexpensive, easy to install and maintain, and able to provide reliable information for irrigation scheduling and control. However, the sensors must be well-calibrated under specific operation conditions including soil type and temperature.

Objectives of this study were to evaluate and calibrate soil moisture sensors (several not included in previously cited studies) with various types of Mississippi Delta soils.

MATERIALS AND METHODS

Sensor Installation

Six 183cm x 183cm x 71cm wood compartments were built in a greenhouse. Six different types of Mississippi Delta soils around Stoneville, Mississippi were collected, and one type of the soil was filled in each soil compartment (Figure 1). Water was applied using a sprinkler installed over the compartments to make the soils in the compartments saturated. This process was repeated four times to allow the soils to resettle in the compartments. Types of soil used were Bosket very fine sandy loam (BVFSL), Sharkey clay (SC), Dundee silty clay (DSC), Dundee very fine sandy loam (DVFSL), Dundee silty clay loam (DSCL), and Tunica clay (TC). Physical properties of the soils were analyzed at the soil test lab of Mississippi State University (Table 1). Sixty-six soil moisture and temperature sensors were tested for measuring soil volumetric water content (SVWC), soil water potential (SWP), and soil temperature, including:

- Eighteen EC-5 SVWC sensors,
- Six 5TM SVWC sensors,
- Eighteen MPS-2 SWP sensors,
- Eighteen 200SS SWP sensors, and

- Six 200TS temperature sensors.

The EC-5, 5TM, MPS-2 sensors were the products of Decagon Devices (Pullman, WA) while the 200SS and the 200TS sensors were manufactured by the Irrometer Company (Riverside, CA). The EC-5 sensors measure SVWC only. The 5TM sensor is able to measure SVWC and soil temperature. The 200SS sensor is only able to measure SWP while the MPS-2 can measure both SWP and soil temperature.

There were three EC-5, three MPS-2, one 5TM, three 200SS, and one 200TS sensors installed in each soil compartment. A hole with a size of 46cm in diameter and 38cm deep was made at the center of each soil compartment for sensor installation. The sensors were installed at a depth of 30.5cm along the perimeter of the hole with a center to center spacing of about 12.7cm between the sensors. The installation was performed according to the instruction given by each sensor's manufacturer. After all sensors were installed, the hole was refilled with the soil dug out and water was applied to make the soils saturated.

Data Collection

Twelve Decagon data loggers (EM50R, Decagon Devices, Pullman, WA) were used to collect data from the EC-5, MPS-2, and 5TM sensors. Six Watermark monitors (900M, Irrometer Company, Riverside, CA) were employed to record the data measured by the 200SS and 200TS sensors. Default calibration for "mineral" soil was selected for Decagon data loggers. A soil temperature sensor was connected to channel 1 of the Irrometer monitors for temperature compensation in its water potential measurement. Data logging devices were set to automatically collect data from the sensors at a time interval of one hour.

Five cycles of soil sample collection were conducted during the 3-month test. In each cycle, three soil samples with 2 replicates were randomly collected using a soil sampler in each soil compartment. Soil samples were taken at a depth of 27.3cm-33.7cm to represent the soil at the depth of 30.5cm in which soil moisture was measured. Sample size was 5.4cm in diameter and 3.0cm deep. After being collected from the soil compartment, the samples were immediately weighed using a balance for wet weight, and then were dried by oven at 110 ^{o}C until completely dry. Dried samples were weighted for dry mass weight.

Volumetric water content of the soil sample, θ, was determined using the formula below.

$$\theta = \frac{V_l}{V_t} = \frac{(W_w - W_d)}{V_t \, \rho_w} \qquad (1)$$

where V_l is the volume of the water, V_t is the total volume of the sample, W_w is the wet weight of the sample, W_d is the dry weight of the sample, and ρ_w is the water density.

Data Analysis

Soil moisture, soil water potential, and soil temperature of the six soil types were continuously monitored and recorded for three months. All data were downloaded from the data logging devices and processed for calibration and evaluation of the sensors. The volumetric water contents determined using the oven-dried method as described above were compared with those measured by Decagon's EC-5 and 5TM sensors. Correlation between the readings of the EC-5 and 5TM sensors and the oven-dried SVWC was established and used to calibrate those sensor measurements. An ANOVA was performed with SAS software (SAS Institute Inc., Cary, NC) to evaluate the differences in soil moisture and soil temperature measurements by sensor and soil type.

RESULTS AND DISCUSSION

Soil Volumetric Water Content

The SVWC readings measured by the EC-5 and 5TM sensors have a linear correlation with the oven-dried SVWC (r^2=0.82) (Figure 2). It was obvious that the sensors over-estimated the SVWC using the Decagon "mineral soil" calibration. The correlation between the oven-dried SVWC and the sensor readings, $y=0.6508x+1.7612$, was then used to calibrate the sensor readings. Figure 3 showed a comparison of oven-dried SVWC with the calibrated sensor-measured SVWC in five soil sampling cycles. Average SVWC and the sensor's prediction error across sampling cycles were given in Table 2. Sensors' prediction error, defined as predicted minus observed percent volumetric water content, varied from -8.6% to 11.8% depending on the soil type. The minimum prediction error was 2.7% with DSC soil while the maximum was 11.8% with the DSCL.

In general, sensor-measured SVWC followed the trend of soil moisture changes for all types of soils during the 3-month test. But the SVWC determined by individual sensors varied. The means of SVWC measured by each EC-5 and 5TM sensors were given in Table 3. ANOVA analysis revealed that the SVWC measured by the EC-5 #2 and #3 sensor in soils BVFSL and TC were not significantly different. However, the rest of the measurements by each EC-5 sensor within the same soil type varied significantly. The SVWC determined by the 5TM sensor was significantly different from that by the EC-5 sensors in all types of soils. Performance consistency across the sensors should be taken into consideration in applications of these sensors.

Soil Water Potential

Figure 4 compared SWP measured by the MPS-2 and 200SS sensors in the five soil sampling cycles. In BVFSL and DVFSL soils, the measurements by these two types of sensors followed each other fairly well. SWP values by the MPS-2 sensors were much higher than those of the 200SS for DSC and DSCL soils. However, in SC and TC soils, the SWP values measured by the 200SS showed a trend of being greater than those of the MPS-2 sensors. This result indicates soil type has an effect on the performance of the sensors.

Both the MPS-2 and 200SS sensors showed their capability in detecting the tendency of SWP changes. However, similar to the SVWC sensors, under the same test conditions the outputs of same model sensors could vary significantly (Table 4, Table 5). For example, as given in Table 4, the SWP measured by the MPS-2 #1 sensor in BVFSL soil was consistent with that of the MPS-2 #3, but significantly different from that of the MPS-2 #2 sensor. Taking another example in Table 5, the SWP measurements by the 200SS #2 and #3 sensors in BVFSL soil agreed with each other well, but they were significantly different from the measurement by the 200SS #1. Table 6 provides a comparison between the mean of SWP measurements by all MPS-2 sensors and that by all 200SS sensors. It indicates that SWP measured by the MPS-2 sensors was significantly different from that by the 200SS sensors across all type of soils used in this study. The relative difference with DVFSL soil is the smallest while that with the DSCL was the biggest.

Soil Temperature

All soil temperature sensors performed very well with all types of soils in the test with individual temperature readings from each sensor very close to the mean of all sensor readings. Means of soil temperature measured by soil temperature sensors during the 3-month test are given in Table

7. ANOVA analysis indicates that soil temperatures determined by the sensors in each soil are not significantly different except two observations. One observation was related with the 5TM sensor in SC soil, in which the temperature measured by the 5TM was slightly higher than that by the other sensors. The other one involved the MPS-2 #1 sensor in TC soil, where this sensor's measurement was about 2.5% lower than the other sensors (Table 7). Soil temperature varied during the testing period and the measurements from all sensors followed the same trend and agreed well (Figure 5). Average soil temperature in different type of soils was about the same in this case.

CONCLUSIONS

The EC-5 and 5TM SVWC sensors, the MPS-2 and 200SS SWP sensors, and the 200TS soil temperature sensors were evaluated with six Mississippi Delta soils. Volumetric water contents of the soils were determined using the oven-drying method. Oven-dried volumetric water contents were compared with the sensor measurements to find their correlation, and their relationship was used to calibrate the SVWC sensor measurements. Results indicated readings from the EC-5 and 5TM sensors had a linear relationship with oven-dried SVWC (r^2=0.82). In general, the soil moisture sensors were capable of detecting the trend of soil moisture changes. However, the accuracy of sensor measurements varied significantly between different sensor models and among the sensors within the same model. To obtain accurate absolute measurements, the soil moisture sensors should be calibrated with specific soils. Soil temperature measurement could be consistently obtained using the 5TM, MPS-2, and 200TS sensors.

Acknowledgements

Authors would like to extend their thanks to Mr. Jonnie Baggard, Joseph DeAngelo, and Richard Horton for their assistance in this study.

This project was partially supported by Cotton Incorporated (Cary, NC).

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Figure 1. Six soil compartments with the sensors and data loggers installed.

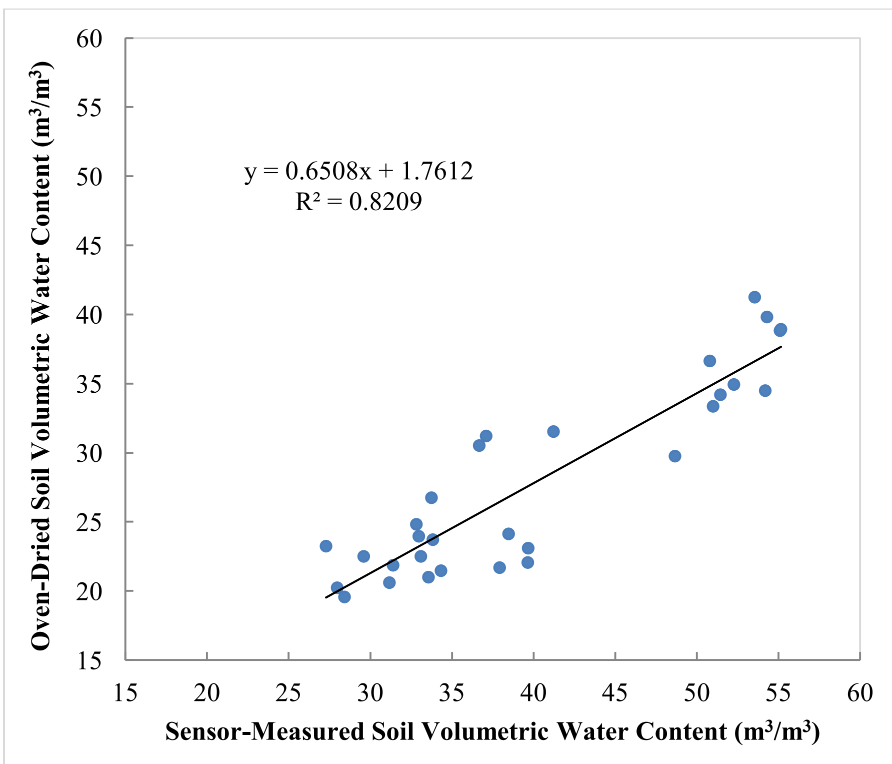

Figure 2. Relationship between sensor-measured SVWC and the oven-dried SVWC.

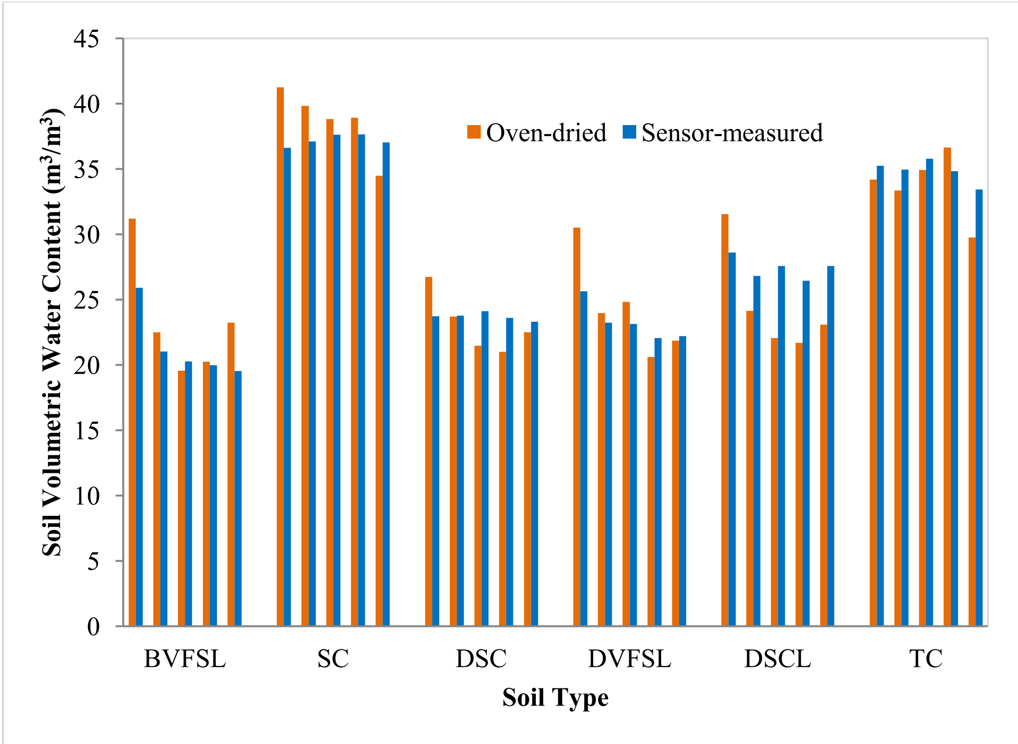

Figure 3. Comparison of calibrated sensor-measured SVWC with the oven-dried SVWC.

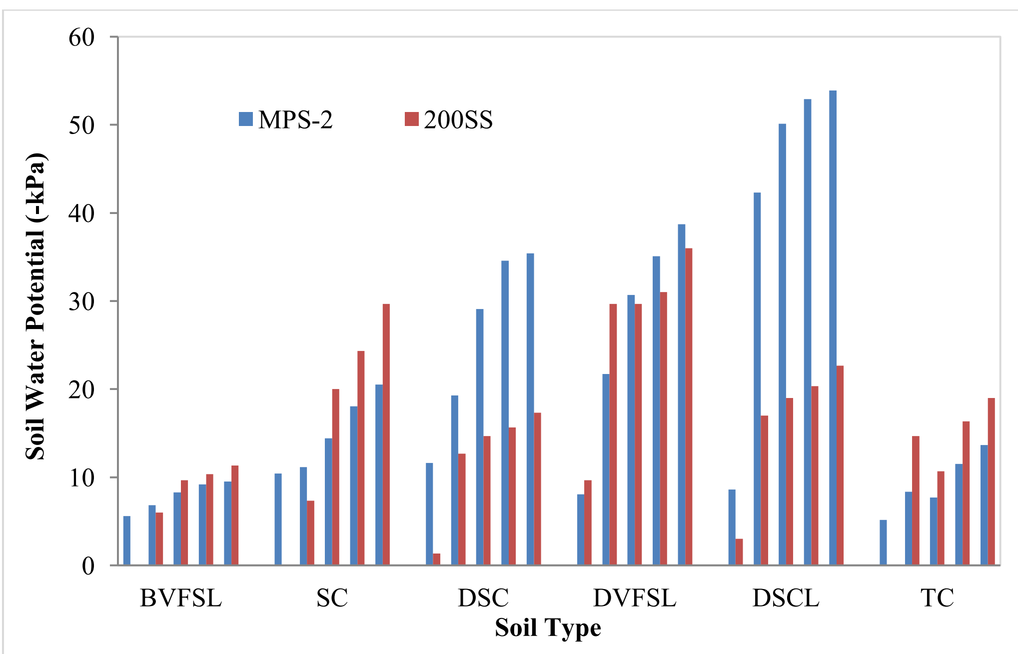

Figure 4. Soil water potential measured by the MPS-2 and 200SS sensors in different soils.

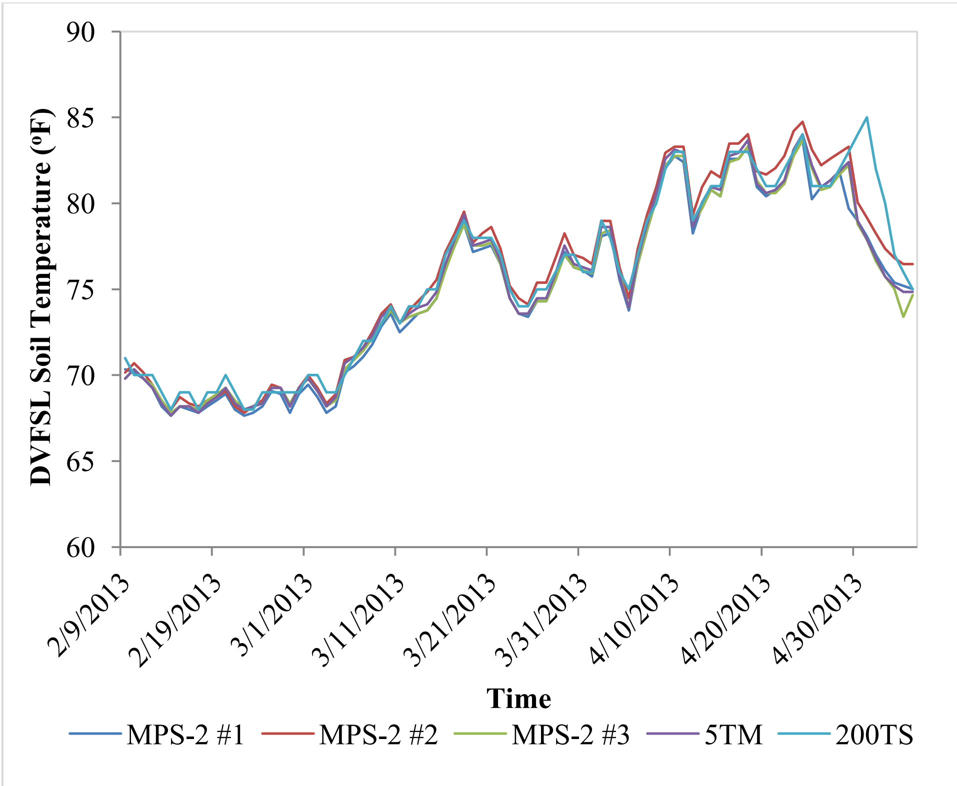

Figure 5. DVFSL soil temperature determined using different sensors.

Table 1. Physical properties of soils used in the sensor test

	Clay (%)	Silt (%)	Sand (%)	Texture
BVFSL	2.5	42	55.5	Sandy Loam
SC	23.75	67.75	8.5	Silt Loam
DSC	8.75	54.5	36.75	Silt Loam
DVFSL	8.75	67.5	23.75	Silt Loam
DSCL	10	72.5	17.5	Silt Loam
TC	21.25	69.5	9.25	Silt Loam

Table 2. Average of soil volumetric water content and sensor measurement error in different soils.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
Oven-dried (m^3/m^3)	23.35	38.67	23.08	24.35	24.5	33.78
Sensor-measured (m^3/m^3)	21.34	37.20	23.70	23.24	27.40	34.85
Error (%)	-8.6	-3.8	2.7	-4.5	11.8	3.2

Table 3. Means of soil volumetric content measured by the EC-5 and 5TM sensors during the 3-month test. The means with same letter under each soil type are not significantly different at the 0.05 level.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
EC-5 #1 (m^3/m^3)	18.0[c]	36.5[c]	16.7[c]	19.5[d]	25.3[c]	33.7[b]
EC-5 #2 (m^3/m^3)	24.5[a]	37.2[b]	26.4[b]	27.8[a]	27.9[b]	36.1[a]
EC-5 #3 (m^3/m^3)	24.2[a]	39.5[a]	29.6[a]	25.5[b]	32.2[a]	37.6[a]
5TM (m^3/m^3)	20.0[b]	35.3[d]	NA*	21.7[c]	24.8[d]	29.1[c]

*The sensor failed during the test.

Table 4. Means of soil water potential measured by the MPS-2 sensors during the 3-month test. Means with same letter under each soil type are not significantly different at the 0.05 level.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
MPS-2 #1 (-kPa)	7.4[b]	13.0[b]	16.9[a]	17.1[a]	34.0[b]	10.7[b]
MPS-2 #2 (-kPa)	6.3[a]	12.3[a,b]	19.2[a]	17.2[a]	48.6[c]	6.5[a]
MPS-2 #3 (-kPa)	7.4[b]	11.9[a]	24.9[b]	29.6[b]	28.9[a]	5.7[a]

Table 5. Means of soil water potential measured by the 200SS sensors during the 3-month test. Means with same letter under each soil type are not significantly different at the 0.05 level.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
200SS #1 (-kPa)	3.2^{b}	23.1^{a}	8.6^{c}	26.9^{a}	12.1^{c}	8.9^{b}
200SS #2 (-kPa)	6.4^{a}	4.8^{b}	10.8^{b}	22.8^{b}	15.2^{b}	7.7^{b}
200SS #3 (-kPa)	6.1^{a}	4.4^{b}	13.9^{a}	26.2^{a}	17.8^{a}	12.9^{a}

Table 6. Means of average soil water potential measured by the MPS-2 and 200SS sensors during the 3-month test. Means with same letter under each soil type are not significantly different at the 0.05 level.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
MPS-2 Avg. (-kPa)	7.0^{b}	12.4^{a}	20.3^{b}	21.2^{a}	37.2^{b}	7.6^{a}
200SS Avg. (-kPa)	5.3^{a}	10.6^{a}	11.1^{a}	25.0^{b}	14.7^{a}	9.8^{b}

Table 7. Means of soil temperature measured by soil temperature sensors during the 3-month test. Means with same letter under each soil type are not significantly different at the 0.05 level.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
MPS-2 #1 (^{o}F)	75.5^{a}	75.7^{b}	76.5^{a}	76.5^{a}	76.4^{a}	75.9^{b}
MPS-2 #2 (^{o}F)	75.4^{a}	75.9^{b}	76.5^{a}	76.5^{a}	76.1^{a}	78.3^{a}
MPS-2 #3 (^{o}F)	76.0^{a}	75.7^{b}	76.3^{a}	76.3^{a}	77.1^{a}	$77.3^{a,b}$
5TM (^{o}F)	76.0^{a}	77.6^{a}	77.1^{a}	77.1^{a}	77.0^{a}	$78.1^{a,b}$
200TS (^{o}F)	76.0^{a}	75.6^{b}	75.8^{a}	75.8^{a}	76.0^{a}	78.1^{a}