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CHARACTERIZATION OF SOIL-WATER RETENTION OF A VERY GRAVELLY LOAM SOIL VARIED WITH DETERMINATION METHOD

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Soil-water characteristic curves were determined for Krome calcareous very gravelly loam soil in the laboratory and *in situ* in an orchard. In the laboratory, soil-water retention was determined with a pressure plate and pressure Tempe cells for soil collected from vegetable fields. In the orchard, soil-water suction measured with tensiometers was compared to volumetric soil-water content (θ) determined with neutron or multi-sensor capacitance probes. Before field measurements, calibration equations were developed for neutron and multi-sensor capacitance probes for this soil. Krome calcareous gravelly loam soil was found to have two distinct solid fractions with 51% coarse particles and 49% loam particles that resulted in a peculiar soil-moisture retention pattern. Two soil-moisture retention regions were identified, each corresponding to one of the soil solid fractions. As shown by a large number of observations, rapid drainage occurs in the gravel fraction corresponding to soil-water suction less than 75 cm. In an orchard, suction values rarely exceeded 125 cm even when there was no rainfall and irrigation was withheld for three weeks. In the orchard, θ measured with a capacitance probe was considerably more variable and less correlated with soil suction than θ measured with a neutron probe. In very gravelly loam soils such as Krome, results from capacitance sensors may be too variable and inconsistent for reliable monitoring of soil-water content. (Soil Science 2006;171:85–93)

Key words: Tensiometers, capacitance sensors, neutron probe, suction, volumetric soil-water content.

THE majority of tropical fruit crops and several winter vegetable crops in the United States are produced in southern Florida on calcareous very gravelly loam soil. This soil, which is made by rock-plowing oolitic limestone (Colburn and Goldweber, 1961), is classified in the Krome series as loamy-skeletal, carbonatic, hyperthermic, Lithic Udorthents (Noble et al., 1996). Vegetable fields are repeatedly rock-plowed and disked, whereas orchard soils are generally trenched in perpendicular directions, trenches are then backfilled, and trees are planted in augured holes at trench intersections (Colburn and Goldweber, 1961).

Several methods and devices have been tested for monitoring soil-water content in Krome calcareous very gravelly loam soil, including tensiometers, neutron thermalization probes, and capacitance probes (Muñoz-Carpena et al., 2002b). However, monitoring soil-water content in this soil is especially challenging because the very coarse nature can pose soil contact problems for some of the available soil-moisture monitoring devices. Monitoring soil-water content with neutron or capacitance probes may be a viable option in Krome soil (Al-Yahyai et al., 2003). Due to the variability in soil properties, calibration equations of multi-sensor capacitance probes for each soil type are essential to accurately assess soil-water content

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(Baumhardt et al., 2000; Hanson and Peters, 2000; Morgan et al., 1999; Paltineanu and Starr, 1997). Depending on the nature of the soil, calibration of multi-sensor capacitance probes can be carried out in the field (Morgan et al., 1999) or in containers (Paltineanu and Starr, 1997). The slope of the neutron probe calibration curve is greater in gravelly soils than in finer-textured soils. Therefore, in gravelly soils it is essential to develop site-specific calibration of the neutron probe for accurate assessment of soil-water content (Lal and Shukla, 2004).

A large change in suction that corresponds to a small change in soil-water content is a characteristic soil-water retention pattern of South Florida's rock-plowed calcareous soils that makes water management difficult (Muñoz-Carpena et al., 2002b). As agricultural managers try to counteract the low water-holding capacity and excessive permeability of these soils, over-irrigation and potential agrichemical leaching into the shallow aquifer has become an environmental concern in the area.

The objectives of this study were to: (1) determine the soil-water characteristics of Krome soil from vegetable fields and an orchard; (2) develop customized calibration curves for multi-sensor capacitance and neutron probes; and (3) test and compare these calibrated instruments for measuring volumetric soil-water content (θ) in an orchard.

MATERIALS AND METHODS

Capacitance Probe Calibration

EnviroScan™ multi-sensor capacitance probes (Sentek Sensor Technologies, Stepney, Australia) were calibrated in 15-L containers of Krome calcareous very gravelly loam soil placed above ground on perforated plastic pads in Homestead, Florida. The soil was obtained from an orchard at the University of Florida, Tropical Research and Education Center (UF-TREC) in South Florida (80.50°W, 25.51°N), oven dried at 105 °C for 5 days, and placed in the containers. Soil was packed every 5 cm as it was added to the container to maintain a bulk density of approximately 1.4 g cm^{-3} throughout the soil profile to a total volume of 11.4 L. One probe was installed in a polyvinyl chloride (PVC) access tube (with 54-mm outer diameter and 50-mm inner diameter). The capacitance sensor was centered 5 cm below the soil surface. Based on the manufacturer's specifications of the soil-water detection sphere, the radius of the soil in the containers was larger than radius of the soil-water detection sphere of the capacitance sensor (10 cm). At the beginning of the experiment, the containers were placed inside larger containers and gradually flooded from the bottom to displace air from the soil. The soil was saturated for 3 h (until 1130 h) and then the containers were weighed at 1130, 1230, 1430, and 1630 h on the first day of drainage and at 1000 and 1600 h each day thereafter for 13 days. The EnviroScan multi-sensor capacitance probe system was described in detail by Paltineanu and Starr (1997). The capacitance probe system was set to record data every 10 min for the duration of the experiment.

Gravimetric soil-water content was determined by weighing the containers. Volumetric water content was calculated as the percentage of nondepleted soil-water per time interval divided by the soil volume of the container. The calibration equation for the multi-sensor capacitance probe was obtained from the relationship between volumetric soil-water content and capacitance probe scaled frequency to obtain the coefficients for the system to correctly calculate the volumetric soil-water content. The scaled frequency was calculated as follows:

$$SF = (F_a - F_s)/(F_a - F_w) \tag{1}$$

where SF is the scaled frequency of oscillation of the capacitance sensor, F_s is the sensor frequency reading in the soil, F_a is the sensor frequency reading in the air, and F_w is the sensor frequency reading in the water (Paltineanu and Starr, 1997). Volumetric soil-water content (θ) can be calculated from SF based on the following equation (Paltineanu and Starr, 1997):

$$\theta = \left(\frac{SF - C}{A}\right)^{1/B} \tag{2}$$

where θ is volumetric water content and A, B, and C are coefficients. The values of the coefficients A, B, and C were determined by nonlinear regression of SF versus θ.

Neutron Probe Calibration

A neutron probe (Model 503DR, Campbell Pacific Nuclear, Inc., Martinez, California) was calibrated in 95-L containers containing Krome soil. The soil volume in the container was within the soil-water detection sphere of the neutron probe. The radius (cm) of the detection sphere was 21.4 cm as calculated by the following equation (Kristensen, 1973):

$$R = 100/(1.4 + 0.1W) \tag{3}$$

where the volumetric water content (W) was 32.7%. One PVC access tube (with 54-mm outer diameter and 50-mm inner diameter) was placed in the center of each of the three containers for neutron probe measurements. The containers were filled with Krome soil that was collected from the same site as that used for the capacitance probe calibration. Before filling the containers, the soil was oven dried at 105 °C for 5 days. The soil was packed as described for the capacitance probe calibration. The total soil volume was 88.4 L per container. The containers were placed above ground on a perforated plastic pad. The bottoms of the containers were flat with multiple holes to allow free water drainage. The containers were saturated with water as described for the capacitance probe calibration. Before installing the probe into the soil, 10 standard counts were recorded while the probe was in its shield 1 m above the soil surface. Raw counts were recorded during 32-s intervals at a depth of 20 cm once a day (at 1600 h) and the containers were weighed simultaneously with a heavy-duty scale (Model CD-11, OHAUS Corp., Florham Park, New Jersey). The depth of the neutron probe was controlled by presetting cable-stop clamps on the cable between the probe and the counter. The calibration equation for the neutron probe was obtained from the relationship between the volumetric soil-water content and the neutron probe count ratio. Count ratios were calculated by dividing the raw counts taken at a 20-cm depth by the average standard count taken at 1 m above ground level (Hanson and Dickey, 1993). Calibration relationships of neutron probes are generally linear through the common range of soil moisture (Merriam and Knoerr, 1961).

Soil-Water Characteristics—Laboratory Measurements

Soil-water characteristic curves were determined on 12 undisturbed soil cores of Krome soil collected from fallow vegetable fields at UF-TREC at a 10–20 cm depth using a centered hammer core sampler containing 10-cm-diameter × 10-cm-length PVC sleeves. Two types of apparatus were used to determine the water release curves: pressure Tempe cells with 10 steps of pressure up to 0.09 MPa and Richard's pressure plates (Klute, 1986) for the additional pressure steps of 0.1, 0.3, and 1.5 MPa.

The van Genuchten (1980) equation,

$$S_e = \frac{\theta(\psi) - \theta_r}{\theta_s - \theta_r} = (1 + (\alpha\psi)^n)^{-m} \tag{4}$$

was used to describe the moisture retention curve for 100 data points of suction versus volumetric soil-water content, where ψ is the matric potential; S_e is the effective saturation; θ is the volumetric water content; θ_r and θ_s are the residual and saturated water content, respectively; α, n, and m are fitting parameters that describe the shape and slope of the curve. The fitting parameters were estimated with the RETC fitting program (van Genuchten et al., 1991).

Measurement of Soil-Water Characteristics in an Orchard

Soil-water characteristic curves were determined for Krome soil in a carambola orchard at the UF-TREC. The orchard had been trenched before planting (8 years before the start of this study) to a depth of about 45 cm. Paired measurements were made of soil suction, determined with low-tension tensiometers (0–40 kPa) (Model LT, Irrometer Co., Inc., Riverside, California), and soil volumetric water content, determined with multi-sensor capacitance probes (EnviroScan, Sentek Sensor Technologies, Stepney, Australia) or a neutron probe (Model 503DR, Campbell Pacific Nuclear, Inc., Martinez, California). Tensiometers were installed between trees within tree rows at 10-cm, 20-cm, and 30-cm depths from the soil surface. Each tensiometer and neutron or capacitance probe pair was replicated at four different locations in the field. Before tensiometer installation, a borehole was made in the soil, slightly larger than the diameter of the tensiometer. A slurry, prepared with sieved Krome soil mixed with water, was poured into the tensiometer hole to ensure solid contact between the ceramic cup and the soil (Núñez-Elisea et al., 2001). Tensiometers were regularly maintained in the field using a hand pump and water was refilled whenever it drained from the tensiometer tube before it reached the vacuum gauge.

One 74-cm-long PVC access tube (with 54-mm outer diameter and 50-mm inner diameter) was installed within tree rows, 23 cm from the tensiometers. The PVC tubes were installed with a motorized drill and slurry was then added to the hole. The slurry (approximately 2 mm thick after it solidified) consisted of 2:1:1 by volume of crushed limestone, cement, and water to prevent large air gaps from forming between the tubes and the surrounding soil, which is typical in Krome soils (Núñez-Elisea et al., 2001). The neutron probe was placed in the access tubes and lowered to 10-cm, 20-cm, and 30-cm depths. The depth of the neutron probe was controlled by clamps on the cable between the probe and the counter. These clamps were preset to achieve the desired depth placement of the probe. Neutron probe readings were recorded for 32 s at each depth.

The same access tubes used for neutron probe determinations were used for multi-sensor capacitance probes. The capacitance probes were placed in the access tubes following the procedure described by Paltineanu and Starr (1997). Sensors were placed in each probe at 10-cm, 20-cm, and 30-cm depths. The sensors in each probe were connected to a data logger powered by a 12-V battery charged by a solar panel. Data were recorded every 30 min and downloaded from the data logger to a portable laptop computer where graphs of soil-water depletion rates at each soil depth and location were created with EnviroSCAN software.

Each tensiometer and neutron or capacitance probe pair was replicated at four different locations in the field. The soil was irrigated once (on July 21) to above field capacity and not irrigated again for 3 months (until October 28). There was a significant amount of total rainfall (61.4 cm) during the 3-month period, but there were extended periods of no rainfall between irrigations that allowed for a range of soil-water depletion levels. Thus, paired tensiometer and neutron probe or capacitance probe measurements made periodically during that time provided a range of soil-moisture contents. Soil-water characteristic curves were calculated with van Genuchten's model (1980) and fitted parameters estimated with the RETC program (van Genuchten et al., 1991) as described for the laboratory curves.

Soil Particle Size Distribution

Twelve soil samples collected from fallow vegetable fields at UF-TREC were sieved (<2 mm), air-dried, and dispersed with sodium hexametaphosphate (HMP) (Gee and Bauder, 1986). Particle size distribution was determined by the Bouyoucos densimeter method (Gee and Bauder, 1986). The particle size distribution was determined on the fine fraction (<2 mm) and the coarse fraction and particles were weighed to determine the percentage of each fraction.

RESULTS AND DISCUSSION

Neutron and Capacitance Probe Calibration

The relationship between capacitance probe scaled frequency (SF) and volumetric soil-water content (θ) was linear [SF = 0.011 (θ) + 0.5206;

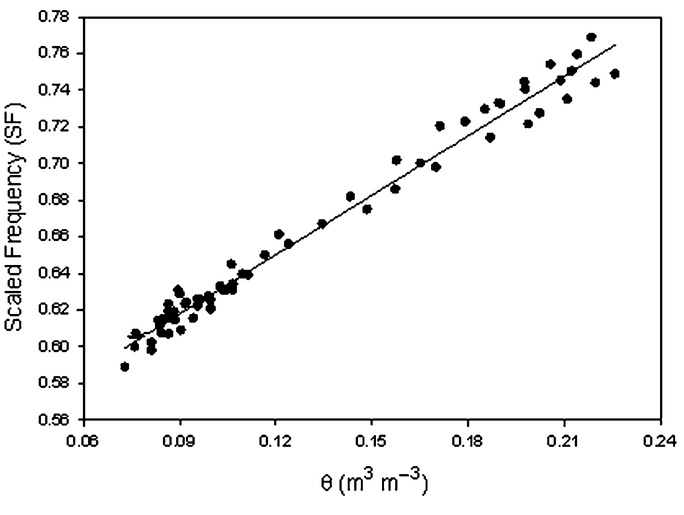

Fig. 1. Relationship between scaled frequency (SF) from a multi-sensor capacitance probe (EnviroSCAN) and volumetric water content (θ) fitted to obtain calibration coefficients for Krome calcareous very gravelly loam soil in containers, y = 0.011x + 0.5206; r^2 = 0.98.

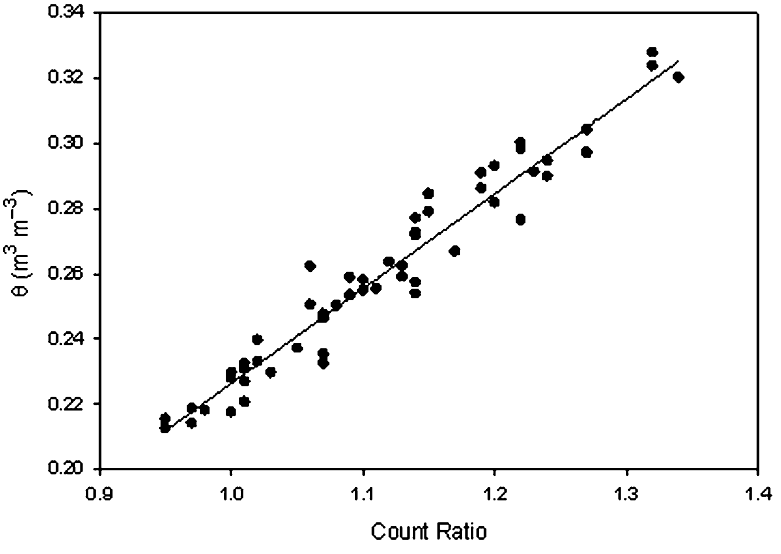

Fig. 2. Relationship between count ratio from the neutron probe and volumetric water content (θ) fitted to obtain a calibration equation for Krome calcareous very gravelly loam soil in containers, y = 29.05x − 6.4; r^2 = 0.95.

r^2 = 0.98, root mean square error (RMSE) = 0.007] (Fig. 1). The coefficients from this equation were A = 0.011, B = 1, C = 0.5206. These coefficients should provide a more accurate determination of volumetric soil-water content in Krome soil than the default equation provided by the manufacturer. There was also a linear relationship between volumetric soil-water content and neutron probe count ratio (x) ($\theta = 29.05x - 6.4$; r^2 = 0.95) (Fig. 2). Although the coefficient of determination was high for the neutron probe calibration, a high RMSE of 0.707 indicated considerable variability in the accuracy of the calibration. This may have been due to escape of fast neutrons to the atmosphere from the 10–cm 20-cm depths. At depths of less than 30 cm, considerable variability can occur in neutron probe readings

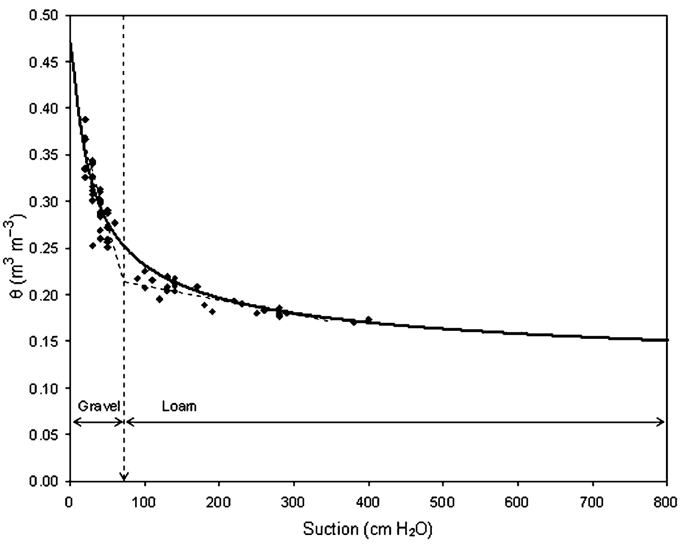

Fig. 3. Soil-water characteristic curve for Krome calcareous very gravelly loam soil collected from fallow vegetable fields. Suction and volumetric soil-water content (θ) were determined with pressure cells and a pressure plate in the laboratory and the curve was fit with van Genuchten's (1980) model.

due to loss of fast neutrons to the atmosphere (Evett et al., 2003; van Bavel et al., 1961). Very carefully controlling the probe depth with the use of a specially designed depth control stand can result in an accurate calibration at depths of less than 30 cm (Evett et al., 2003). However, the cable stop clamps that we used for controlling the probe depth presumably did not provide the repeated accuracy in depth needed to achieve a very accurate calibration. Also, the radius of 95-L container used for calibration was only slightly larger in diameter than the measurement sphere of the neutron probe. Therefore, some fast neutrons may have escaped from the sides of the container.

Soil Particle Size and Water Release Characteristics

The Krome soil that we sampled had two distinct solid fractions with 51% coarse particles (>2 mm) and 49% loam particles [distribution of the median particle size (d50) = 0.035 mm, coefficient of variation (CV) = 16]. This fractionation resulted in an unusual soil-moisture retention pattern where two soil-moisture regions

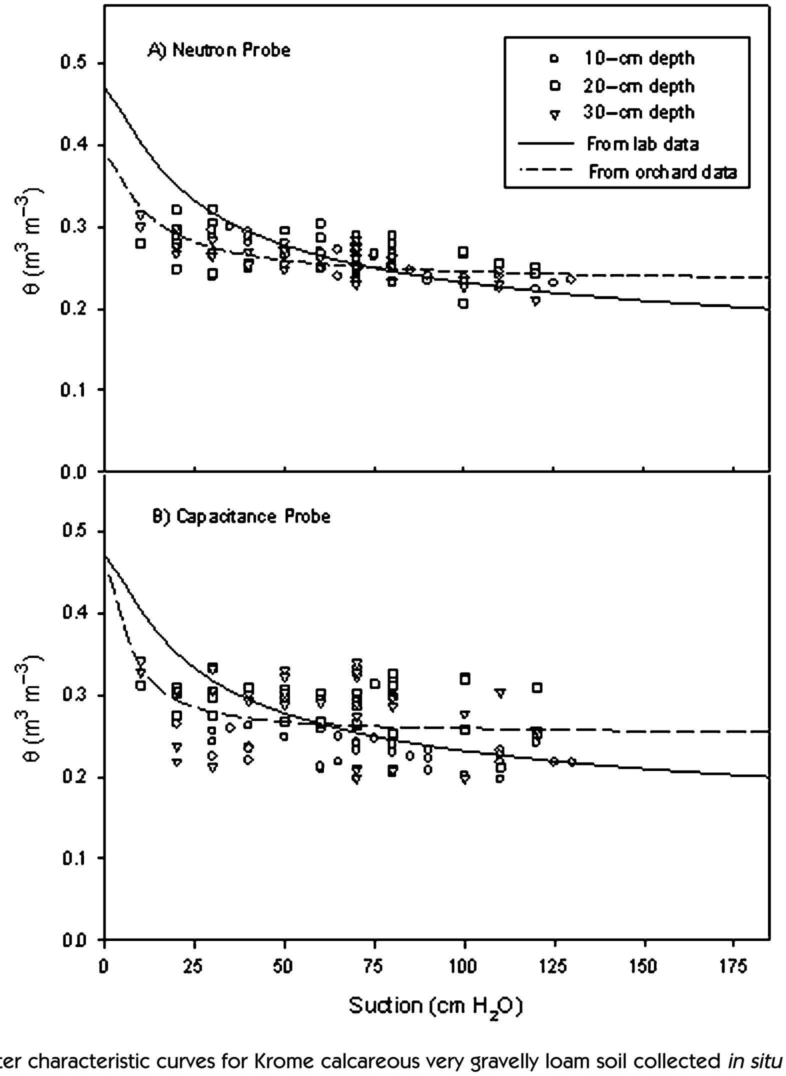

Fig. 4. Soil-water characteristic curves for Krome calcareous very gravelly loam soil collected *in situ* in an orchard. Volumetric soil-water content (θ) was determined with (A) a neutron probe and (B) multi-sensor capacitance probes. Soil-water suction was measured with tensiometers. Van Genutchen's (1980) model was used to fit the curves. The solid line in each graph was fitted to the laboratory data (see Figure 3; r^2 = 0.93) and the dotted lines were fitted to the (A) neutron probe (r^2 = 0.52) and (B) capacitance sensor (r^2 = 0.24) data in the orchard from the 10-cm, 20-cm, and 30-cm soil depths combined.

TABLE 1

Fitted parameters of van Genuchten's (1980) model used to describe soil-water characteristics of Krome calcareous very gravelly loam soil where soil-water content was measured in the laboratory and in the field using capacitance sensors or a neutron probe at soil depths of 10, 20, and 30 cm

Parameters[a]	Laboratory	Capacitance sensors			Neutron probe		
		10 cm	20 cm	30 cm	10 cm	20 cm	30 cm
θ_s	0.47	0.47	0.47	0.47	0.47	0.47	0.47
θ_r	0.10	<0.01	<0.01	0.14	0.05	<0.01	<0.01
α	0.09	10.66	22,518.84	23.18	1.78	21.48	17.48
n	1.46	1.09	1.03	1.12	1.15	1.08	1.09
m	0.32	0.08	0.03	0.11	0.13	0.07	0.08
r^2 [b]	0.93	0.35	0.62	0.36	0.91	0.70	0.86

[a] θ_s is saturated water content; θ_r is residual water content; and α, n, and m are model fitting parameters.

[b] r^2 values for observed versus fitted values, n = 12 for laboratory determinations, n = 4 for field determinations.

were identified, each corresponding to one of the soil solid fractions (Fig. 3). Very rapid soil-water depletion occurs in the gravel fraction.

Soil suction values in the orchard were generally below 125 cm (Fig. 4), even when there was a 3-week period with no rainfall (and no irrigation) during the measurement period. Thus, there was a much narrower range in suction values in the orchard compared to the laboratory where soil water could be largely depleted. In orchards in Krome soil, it is often very difficult to obtain suction values greater than

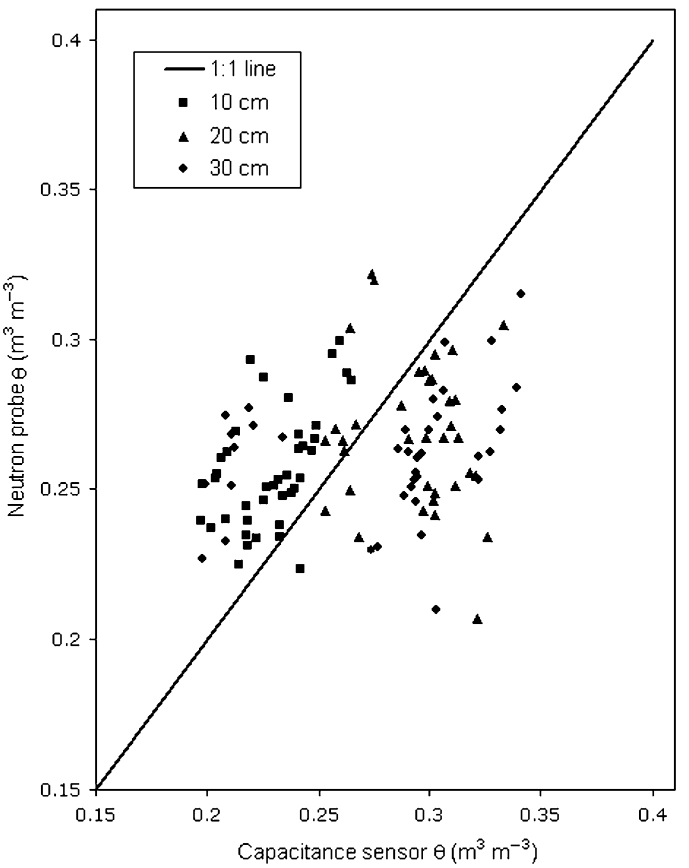

Fig. 5. Comparison of volumetric soil-water content (θ) of Krome calcareous very gravelly loam soil in an orchard determined with a neutron probe and capacitance sensors showing the deviation for a 1:1 correlation line for data collected at 10, 20, and 30 cm below the soil surface.

125 cm even if the orchard is not irrigated for several weeks due to rainfall during the rainy season or capillary rise from the relatively shallow water table (1–2 m below the soil surface) during the dry season (Al-Yahyai et al., 2005). The differences in fitted lines between the orchard and laboratory data were presumably due to the very narrow range of soil moisture observed in the orchard compared to the laboratory. Despite these differences, the fitted lines for the laboratory and orchard data were similar (Fig. 4).

In the orchard, the variability in the relationship between suction and θ was probably due to the heterogeneity of the soil. In gravelly soils, water is stored between contact points of rocks up to 3 cm and skeletal fractions (portions of the parent material not ground by rock plowing) can hold large quantities of water available for plant uptake. If these gravels are porous, they can further increase water retention depending upon their water-holding capacity. Also, weathering of some skeletal soil particles (in the range 0.2–7.5 cm) increases porosity and water holding per unit mass of soil (Lal and Shukla, 2004). Thus, variability of θ at similar suctions in the orchard may have been a result of different particle sizes and/or weathering of soil particles.

In the orchard, the relationship between soil suction (in the loam fraction) and θ varied by depth in the soil profile more for the capacitance probe than the neutron probe measurements as indicated by different coefficients of determinations at the different depths for the capacitance probe than for the neutron probe measurements (Table 1). Núñez-Elisea et al. (2001) found that in a trenched orchard the volumetric soil-water content determined with multi-sensor capacitance probes was more highly correlated with soil-water suction at the 30-cm than at the 10-cm depth. They attributed the better correlation to a larger percentage of large soil particles (>2 mm) at the 30-cm depth. However, this does not explain the poor correlation between soil suction and capacitance sensor measurements at the 10-cm and 30-cm depths in the present study. We can only assume that different degrees of variability at different depths in the soil profile were due to the large heterogeneity of pore spaces within this soil.

In the orchard, the coefficients of determination between observed and fitted data of the soil-water characteristic curves were considerably larger for the neutron probe than for the capacitance probes at different depths in the soil profile (Fig. 4, Table 1). There was also more variability in the capacitance probe data (CV for all soil depths combined = 15.5) than for neutron probe data (CV = 8.6). Paired t test comparisons between instruments at 10-cm, 20-cm, and 30-cm depths combined indicated a significant difference ($P \leq 0.05$) between the instruments. Figure 5 shows the relationship between instruments for the measured θ values at each depth and the deviation of these relationships from the 1:1 correlation line. Also, the better correlation between soil suction and θ determined with the neutron probe than with the capacitance sensors (Fig. 3, Table 1) indicates that the lack of agreement between instruments was mostly due to the variability of the capacitance probe measurements in this soil. Differences in precision of the neutron probe and capacitance probes can be caused by differences in principles of operation of the devices and volume of the soil-water detection zone. Several studies suggested that the neutron probe is more consistent than capacitance probes under field conditions (Evett, 2000; Evett and Steiner, 1995; Evett et al., 2002; Heng et al., 2002). This premise is especially true in coarse-textured soil such as Krome where the potential for air gaps is high (Al-Yahyai et al., 2003; Tomer and Anderson, 1995), possibly resulting in large errors for capacitance probe readings that are based on the combined dielectric constants of air, soil, and water. However, at depths less than 30 cm, great care must be made in precisely placing the neutron probe at the desired depths during calibration and field measurements to avoid inaccuracy of measurements due to fast neutrons escaping into the atmosphere (Evett et al., 2003; van Bavel et al., 1961).

Another important consideration is the difference in volume of soil measured by each instrument. The volume of soil necessary to accurately assess soil-water characteristics, often referred to as the representative elementary volume (REV), is 1–2 orders of magnitude larger in structureless soils such as gravelly loams compared with highly structured soils (Kutilek and Nielsen, 1994; Muñoz-Carpena et al., 2002a). In Krome calcareous gravelly loam soil, the neutron probe measurements may encompass the REV, whereas the smaller volume of soil measured by capacitance sensors does not. Thus, in Krome soil θ measurements with capacitance sensors may be too variable and inconsistent for reliable soil-water monitoring in an orchard.

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