Soil Science Society of America Journal, pp. 1940-1946, Vol. 64, No. 6, Nov.-Dec. 2000.

Soil Material, Temperature, and Salinity Effects on Calibration of Multisensor Capacitance Probes

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ABSTRACT

Multisensor capacitance probes (MCAP) are an alternative to gravimetric or nuclear soil water content (θ_v, m^3 m^{-3}) measurements. Their θ_v measurements are more convenient than gravimetric, and don't carry the nuclear regulatory burdens. Previous studies noted potential salinity and temperature effects on MCAP θ_v determinations. Our objectives were to calibrate and verify MCAP θ_v measurement accuracy in two soil materials, two water salinities (1.3 and 11.3 dS m^{-1}), and with diurnal temperature fluctuations. The surface and calcic horizons of an Olton soil (fine, mixed, superactive, thermic Aridic Paleustoll) were packed into triplicate, 0.5-m-tall, 100-L columns and wetted. We compared θ_v determined by volumetric measurements, time domain reflectometry (TDR), and MCAPs. The TDR θ_v were within ± 0.01 m^3 m^{-3} of volumetric determinations for air-dry and saturated soil. The factory supplied universal MCAP calibration provided accurate θ_v estimates for air dry (± 0.01 m^3 m^{-3}) surface and calcic soil materials but not after wetting (≈ -0.05 m^3 m^{-3}). Also, imprecise MCAP sensor positioning during water frequency parameter determination was problematic and biased initial θ_v measurements. After calibration against TDR, the MCAP θ_v varied ± 0.01 m^3 m^{-3} from measured θ_v for air-dry and saturated conditions for both soil materials, which were then pooled to obtain one calibration. Column resaturation with saline water affected permittivity and elevated MCAP θ_v ≈ 0.25 m^3 m^{-3} above the available pore space. Cyclical soil temperature fluctuations of 15°C induced similar fluctuations in indicated θ_v throughout the column (0.04 m^3 m^{-3} for MCAP and 0.02 m^3 m^{-3} for TDR), which was attributed to variations in permittivity.

KNOWING SOIL WATER CONTENT and the rate of uptake by a crop is a critical part of crop water management. Evaporation and crop use of soil water can be inferred from periodic measurement using gravimetric or neutron scattering methods. Gravimetric soil water measurements are laborious and invasive when used to characterize water use during a growing season. The neutron scattering method of soil water measurement is often preferred for seasonal water use measurements, but regulations governing the use of radioactive materials have made it less desirable. As an alternative to gravimetric or neutron scattering methods to determine crop use of soil water, techniques for automating continuous measurement of soil water content based on the dielectric behavior of soil and water are being used (Baker and Allmaras, 1990; Herkelrath et al., 1991; Starr and Paltineanu, 1998). The technologies used include TDR, frequency domain reflectometry (FDR), and capacitance methods.

A multisensor capacitance probe (MCAP) marketed as EnviroSCAN (Sentek Pty. Ltd., South Australia; SENTEK, 1995) determines soil water content by measuring the frequency change induced by the changing permittivity of the soil permeated by the fringing fields of the capacitor sensor.[1] Paltineanu and Starr (1997) described the EnviroSCAN system components and function as part of their instrument calibration experiment. Briefly, the capacitance sensor output frequency varies proportionally with the soil permittivity and increasing soil water. The sensor frequency in soil, F_s, is scaled, SF, using the equation:

$$\mathrm{SF} = \frac{(F_a - F_s)}{(F_a - F_w)} \qquad [1]$$

where F_a is the sensor frequency in air and F_w is the sensor frequency in water. Volumetric soil water content (θ_v) can be calculated using the factory supplied calibration equation

$$\theta_v = (0.792\mathrm{SF} - 0.023)^{2.475} \qquad [2]$$

(SENTEK, 1995) or a soil specific calibration. Paltineanu and Starr (1997) developed a power function relationship between SF and θ_v. They concluded that the shapes of the soil water–SF relationships developed from independent data sets were "essentially the same", and that soil temperature effects on sensor-estimated θ_v were minimal. These results support a universal calibration independent of soil temperature. In contrast, significant salinity and temperature effects on soil water measurements have been reported while using this equipment (Mead et al., 1995, 1996).

Further tests are needed to establish whether soil water content can be estimated accurately with a universal calibration equation supplied either by the factory (SENTEK, 1995) or reported in the literature. Furthermore, soil temperature and salinity affects on MCAP measured soil water content need to be clearly established and characterized or eliminated from consideration. Therefore, the objectives of our study were (i) to test the accuracy of MCAP soil water measurements using the factory calibration and other published calibrations, (ii) to develop specific laboratory calibrations for two soil materials, and (iii) to characterize soil temperature and water salinity effects on MCAP and TDR soil water measurements under laboratory conditions.

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Published in Soil Sci. Soc. Am. J. 64:1940–1946 (2000).

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by the USDA-ARS.

Abbreviations: DOY, day-of year; EC, electrical conductivity; MCAP, multisensor capacitance probe; TDR, time domain reflectometry; F_s, F_a, and F_w, sensor frequency in soil, air, and water; RMSE, root mean square error; SD, standard deviation; SF, scaled sensor frequency; θ_v, volumetric water content.

MATERIALS AND METHODS

Multisensor capacitance probes were calibrated and the accuracy of soil water measurements verified gravimetrically and with TDR sensors under greenhouse conditions at the Texas Agricultural Experiment Station, Lubbock. Samples of an Olton soil were collected from the plowed surface Ap horizon, (0–0.15 m) and calcic (1.5–2.0 m) soil horizon. Surface soil characteristics determined in an earlier study were 270 g kg^{-1} clay, 480 g kg^{-1} sand, and an electrical conductivity (EC) of 1.08 dS m^{-1}, while the calcic layer had 300 g kg^{-1} $CaCO_3$, 135 g kg^{-1} clay, 480 g kg^{-1} sand, and an EC of 0.50 dS m^{-1} (Baumhardt and Lascano, 1993). Each soil material was collected, passed through a 12-mm hardware cloth screen, air-dried in a greenhouse, and packed into triplicate columns (six columns total).

Soil Column Preparation

Soil column containers were made from 1.02 m tall by 0.5 m diameter 120-L plastic barrels by removing the tapered upper 0.26 m and installing a 12-mm-o.d. hose barb in the bottom for water addition. By wetting the soil columns from the bottom, air entrapment and uneven water distribution were avoided. Washed and air-dried coarse gravel with a mean diameter >12 mm was placed into the tapered bottom to a depth of 0.26 m at the same time that MCAP access tubes were positioned near the soil column center. The gravel was covered by a 0.5-m-diam. nylon window screen disk and cheesecloth to reduce soil sifting into and mixing with gravel during soil column preparation. Plastic barrels, nylon window screen, and cheesecloth materials were used to avoid potential interference with electrical soil water content sensors. The barrel above the gravel was a nearly cylindrical column 0.5 m tall and 0.5 m in diameter (Fig. 1) with a volume of ≈93 L (92.75 L as measured using water). All six soil columns were packed in 0.10-m increments above the gravel to an overall average density of 1.40 Mg m^{-3} with a standard deviation (SD) of ±0.02 Mg m^{-3} for the three surface soil columns and 1.39 ± 0.04 Mg m^{-3} for the three calcic soil columns.

Instrumentation to measure θ_v was installed during soil column preparation. The MCAP access tubes were positioned near the center of the soil column, while TDR sensors were installed equidistant from the soil column wall and MCAP access tube (Fig. 1, TOP). Sensors of the MCAP array (EnviroScan) were positioned at depths of 0.1, 0.2, 0.3, and 0.4 m; and 0.2-m trifilar TDR probes (TR-100, Dynamax, Houston, TX) were placed horizontally at depths of 0.05, 0.15, 0.25, 0.35, and 0.45 m (Fig. 1). Vertical and horizontal separation between MCAP and TDR sensors was ≈5 cm to avoid potential interference. In each soil column, temperatures at 0.05-, 0.1-, and 0.3-m depths were measured on the side opposite of the TDR probes and 0.1 m from the soil column wall using copper-constantan thermocouples mounted on 1-cm-square 0.45-m-long wood stakes.

Measurements

Measurements included soil temperature, θ_v, and the amount of water added to each soil column. Soil temperature was measured every 15 s with sealed thermocouples made from twisted and soldered 22-ga Cu-Constantan wire (Omega Engineering, Stamford, CT) averaged and electronically recorded every 10 min using a CR-10 data logger (Campbell Scientific, Logan, UT). Using automated data collection systems, the soil water content was determined from F_s measurements recorded every 2 min during initial water additions for calibration data, and then every 10 min after wetting. The TDR probes were connected to a cable tester (model 1502C, Tektronix, Beaverton, OR) through multiplexers (model TR-200, Dynamax), which were controlled by a laptop computer running the TACQ software (Evett, 1998). The equation of Topp et al. (1980) was used to relate apparent permittivity to water content. Values for F_a and F_w in Eq. [1] were determined for the MCAP sensors according to the recommended factory procedures in air and in a water bath using local tap water (EC of 1.30 dS m^{-1}). Water added to soil columns from the constant head Marriott system was measured to obtain a mean θ_v for the soil column using an electronically recorded balance (Mettler PM34, Mettler-Toledo, Greifensee, Switzerland).

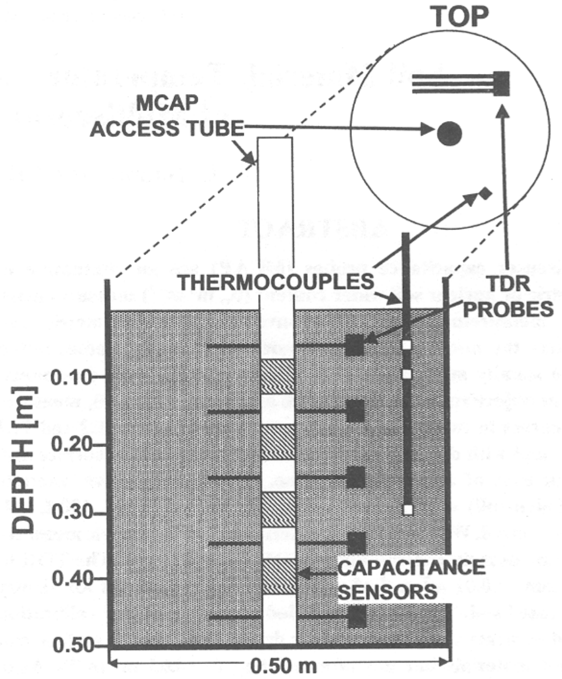

Fig. 1. Diagram (not-to-scale) showing the relative position of soil temperature and water content sensors in each soil column. Thermocouples measured soil temperature 0.05, 0.1, and 0.3 m below the surface. Soil water content was measured in 0.1-m intervals beginning at the 0.05-m depth for time domain reflectometry (TDR) wave guides and 0.1-m depth for multisensor capacitance probe (MCAP) sensors with a lateral separation of 0.05 m to minimize potential interference.

Experimental

Our experiment proceeded in four steps that included measurement of soil water content gravimetrically and by the TDR or MCAP systems with collateral measurement of soil temperature. First, the volumetric water content of the air-dry soil was determined from the gravimetric water content of the soils used for packing and the mean bulk densities of the packed soil columns. The soil columns were sealed with 0.0254-mm plastic bags, and measurements of soil temperature and air-dry water content using TDR and MCAP sensors were made during day of year (DOY) 89 to 125 in 1997. Second, for calibration, θ_v with depth was measured by TDR and MCAP sensors from DOY 126 to 136 while adding water (EC of 1.30 dS m^{-1}) from a constant head supply (0.5 m above the soil surface) through the bottom inlet of the column. Soil water content measured using TDR was regressed on the calculated scaled frequency, Eq. [1], using nonlinear fitting methods (SAS Institute, 1988). Third, the near-saturated θ_v (MCAP and TDR) and soil temperature were measured for resealed soil

Table 1. Mean θ_v ± SD was determined volumetrically (gravimetric water content times bulk density) or from the soil permittivity using time domain reflectometry (TDR) or multisensor capacitance probe (MCAP) sensors in surface and calcic soil materials. Measurements were under air-dry, saturated tap water (electrical conductivity [EC] of 1.30 dS m^{-1}), or saline water (EC of 11.30 dS m^{-1}) conditions. Listed MCAP results include the factory and custom calibrations. For saline-saturated soil, the TDR system did not return interpretable wave forms.

	Air-dry		Saturated tap		Saturated saline	
	Surface	Calcic	Surface	Calcic	Surface	Calcic
	$m^3\ m^{-3}$					
Volumetric	0.02 ± 0.01	0.03 ± 0.01	0.40 ± 0.01	0.39 ± 0.01	–	–
TDR	0.02 ± 0.01	0.02 ± 0.01	0.41 ± 0.02	0.40 ± 0.01	–	–
MCAP, factory	0.01 ± 0.01	0.02 ± 0.01	0.35 ± 0.01	0.33 ± 0.01	0.45 ± 0.01	0.43 ± 0.01
MCAP, custom	0.02 ± 0.01	0.02 ± 0.01	0.41 ± 0.01	0.38 ± 0.01	0.62 ± 0.02	0.60 ± 0.03

columns (sealed surface and inlet), from DOY 136 to 160. Fourth, from DOY 161 to 168, θ_v with depth was measured while adding saline water (EC of 11.30 dS m^{-1}) from a constant head (2.5 cm above the soil surface) supply to the unsealed column surface. Effluent from the columns was measured with 1-L graduated cylinders and an aliquot taken for EC determination. The EC of the column effluent indicated the breakthrough of saline water in the column (EC elevated more than 2.0 dS m^{-1} above the initial value), at which time infiltration was terminated and drainage allowed. After the completion of the experiment (DOY 170), soil columns were destructively sampled to verify all sensor positions. Comparisons of different water measurement methods and water quality effects on indicated water contents were based on univariate and unpaired *t*-test statistics.

RESULTS AND DISCUSSION

Calibration

Calculated θ_v, using the gravimetric water content and column bulk density data, averaged 0.02 $m^3\ m^{-3}$ with a SD of ±0.01 $m^3\ m^{-3}$ for the air-dry surface soil and 0.03 ± 0.01 $m^3\ m^{-3}$ for calcic soil. The air-dry surface and calcic soil θ_v measured using TDR and MCAP sensors, shown in Table 1, agreed with the calculated values to within ±0.01 $m^3\ m^{-3}$ or the level of precision for our test. Postsaturation θ_v calculated from the added water volume was 0.40 ± 0.01 $m^3\ m^{-3}$ for the surface soil and 0.39 ± 0.01 $m^3\ m^{-3}$ for the calcic soil. The corresponding TDR measured θ_v of 0.41 ± 0.02 $m^3\ m^{-3}$ for the surface soil and 0.40 ± 0.01 $m^3\ m^{-3}$ for the calcic soil were not statistically different from gravimetric measurements. The initial saturated calcic and surface soil θ_v determined using the MCAP and factory calibration, however, were about 50% larger than the gravimetric measurements.

Accuracy of the MCAP θ_v calculated from SF using Eq. [1] and measured F_s depends on accurate F_a and F_w sensor values and an appropriate calibration equation. The mean sensor F_a values of 36 121 ± 226 ($n = 24$) were consistent with the factory-suggested typical 35 000 to 37 000 range (P. Buss, 1999, personal communication) and F_a values of 36 243 ± 183 ($n = 32$) and 36 345 ± 230 ($n = 32$) determined for two MCAP systems in 1995 by J.L. Starr (1999, personal communication). Measurements of F_w made in a factory-supplied portable water container averaged 26 112 ± 107 ($n = 24$), which exceeded the factory-suggested range of 23 500 to 25 500 for fresh and saline water and Starr's F_w values of 25 229 ± 84 ($n = 32$) and 25 292 ± 100 ($n = 32$). Consequently, the MCAP returned unrealistically high SF values (>1.0) for near-saturated soil conditions. We, therefore, abandoned the suspicious F_w and repeated the F_w and F_a determination for tap water and air using a 0.30 m diam. by 1.70 m tall polyvinyl chloride plastic column that contained the entire MCAP and access tube unit. The resulting F_a of 35 950 ± 290 remained practically unchanged, but the repeated F_w measurement averaged 23 695 ± 130 ($n = 24$), was consistent with the factory specified typical range, and produced SF values that never exceeded 1.0.

Imprecise sensor positioning while determining the F_w value within the portable containers may have permitted the sensors to integrate air effects resulting in an upward bias. When using the new mean F_a of 35 950 and F_w of 23 695 to obtain SF, the air-dry θ_v calculated from the factory calibration for the soil and calcic horizons was not different from either volumetric or TDR measured soil water contents (Table 1). The MCAP-measured θ_v was, however, less than either the volumetric or TDR-measured values for near-saturated conditions. Because the differences in measured θ_v and the factory-calibrated MCAP varied as a fraction of the actual water content, the resulting MCAP indicated relative changes in θ_v would not duplicate actual changes in soil water content. This illustrates the need to calibrate the MCAP instrument.

The MCAP was subsequently calibrated by regressing the indicated SF on the corresponding TDR-measured θ_v values obtained while wetting air-dry surface and calcic soil materials to near saturation. The 5-cm vertical separation between TDR and MCAP sensors limited calibration comparisons to air-dry conditions and to water contents >0.20 $m^3\ m^{-3}$. The θ_v of the calcic and surface soil materials, shown in Fig. 2A, were similar across the range of SF measured; therefore, regression analyses were performed for individual and pooled data sets. Soil temperatures corresponding with these θ_v data averaged 29.6 ± 5.3°C.

Calibrations of θ_v as a function of SF by Paltineanu and Starr (1997) used an equation of the form

$$\theta_v = a\mathrm{SF}^b \qquad [3]$$

where *a* and *b* are fitted parameters. Our least squares linear regression of 89 natural log-transformed θ_v and SF measurements from the pooled surface and calcic soil materials resulted in values of $a = 0.560$ and $b = 2.508$ (Table 2). While the coefficient of determination, r^2, was 0.987, the resulting fit appeared undesirable (Fig.

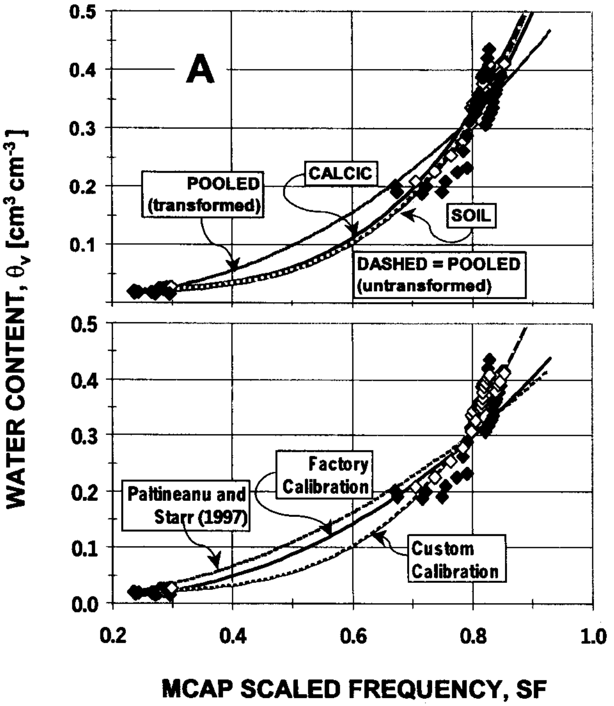

Fig. 2. Measured θ, plotted as a function of the multisensor capacitance probe (MCAP)-scaled frequency, SF for the calcic (open diamond) and surface (filled diamond) soil materials and calculated using the regression relationships listed in Table 2. (A) The least squares regression using Eq. [3] and ln-transformation of the pooled Texas-data appears to fit poorly. Nonlinear fits of Eq. [4] to the untransformed calcic and surface Texas-data were similar and, therefore, pooled. (B) Measured θ_v and water contents calculated using calibrations reported by Paltineanu and Starr (1997), supplied by the factory, or developed in this paper are shown.

2A) with a root mean square error (RMSE) of 0.147 $m^3\ m^{-3}$. Because log transformation of data imparts multiplicative type error in a least squares regression that assumes additive error, the fit is biased in favor of points occurring near the extremes (Myers, 1986). As recommended by Myers (1986), we attempted a nonlinear fit of the untransformed data to Eq. [3]. The r^2 was reduced from 0.987 to 0.967 (Table 2), but the RMSE was improved to 0.028 $m^3\ m^{-3}$ or 20% of the RMSE obtained when regressing the ln-transformed data. This relationship did underestimate air-dry θ_v (= 0.02 $m^3\ m^{-3}$) when SF was ≈0.30 ± 0.05 because the equation asymptotically approaches $\theta_v = 0.0\ m^3\ m^{-3}$.

By including a value for a non-zero residual water content, *c*, in Eq. [3], the resulting equation

$$\theta_v = a\mathrm{SF}^b + c \qquad [4]$$

produces MCAP θ_v values that approach a residual water content value asymptotically at the low SF, air-dry, conditions. Both surface and calcic soil materials were individually fitted to Eq. [4], resulting in similar parameter estimates of 0.798 and 0.752 for *a*, 4.25 and 4.26 for *b*, and 0.020 and 0.017 for *c*, respectively (Table 2). Because of the similarity in the relationship between θ_v and SF for these two different soil materials (Fig. 2A), the data were pooled and fitted using Eq. [4] to obtain parameter values of $a = 0.794$, $b = 4.39$, and $c = 0.019$.

Table 2. Data source, equations, coefficient of determination (r^2), root mean square error (RMSE), and the number of observations (n), from calibrations developed for the MCAP system during this study and from other sources. The fitted relationships were: Eq. [3] $\theta_v = a\mathrm{SF}^b$ and Eq. [4] $\theta_v = a\mathrm{SF}^b + c$.

Data source	Equation	r^2	RMSE	n
			$m^3\ m^{-3}$	
	Eq. [3]			
Texas, pooled (ln-transformed)	$\theta_v = 0.560\mathrm{SF}^{2.508}$	0.987	0.147	89
Texas, pooled (un-transformed)	$\theta_v = 0.752\mathrm{SF}^{3.841}$	0.967	0.028	89
	Eq. [4]			
Texas, Calcic	$\theta_v = 0.798\mathrm{SF}^{4.25} + 0.020$	0.993	0.014	41
Texas, surface soil	$\theta_v = 0.752\mathrm{SF}^{4.26} + 0.017$	0.955	0.032	48
Texas, pooled	$\theta_v = 0.794\mathrm{SF}^{4.39} + 0.019$	0.971	0.027	89
	Other sources			
Sentek (1995)	$\theta_v = (0.792\mathrm{SF} - 0.0226)^{2.4752}$	0.974	–	–
Beltsville†	$\theta_v = 0.490\mathrm{SF}^{2.1674}$	0.992	0.009	15
Beltsville, California, and Australia‡	$\theta_v = 0.501\mathrm{SF}^{2.006}$	0.947	0.026	77

† Silt loam soil at Beltsville, MA (Paltineanu and Starr, 1997).

‡ Combined data from Beltsville, California, and Australia (Paltineanu and Starr, 1997).

These nonlinear fits had $r^2 > 0.95$ and RMSE < 0.032 $m^3\ m^{-3}$ without biasing the additive error.

The θ_v calculated using our calibration and the calibrations supplied by the factory or presented by Paltineanu and Starr (1997) are plotted in Fig. 2B. Our calibration of the MCAP system produced little difference in the calculated air-dry θ_v compared with the factory calibration for the calcic and surface soil (see also, Table 1). Compared with the other calibration equations, however, our calibration significantly improved the accuracy of θ_v estimated by the MCAP system in the 0.20 to 0.45 $m^3\ m^{-3}$ range (Fig. 2B). Our results show that the MCAP instrument yielded soil specific θ_v measurements and must be calibrated for individual soils. Paltineanu and Starr (1997) concluded that differences in soil mineralogy, especially 2:1 clays, could also affect MCAP instrument calibration. That is, the increased surface area of 2:1 clays affect the bound water and corresponding bulk permittivity (Bridge et al., 1996; Wraith and Or, 1999). The Olton soil used in this test has mixed mineralogy that includes the 2:1 clay, montmorillonite, as the dominant species (USDA-NRCS, 1999).

Temperature

The MCAP instrument was calibrated in a greenhouse, which had diurnal air temperature fluctuations as much as 20 to 25°C. Examples of the cyclic air and soil temperatures at depths of 0.1 and 0.3 m for DOY 100 to 106 in 1997 are shown (Fig. 3A). Maximum air temperature occurred around mid day, while peak soil temperatures occurred later; lagging more with increasing soil depth. Beginning on DOY 102, both maximum and minimum soil and air temperatures increased gradually, with greenhouse heaters maintaining a minimum 15°C air temperature after DOY 103.

The MCAP-measured air-dry θ_v in sealed columns varied cyclically, but less than one SD, with the diurnal soil temperature variations (Fig. 3B). The gradually in-

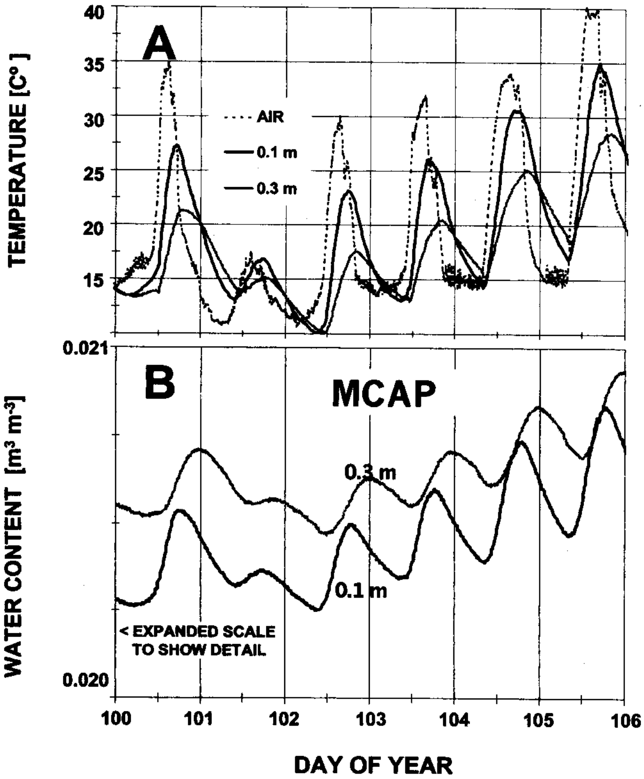

Fig. 3. Diurnal (A) air and soil temperature and (B) the multisensor capacitance probe (MCAP)-measured water content for sealed air dry soil columns. Note that the θ_v scale is expanded to 0.001 m^3 m^{-3} for detail (0.1 of error). Greenhouse heating began on DOY 103, resulting in 15° minimum air temperature. The gradual warming of the soil is also reflected by similarly increasing MCAP water contents.

creasing θ_v corresponded with increasing soil temperature after DOY 102. Maximum indicated θ_v at 0.1-m depth corresponded with the maximum temperature for that depth; however, at 0.3-m depth the maximum θ_v lagged 4 to 6 h after the maximum temperature. Because the MCAP sensors centered in the soil column were further from the warming surface than the thermocouples, except at the 0.1-m depth, the MCAP measured water content lagged behind the soil temperature. The diurnal MCAP-measured θ_v fluctuation for air-dry soil (θ_v = 0.02 m^3 m^{-3}) was <0.1% (i.e., 0.001 m^3 m^{-3}) but no corroborating TDR θ_v data were available after a nearby lightning strike and electrical surge damaged (hard disk crash) the lap-top system used to monitor TDR equipment.

The diurnal air and soil temperature fluctuations, after wetting the columns to near saturation, are shown for a representative period, DOY 150 to 155, in Fig. 4A. Air temperature ranged from a minimum of 15 to >35°C, with warmer minimum temperatures for the soil. As in the case of the air-dry soil, the lag between peak soil and air temperatures increased with increasing sensor depth. The corresponding MCAP-measured θ_v for the sealed soil columns fluctuated 0.02 to 0.04 m^3 m^{-3} diurnally in close synchronization with soil temperature (Fig. 4B) at both 0.1- and 0.3-m depths. We attributed this, primarily, to more rapid heat conductance under

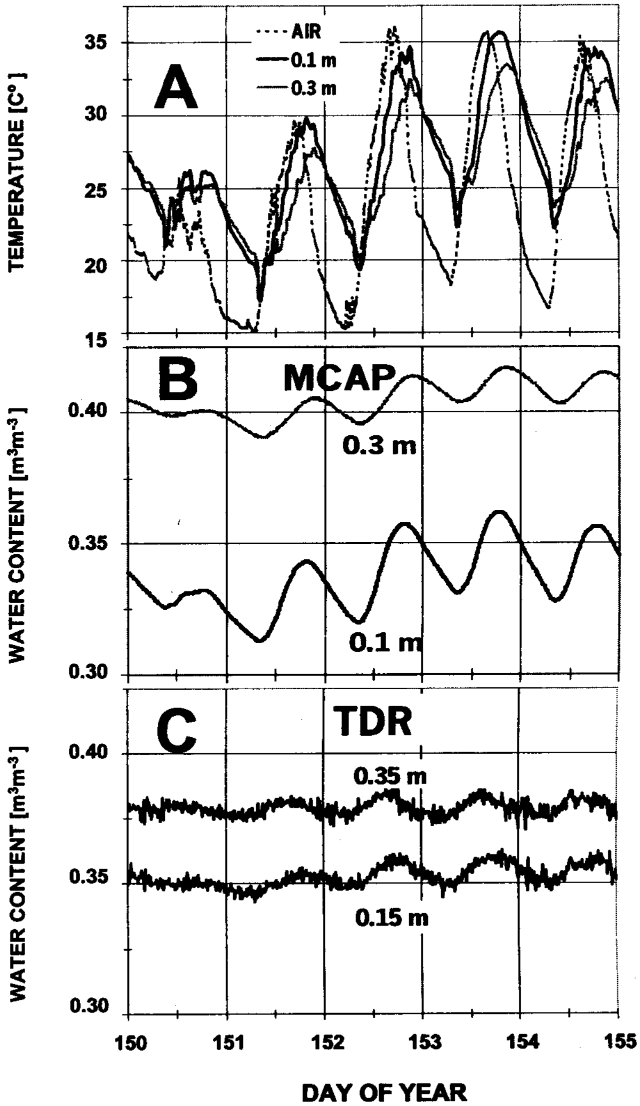

Fig. 4. Diurnal (A) air and soil temperature and (B) measured water content using multisensor capacitance probe (MCAP) and (C) time domain reflectometry (TDR) sensors for sealed nearly saturated soil columns. Increased soil temperature resulted in a corresponding increase of water content measured by both the MCAP and TDR probes.

saturated conditions. Similarly, diurnal fluctuations in θ_v of 0.01 to 0.02 m^3 m^{-3} were indicated by TDR measurements, especially, after DOY 152 (Fig. 4C).

As soil temperature fluctuated diurnally, the soil permittivity either changed due to temperature alone, or in response to water vapor moving in near-saturated, sealed soil columns. Mead et al. (1996) attributed diurnal water content fluctuation to vapor transport that increased θ_v with increasing soil temperature. Using vapor transport, Parlange et al. (1998) calculated diurnal field θ_v fluctuations; however, the calculated moisture content change was lowest at mid day due to water losses with warmer temperatures. Using gravimetric methods, Jackson (1973) also measured diurnally fluctuating surface θ_v that peaked at sunrise and declined until mid afternoon because of evaporation. We consider water transport, whether as vapor or otherwise, within nearly saturated sealed soil columns along an increasing temperature gradient an unlikely explanation for the diurnal fluctuations in our θ_v observations.

Recently, it was theoretically established that changes in temperature of the mineral soil fraction had little impact on soil permittivity (Yu et al., 1999). However, Wraith and Or (1999) demonstrated experimentally that temperature affects the dielectric properties of water bound near the surface of 2:1 clay minerals, thus changing soil permittivity. They calculated the effect of soil temperature changes on the apparent θ_v as measured using permittivity detection methods (Or and Wraith, 1999). Diurnal θ_v fluctuations indicated by both TDR and MCAP systems for our sealed soil columns were attributed, therefore, to temperature dependent fluctuations in the soil permittivity.

A basis for correcting temperature effects on MCAP sensor water content estimates could be implemented with a calibration relationship to concurrently measured soil temperature. However, an effective system for doing this is complicated by two factors. First, the temperature effect is probably soil (and soil horizon) specific, that is, greater with 2:1 clays and negligible in sandy soils, as was shown for TDR by Wraith and Or (1999). Second, integrating temperature measurements with each MCAP sensor must address temperature effects on soil permittivity and not the sensor. The MCAP uses a type of capacitance sensor that is unaffected by temperature changes (<0.005 m^3 m^{-3} for a 30°C temperature variance, Dean et al., 1987). Therefore, an integrated temperature and capacitance sensor used within an access tube would have to detect temperature changes in the surrounding bulk soil that are synchronous and of equal magnitude to achieve dependable temperature correction.

Salinity

The effects of water salinity on MCAP- and TDR-measured θ_v were determined by adding saline water (EC of 11.30 dS m^{-1}) during a period of $\approx$10 h. The amount of saline water required to achieve saline water breakthrough in surface and calcic soil materials was 0.92 ± 0.05 and 0.86 ± 0.03 pore volumes, respectively, as indicated by increased EC of drainage water. About 0.70 pore volume of water was drained from the near-saturated column as saline water was added.

Soil water content is independent of solution electrolyte concentration; therefore, the gravimetrically calculated saturated water content remains unchanged from that listed in Table 1. When the wetting front of the saline water passed TDR wave-guides, these sensors failed to generate an interpretable waveform, resulting in no θ_v measurement under the conditions of our test. In contrast, the MCAP system continued to measure θ_v under these saline conditions. However, the MCAP indicated mean θ_v for near-saturated conditions using the factory calibration increased $\approx$0.10 m^3 m^{-3} more than the corresponding tap water (Table 1), thus illustrating MCAP sensitivity to soil salinity conditions. The mean θ_v using our custom calibration was $\approx$0.20 m^3 m^{-3} greater than the gravimetrically determined θ_v (Table 1). Neither the factory nor the custom calibrations diminished MCAP sensitivity to saline conditions or improved the accuracy of the indicated saturated θ_v.

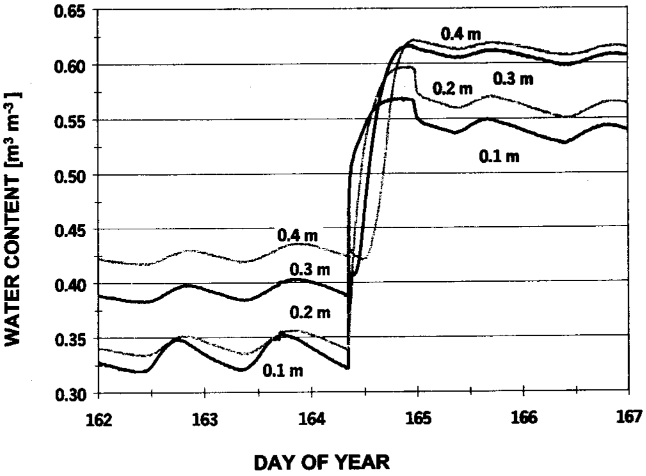

Fig. 5. The multisensor capacitance probe (MCAP)-measured soil water content with depth before and after resaturation with saline water.

Typical increases in θ_v measured using the MCAP system with our custom calibration during the addition of saline water are illustrated in Fig. 5. Also shown are practically simultaneous diurnal variations in measured water content with depth that are attributed to corresponding soil temperature variations. Before saline water was added, θ_v at 0.3- and 0.4-m depths were 0.40 m^3 m^{-3}, nearly saturated, but the upper soil column was not saturated (0.1 and 0.2 m θ_v of 0.32 and 0.35 m^3 m^{-3}). The addition of saline water on DOY 164 caused MCAP sensors to show an immediate increase in θ_v. While some increase in θ_v was expected because of column resaturation, the θ_v increase measured by the MCAP to 0.60 m^3 m^{-3} exceeded the available pore space ($\approx$0.40 m^3 m^{-3}). We attribute this overestimation of soil water content to salinity effects on permittivity. A gradual increase in soil salinity due to irrigation, which is typical for many areas, may result in a subtle increase in the MCAP-indicated water content that does not occur and could be misleading.

SUMMARY AND CONCLUSIONS

We compared gravimetric and permittivity-based measurements of θ_v in controlled column experiments for the purpose of testing the MCAP factory calibration, developing a calibration specific for our soils, and characterizing instrument response to soil temperature and salinity conditions. Accuracy of the MCAP-estimated θ_v depended on accurate F_w and F_a sensor values and an appropriate calibration equation. Imprecise sensor positioning within the factory-supplied portable water container allowed the integration of air effects on F_w and biased initial measurements. The factory-supplied universal MCAP calibration equation accurately estimated θ_v from SF for both soil materials when air dry but not when nearly saturated, thus illustrating the need for a soil specific calibration. Without calibration, θ_v measured using the TDR system was within ±0.01 m^3 m^{-3} of volumetrically determined air-dry and saturated values for both soil materials. A custom calibration of the MCAP instrument obtained using a nonlinear fit of untransformed TDR-measured θ_v regressed on the MCAP SF improved θ_v determinations across the entire water content range.

The MCAP-indicated θ_v was sensitive to both soil temperature and soil water salinity, which were attributed to related soil permittivity changes. For example, diurnal soil temperature fluctuations resulted in synchronized θ_v fluctuations that increased in amplitude with increasing real soil water content. We conclude that variations in temperature must be considered when interpreting MCAP-determined θ_v under variable soil temperature conditions. Concurrent soil temperature measurements during calibration and use of MCAP sensors would be a basis for recalculating the correct soil water content. The addition of saline water caused uninterpretable TDR wave forms and an overestimation of θ_v by MCAPs. Because of MCAP system's sensitivity to soil salinity, we conclude that variations in soil salinity resulting from irrigation should also be considered when interpreting the MCAP θ_v data. Soil specific calibration of MCAP θ_v for various soil salinities could be a basis to recalculate corrected water content.

ACKNOWLEDGMENTS

We wish to thank Mr. James Prochaska, JNM Technologies, Inc., Bryan, TX, and Mr. Peter Buss, Sentek Pty. Ltd., Kent Town, South Australia, for technical assistance and the use of configured EnviroSCAN equipment.

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