Evaluation of a Low Cost Capacitance ECH$_2$O Soil Moisture Sensor for Citrus in a Sandy Soil

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ABSTRACT

Most citrus in central Florida is grown on sandy soils that have very low water holding capacities. A small change in soil volumetric water content can greatly affect available water. The purpose of this study was to determine if a moderately low cost sensor (ECH$_2$O probe) can perform well in this sandy soil. Three water stress treatments (irrigated, non-irrigated, and non-irrigated with rain exclusion) were imposed on Valencia orange trees in the fall and winter (2003-2004) to determine the effects of stress on sugar accumulation in the fruit. Five ECH$_2$O probes were installed in each treatment plot at depths ranging from 10 to 90 cm. Sensors were calibrated in the laboratory. Real time probe responses due to irrigation, rainfall, and water uptake by the plants were collected and analyzed. These probes were able to detect small changes in soil water content at the lower end of the soil water regime and performed well in this soil.

INTRODUCTION

Designing an efficient irrigation scheduling system is problematic in a sandy soil with low water holding capacity and high percolation rate. Sandy soil requires small but frequent water applications to keep the root zone at optimum moisture content. A small change in soil water content can greatly affect plant-available water. Thus, accurate measurement of water is very important in a sandy soil. Currently, some Florida citrus growers use the EasyAG, Diviner, and EnviroSCAN devices manufactured by Sentek (Sentek Sensor Technologies, Adelaide South Australia) and C-probe (AgWise, Agrilink Florida Inc. FL). These sensors are reasonably accurate and easily adapted to reading by either remote communication or dedicated data logging. However, a major factor influencing purchase decision is price. The cost of the single portable unit (e.g.

Diviner) is more than $2000, and a permanent setup with several sensors can range from $4,000 to $15,000. In this study, we investigated a lower cost alternative. The aim of this research was to identify more affordable yet reasonably reliable soil moisture sensors for citrus growers.

The ECH_2O probe is a relatively low cost (<$1000 for five probes, data logger and software) soil water probe manufactured by Decagon (ECH_2O probes, Decagon Devices Inc., Pullman, WA) that has recently become available for scientific and agricultural use. This probe is easy to install, data can be stored in a data logger for manual down load, or data can be radioed to a remote location. However, little information concerning the performance of the ECH_2O probe is available for the fine sandy soils of central Florida. Our objectives were to: (i) to develop a soil-specific calibration model (equation) for a fine sand soil in a water content range commonly found on the central Florida ridge (0.02 to 0.10 cm^3 cm^{-3}), (ii) to test the performance of ECH_2O probes for real time monitoring of volumetric water content (θ_v) under different irrigation treatments, and (iii) to compare the performance of ECH_2O probes with the more expensive C-probes for real time monitoring of θ_v using laboratory calibration models.

Materials and Methods

Study Area

This study was conducted at the University of Florida's Citrus Research and Education Center (CREC), Lake Alfred, Florida. Average annual rainfall there is approximately 1270 mm (Anonymous, 2002), with 60 % of the precipitation occurring in the summer. The soil at the study site was a Candler fine sand (hyperthermic, uncoated Typic Quartzipsamments) that contains > 95% sand, <3% clay, <1% organic matter and has a low water holding capacity (available water = approx. 6%).

Probe Description

The ECH_2O is a capacitance based probe that measures the dielectric constant of the surrounding soil. The probe is 25.4 cm long, 3.17 cm wide and 0.15 cm thick. The probe requires an excitation voltage of 2.5 or 5.0 VDC and outputs a voltage proportional to the dielectric properties of the soil. Claimed accuracies were ± 3% without or ± 1% with soil-specific calibration. The manufacturer indicated that the output is influenced by soil temperature, texture and salinity (Decagon Devices, Inc. Pullman, WA). The standard calibration equation (factory calibration) supplied by the manufacturer for the ECH_2O probe is:

$$\theta_v = 0.000695mV - 0.29 \quad (1)$$

where mV is the probe output in millivolts with a 2.5 V excitation, and θ_v is the volumetric water content.

Probe Calibration, Installation, and Data Acquisition

The standard procedure for calibrating capacitance probes outlined by Starr and Paltineanu (2002) and Campbell (2004) was followed. Details of ECH_2O calibration in the laboratory were described by Borhan and Parsons (2004a). The experiment was conducted in a citrus (Valencia orange) grove where three treatments were imposed: 1) irrigated with rain, 2) non-irrigated with rain, and 3) non-irrigated with rain exclusion. In spring 2003, 15 ECH_2O capacitance probes were permanently installed in three pre-selected treatment plots. Five ECH_2O probes were installed 90 cm from the tree trunk at five depths (10, 20, 30, 50, and 90 cm) from the soil surface that matched the depth of sensors in the C-probe at each plot. A data logger was programmed to collect data hourly. Later on, ECH_2O data were manually downloaded from the data logger and exported to a spreadsheet for further processing.

Two calibration models were developed and evaluated to determine the θ_v of sandy soil. The entire dataset consisted of 48 (6 moisture levels×8 probes) observations used for calibration. Each model was validated using the "leave-one-out" procedure (Borhan et al., 2004). In this procedure, one set of data (6 observations) from a probe was left out and the remaining 42 observations from 7 probes were used to validate the model. This process continued until none of the data sets were left. Models for determining θ_v from ECH_2O probe responses are described below (Borhan and Parsons, 2004a).

Model 1. This is a linear regression of volumetric water content (θ_v) with the corresponding probe's output as millivolt (*mV*) in the laboratory.

$$\theta_v = \beta_1 * mV + \alpha_1 \qquad (2)$$

Model 2. This is a linear regression of θ_v with the corresponding probe's normalized output values (Equation 3). In this model, probe output in *mV* was normalized with respect to two extreme conditions of the soil moisture content (air and water).

$$\theta_v = \beta_2 * \eta_{air-water} + \alpha_2 \qquad (3)$$

$$\eta_{air-water} = \frac{X_i - X_{air-j}}{X_{water-j} - X_{air-j}} \qquad (4)$$

where $\eta_{air-water}$ is the normalized *mV* with minimum (air) and maximum (water); X_i, X_{air-j}, $X_{water-j}$, were the sensor reading in soil, air, and water, for i=1,2,3,…N and j=1,2,3,….K. N and K are the number of observations and sensors, respectively, under measurement. β_1 and β_2 are slopes, and α_1 and α_2 are the intercepts of the regression lines.

Model 3. This is a linear regression between θ_v and the corresponding probe's output as millivolt (*mV*) in the factory (Equation 1).

Statistics of mean error or bias (ME), root mean square error (RMSE), average prediction accuracy (APA), standard error of prediction (SEP), and correlation coefficient (R) were used as evaluation criteria to measure performance of the above two models best approximate measured values. The ME and RMSE, APA, and SEP were calculated based on the following equation (Kramer, 1998; Borhan et al., 2004).

$$ME = \frac{\sum (y_i - \hat{y}_i)}{N} \quad (5)$$

$$RMSE = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{N}} \quad (6)$$

$$\text{APA (\%)} = \frac{1}{N}\sum_{1}^{N}\left[1 - \left(\frac{\left|y_i - \hat{y}_i\right|}{y_i}\right)\right] \times 100 \quad (7)$$

$$\text{SEP} = \sqrt{\frac{\sum \left((y_i - \hat{y}_i) - \bar{y}\right)^2}{N - 1}} \quad (8)$$

where y_i and $\hat{y}_i$ are the actual and predicted values, respectively, for i = 1, 2, 3, …N; $\bar{y}$ is the mean difference between actual and predicted values; and N is the total number of observations (data points).

Real time Monitoring of Soil Water Status and Performance Comparison

Real time soil water status in three irrigation treatment plots were monitored with ECH_2O probes from 1 January 2004 to 31 January 2004. In addition, the performance of ECH_2O probes for real time monitoring of soil moisture status was also compared with the more expensive C-probe. Real time probe responses due to irrigation and rainfall were collected from 1 November 2003 to 30 November 2003. The data logger was programmed to collect responses (*mV*) from ECH_2O probes every hour. The responses from both probes were converted into volumetric water content using calibration equations (Borhan and Parsons, 2004b; Agrilink Florida Inc.).

Results and Discussion

Development of Calibration Models

In the laboratory, six pre-selected levels (0.0133, 0.0267, 0.04, 0.0533, 0.08, and 0.10 cm^3 cm^{-3}) of moisture content were maintained and corresponding probe outputs in mV were downloaded from the data logger. Statistical analysis showed that mean responses at different moisture levels were significantly different (α=0.05) (Table 1). Thus, ECH_2O probes were found to be capable of differentiating small changes in moisture content in the Candler soil. The regression analysis between probe responses (mV and normalized mV values) and measured volumetric water content (θ_v) resulted in the following equations (Borhan and Parsons, 2004b):

Model 1: $$\theta_v = 0.000964 * mV - 0.3481 \qquad (9)$$

Model 2: $$\theta_v = 0.6667 * \eta_{air-water} - 0.10394 \qquad (10)$$

No significant differences were observed between these two models in the calibration phase. Observed R^2 for both the models was 0.98 (Table 2). Average prediction accuracy was about 89%. However, minimum and maximum accuracies varied from 45 to 47% and 99.93 to 99.99%, respectively. Calculated SEP and RMSE varied from 0.0038 to 0.004 cm^3 cm^{-3} and 0.0037 to 0.004 cm^3 cm^{-3}, respectively. Similar performances were observed with both models in the validation phase. Observed R^2 was 0.98 and RMSEs were found to be 0.0043 and 0.0041 cm^3 cm^{-3} for model 1 and model 2, respectively. The correlation between actual and predicted soil water content showed a strong relation (Figure 1). The slope and intercept of the correlation line was close to 1 (0.98) and 0 (0.0009), respectively. Thus, this research revealed that ECH_2O probes are able to detect small changes in soil water at the lower end of soil water regime. However, validation of the factory calibration model (Equation 1) resulted in a very low average prediction accuracy, which showed under-prediction of soil water content in a sandy soil (Figure 2). Thus, this result reflected the importance of using the soil specific calibration model.

Real time Monitoring of Soil Moisture Status at Three Treatments Plots

Figure 3 shows a comparison of real time soil moisture status measured by ECH_2O probe at the 20 cm depth in the irrigation treatment plots during January 2004. In the irrigated treatment, a sharp and rapid increase in soil water content was observed after each irrigation event. Then, a gradual decrease in soil water content with time occurred due to drainage and evapotranspiration (ET). ECH_2O probes in the non-irrigated plot responded similarly to rainfall. It was also observed from the real time moisture curve (Figure 3) that probes installed in non-irrigated with rain exclusion treatment did not respond at all during each irrigation and rain event. ECH_2O probes responded fairly well in these three different irrigation treatments. Thus, this research reflects the suitability of ECH_2O probes for real time monitoring of water content in a sandy soil.

Performance Comparison with C-probe

Figure 4 shows the real time soil moisture status of ECH_2O and C-probes at 20 cm depths during November 2003. A sharp and rapid increase in soil water content was observed after each irrigation and a gradual decrease in soil water content with time was also observed when the soil began to dry out due to drainage and ET. For both probes, the overall trends in soil water content were similar and consistent with respect to irrigation and rainfall. ECH_2O probes showed higher soil water content at each depth on irrigation days compared with the C-probes (Figure 4, shows 20 cm depth only for clarity). In general, the probe predicted slightly different soil moisture content, perhaps due to the variations in sensor placement, installation method, root zone depth and distribution, and sprinkler wetting pattern that existed in the field. We do not know which probe produced the most accurate results at this point, but detailed calibration of the C-probe has not been done yet on this type of soil. It should be noted that the accuracy of probes for predicting soil water content might not be very important to the grower. In this situation, growers could correlate the relative position of the probe response curve with current soil moisture status of the grove to trigger an irrigation.

SUMMARY AND CONCLUSIONS

Accurate measurement of soil water is a prerequisite for devising an efficient irrigation scheduling system in sandy soil. A relatively low cost ECH_2O capacitance-based soil moisture probe was calibrated and evaluated for monitoring soil water status in different irrigation treatments in the field. The performance of the ECH_2O probe was compared with the more expensive C-probe for real time monitoring of soil water status in a central Florida sandy soil. The goal of this research was to determine the capability of the ECH_2O probe to monitor small changes in water content across a narrow moisture range. Two models were developed in this study. Observed R^2, average prediction accuracy, standard error of prediction, and root mean square errors were about 0.98, 88%, 0.0042 $cm^3\ cm^{-3}$ and 0.0041 $cm^3\ cm^{-3}$, respectively, in the validation phase. Real time moisture curves showed that ECH_2O probes responded fairly well to three different irrigation treatments. The overall trends in soil water content of ECH_2O probes appeared to be similar and consistent with respect to irrigation, rainfall, drainage, water use by the plants and ET when compared with the C-probe. Thus, the relatively low cost ECH_2O probes appear to be suitable for real time monitoring of water in a sandy soil.

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Table 1. Statistics describing measurement variability of ECH_2O probe (mV) response.

Measured Moisture ($cm^3\ cm^{-3}$)	Probe responses at different moisture levels						
	Mean (mV)	Minimum (mV)	Maximum (mV)	Range (mV)	STD (mV)	CV (%)	STDER (mV)
0.0133	379.57 [a]	377.59	382.47	4.88	1.62	0.43	0.57
0.0267	385.06 [b]	381.86	388.57	6.71	2.25	1.59	0.80
0.0400	403.74 [c]	401.38	406.26	4.88	1.80	0.45	0.64
0.0533	413.96 [d]	411.14	417.24	6.10	2.19	0.53	0.77
0.0800	442.55 [e]	438.59	452.01	13.42	4.52	1.02	1.60
0.1000	467.26 [f]	459.33	480.07	20.74	6.25	1.34	2.21

Mean values with same letter are not significantly different at $\alpha = 0.05$.
STD is standard deviation; STDER is standard error; CV is coefficient of variation.

Table 2. Performance of calibration models in predicting soil moisture in the laboratory (Borhan and Parsons, 2004a).

Performance with calibration dataset						
Model Types	Calibration accuracies (%)			R^2	SEP ($cm^3\ cm^{-3}$)	RMSE ($cm^3\ cm^{-3}$)
	Min	Max	Average			
Model 1	45.18	99.99	89.30	0.98	0.0038	0.0037
Model 2	47.43	99.93	88.91	0.98	0.004	0.004
Performance with validation dataset						
Model Types	Prediction accuracies (%)			r	SEP ($cm^3\ cm^{-3}$)	RMSE ($cm^3\ cm^{-3}$)
	Min	Max	Average			
Model 1	41.02	99.58	88.44	0.98	0.0043	0.0043
Model 2	45.87	99.67	88.76	0.98	0.0042	0.0041
Model 3	-207.33[a]	43.65	-41.98[b]	0.98	0.0090	0.0543

Model 1 used probe responses in *mV*; Model 2 used normalized responses (*mV*); Model 3 used probe response in mV and factory calibration equation; R^2 is the coefficient of determination SEP is the standard error of prediction; RMSE is the root means square error; r is the coefficient of correlation between actual and measured moisture content; and [a] and [b] indicates predicted values are about 3 and 0.41 times lower than actual values, respectively.

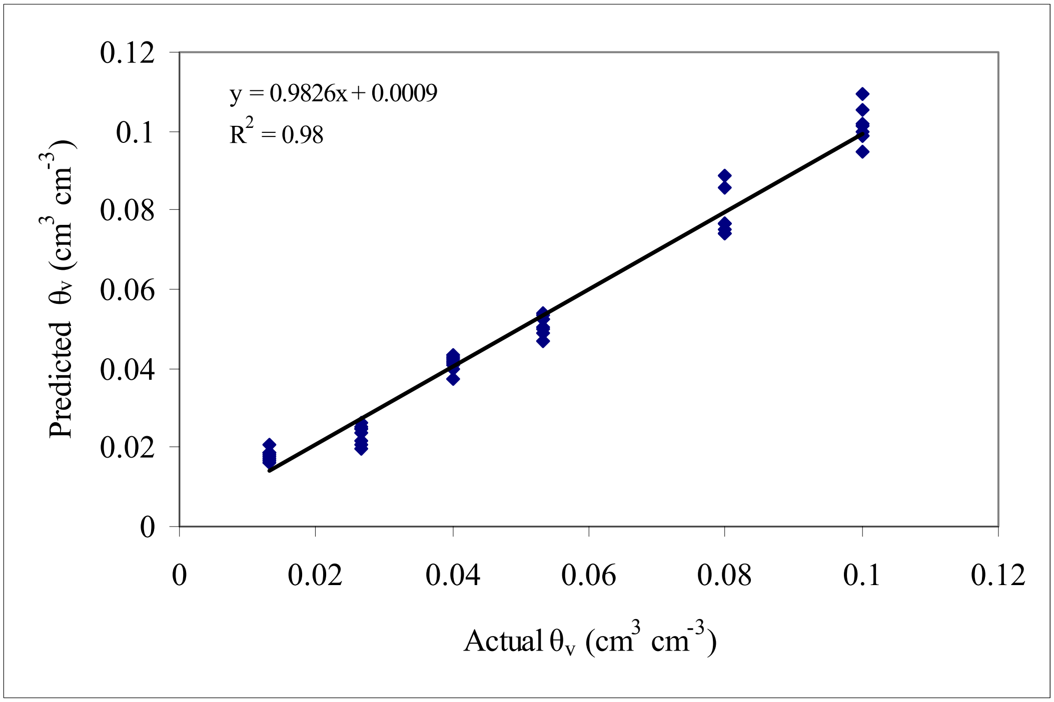

Figure 1. Relation between actual and predicted soil moisture content in validation phase (using Model 2) (Borhan and Parsons, 2004b).

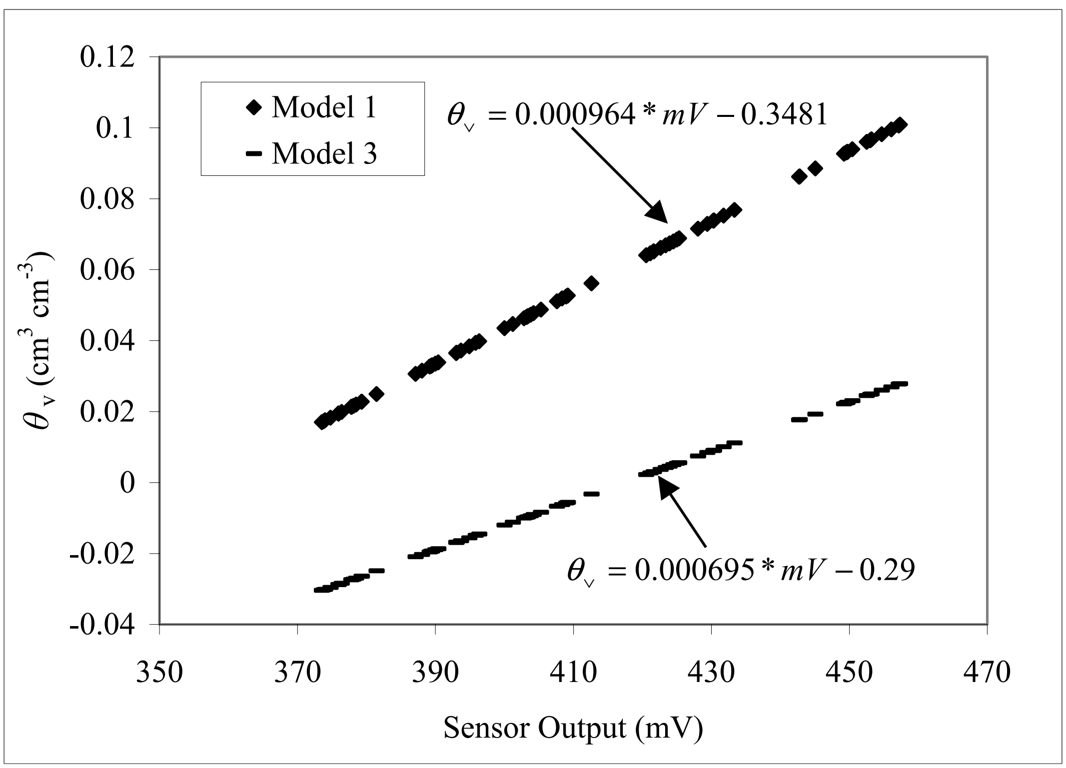

Figure 2. Comparison of Model 1 (Equation 2) and Model 3 (factory calibration model, Equation 1) using validation dataset (Borhan and Parsons, 2004a).

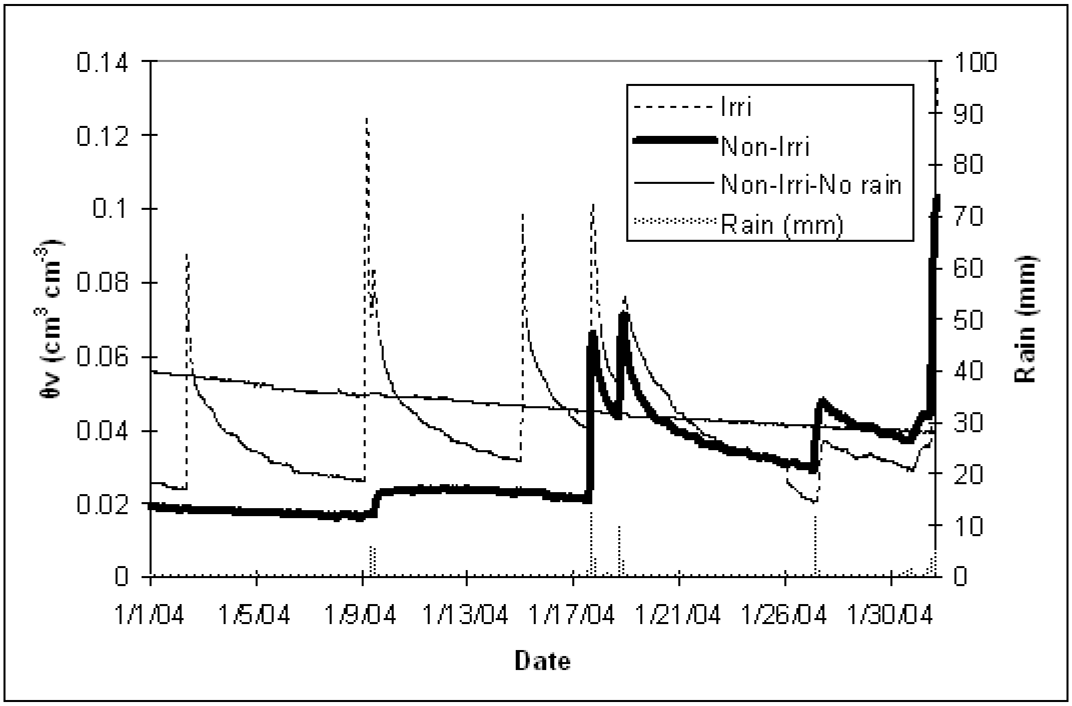

Figure 3. Comparison of real time soil moisture status measured by ECH_2O probe at 20 cm depth in three irrigation treatments plots.

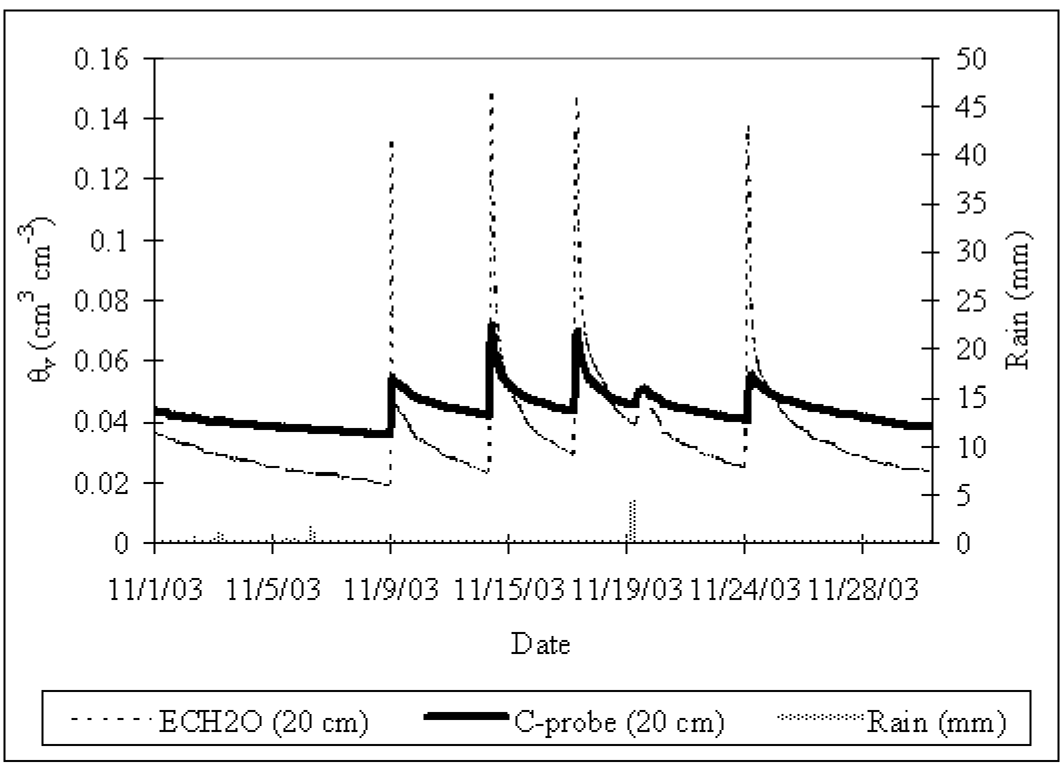

Figure 4. Comparison of real time soil moisture status measured by ECH_2O probe and C-probe at 20 cm depth (Borhan and Parsons, 2004b).