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Soil Profile Water Content Determination: Spatiotemporal Variability of Electromagnetic and Neutron Probe Sensors in Access Tubes

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Since the late 1980s, electromagnetic (EM) sensors for determination of soil water content from within nonmetallic access tubes have been marketed as replacements for the neutron moisture meter (NMM); however, the accuracy, variability and physical significance of EM sensor field measurements have been questioned. We studied the accuracy and variability of four EM sensors and the NMM, compared with gravimetric measurements, in transects of 10 to 20 access tubes during three field seasons, using soil-specific calibrations. The three capacitance EM sensors produced water content readings for which SD values were up to an order of magnitude larger than those from the NMM. The EM sensor based on travel time (waveguide) principles produced SD values up to six times larger than those of the NMM or gravimetric sampling. The EM sensors would require from two to 72 times as many access tubes to obtain a mean profile water content to a given precision than would the NMM or gravimetric sampling, with more tubes required for drier conditions. The NMM exhibited spatial variation of similar magnitude and pattern as that of gravimetrically sampled profile water contents. The EM methods poorly reproduced the spatial and temporal behavior of NMM and gravimetric sampling and implied spatial variability of profile water content that was not evident in either the NMM or gravimetric data, even though EM sensing volumes were larger than the ~75-cm^3 volume of the gravimetric samples. We infer that EM sensors were influenced not only by the mean water content in the sampling volume but by the smaller scale structure of soil electrical properties.

Abbreviations: EM, electromagnetic; ET, evapotranspiration; NMM, neutron moisture meter.

Studies of root water uptake, crop water use and water use efficiency, irrigation methods and efficiency, and soil hydrology all require accurate determination of the volumetric soil water content (θ_v, m^3 m^{-3}) and of the water content considered as a depth, S (m), stored in a soil profile. Most of these studies require knowledge of the change in water, ΔS, stored in a soil prism of given x, y, and z dimensions, known as the control volume, to which the soil water balance equation is applied, e.g.:

$$\mathrm{ET} + \Delta S + R - P - I - F = 0 \qquad [1]$$

where ET is crop water use, P is precipitation, I is irrigation, R is the sum of runoff and run-on, F is the flux across the lower boundary of the soil profile (control volume), all as depths of water, and the sign conventions are as given in Evett et al. (2009).

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For Eq. [1], it is assumed that the z dimension begins at the soil surface, and it is typically assumed that it extends to well below the root zone and the depth of wetting. The divergence of horizontal soil water fluxes and nonuniform root water uptake are considered negligible in the formulation of Eq. [1], but in the case of row crops or tree crops, the dimensions of the control volume are often adjusted to include a symmetry of horizontal water movement, and a sampling strategy is devised to accurately determine ΔS. Typically, Eq. [1] is applied to an ensemble of plants, or at minimum a single plant. Studies at smaller scales, e.g., studies of root water uptake at explicit depths and locations in the root zone of a single plant, will use a more detailed water balance formulation.

Irrigators recognize the spatial variability and temporal stability of water distribution when they observe the crop in a field for signs of water stress or when they probe the soil for water content. For example, an irrigator may ignore drier crops at the edge of a field, or a low, wet corner of the field when assessing the need to irrigate. The tendency is to make observations in places that show the perceived mean behavior of the field. In addition, other than mean locations often might be chosen due to an operator's unintended bias toward areas in the field with better crop establishment and growth. This is not an adequate way of choosing observation locations for a scientific experiment for which blocking, randomization, replication, and other considerations are required for statistical validity. For irrigation management in production agriculture, however, the choosing of measurement locations on the basis of observed soil and plant properties that are representative of the field may be the most cost-effective and

time-efficient method. That said, the scheduling of irrigations on the basis of a single profile water content measurement in a field is prone to error, particularly considering the spatial distributions associated with *P*, *I*, *R*, and *F* in Eq. [1]. Also, there is strong evidence that actively growing vegetation can reduce or eliminate the temporal stability of spatial patterns of water content, particularly in the root zone (Hupet and Vanclooster, 2002) and in fields with little topographic relief. Elimination of temporal stability implies establishment of a new structure of spatial variability.

The aforementioned spatial scales relevant to scientific studies and irrigation management needs range from crop rows to fields and watersheds, i.e., from ~1 m to several hundreds or thousands of meters or greater. It is expected that water content will vary in space, yet for field plot research it is common to use blocking to control for spatial variations and plot replication and randomization to provide the basis for statistical analysis. In this context, a persistent question is the number, *n*, of soil water content profiles needed to determine the mean *S* in a plot or field to a given precision, *d*, so that differences between plots and treatments, including differences with time, may be tested with sufficient statistical power. A statistical calculation of *n* depends on knowledge of the standard deviation of *S*. As will be seen, the same question has relevance to the study of temporal-spatial variation in water content.

Several researchers have studied the spatial variability of soil water content and surface temperature (e.g., Vauclin et al., 1982; Vieira et al., 1983; Yates and Warrick, 1987; Mulla, 1988; Yates et al., 1988). Among the tools used by these and other researchers to describe spatial variability are the covariance, the autocorrelation function, the semivariogram, and the covariogram. The use of these tools involves the hypothesis that sample values are not randomly distributed in space but are to some degree autocorrelated in space, with samples taken closer together more likely to have similar values than those taken farther apart. Vieira et al. (1983) and Warrick et al. (1986) reviewed spatial variability analysis with an emphasis on soil and water science. The most useful tool for studying spatial variability may be the semivariogram, since it can be used in the kriging process to estimate values and variances of the variable at unsampled locations in the field.

The theory of spatial variability analysis assumes that values of the studied property are representative of a volume, known as the *support volume*, which raises questions about the volume of sensitivity, accuracy, and variability of readings from different soil water sensing systems. Appropriate support volumes depend on the scale of the processes and properties under study. For example, an appropriate support volume for studies of the spatial variability of ET under irrigation would be the control volume defined by *z* greater than the depth of rooting and soil wetting from irrigation, and by *x* and *y* dimensions on the order of plant row widths and the spatial pattern of irrigation applications as determined by sprinkler head spacing or drip line and emitter spacing. It is inevitable that spatial variation in the soil water content will exist at scales smaller than that of the support volume. Given this fact, the number of samples, *n*, must be chosen to support sufficient precision in the determination of the water content in the support volume such that larger scale spatial variation can be studied (Vauclin et al., 1984).

There is considerable experimental evidence that soil water content becomes more variable as sample size decreases (Hawley et al., 1982; Allen et al., 1993; Dickey et al., 1993). Sample sizes considered by these researchers were 7, 15, 60, and 825 cm^3. Also, water content variability increases as fields dry (Hawley et al., 1982), and for a particular location, variability increases with time after wetting (Schmitz and Sourell, 2000) and decreases as water content increases (Famiglietti et al., 1999; Hawley et al., 1982; Hupet and Vanclooster, 2002; Schmitz and Sourell, 2000). These facts mean that the number of samples required to determine a mean value of *S* to a given precision may change with time and with sampling volume depending on the complex interaction between the sensing volume of the method used to determine *S* and the small-scale spatiotemporal variability of soil water content.

For many years, the NMM has been used successfully for studies of spatial variability of soil water content (e.g., Haverkamp et al., 1984; Vauclin et al., 1984), root water uptake, crop water use, and water use efficiency. For water contents in the range of 0.05 to 0.50 $m^3\ m^{-3}$, the NMM sensing volume may lie somewhere in the range of ~4.2 m^3 in a dry soil to as small as ~900 cm^3 in a saturated soil of low bulk density (International Atomic Energy Agency, 1970; Evett et al., 2008). The NMM sensing volume is large enough that a single access tube often meets the requirements for precision and statistical power.

If no other information were available about soil water variability, sampling a field for profile water content would typically require many profiles to be sampled, either directly or using water content sensors. the spatial distribution of the profile water content, however, tends to be temporally stable in some fields (Vachaud et al., 1985; Villagra et al., 1995). The relative difference, δ_{ij}, for location *i* and time *j* was defined by Vachaud et al. (1985):

$$\delta_{ij} = \frac{S_{ij} - \mathrm{E}\left[S_{ij}\right]}{\mathrm{E}\left[S_{ij}\right]} \qquad [2]$$

where E[ ] is the expected value operator and S_{ij} is the profile water content at location *i* and time *j*. They calculated δ_{ij} for all times and locations and found the mean relative difference with time, $\overline{\delta_i}$, for each location. Plotting of $\overline{\delta_i}$ vs. rank, with limit bars for the maximum and minimum relative difference at each location, allowed easy identification of locations that represented the mean, of locations with extreme values, and of locations that maintained their relative rank with the least variation with time, including locations in a field where the profile water content was usually very representative of the mean for the field. Ranked $\overline{\delta_i}$ plots also indicate the overall spatial variability of the data in the area under study.

Since the late 1980s, electromagnetic (EM) methods of sensing soil water content have become commercially available, and these are increasingly popular because regulation and training requirements are much less than for the NMM and because many of these systems may be left unattended for data acquisition at small time intervals. All EM systems measure an electronic signal response that is related to soil water content through the large effect that water content has on the apparent electrical permittivity, ε_a, of the soil. Systems suitable for assessing profile water content are typically used within nonconductive access tubes made of plastic or plastic composites, which are installed vertically in the soil. Most of the available systems are based on the

fringing EM field of a capacitor having two cylindrical electrodes that share the same axis but are separated by a short axial distance. As described by Dean et al. (1987), the two electrodes, and associated electronic oscillator and support structure, form a sensor that may be moved up and down within an access tube placed in the soil to sense water content at the depths desired. Sensors of this type are called capacitance sensors, and the signal measured is the frequency of oscillation, which decreases as the dielectric permittivity increases (largely due to increased soil water content). Another approach used from within an access tube consists of a waveguide composed of two electrodes, positioned on opposite sides of a plastic cylinder and pressed against the inside wall on opposite sides of the access tube. A fast rise time electronic pulse is injected into this waveguide and a pseudo travel time of the pulse is recorded (Stacheder et al., 1994). The travel time is termed *pseudo* because it includes the travel time in the cable linking the pulse generator and the probe and because the waveform of the reflected pulse is not fully recorded, as discussed in Evett et al. (2006).

For the EM sensors studied here, Evett et al. (2006) determined that sensor readings were affected by soil temperature and bulk electrical conductivity, and that factory calibrations were not accurate in the three soils that they studied. They also found that measurement volumes were small and that the axial distance sensed decreased as water content increased. The small measurement volumes raise a question of the suitability of these sensors for field investigations of profile water content and crop water use. Indeed, in a preliminary study, we found that many more access tubes would be needed to determine the mean profile water content in a uniform field to a given precision using the EM sensors studied here than were required using the NMM or gravimetric samples (Evett, 2005).

Here we use the definitions of accuracy and precision given by Hignett and Evett (2008). Precision is how well a value is known, often assessed by studying the variability of repeated measures in place and time. For example, as the sample SD associated with the mean of a number of replicate values becomes smaller, we say that the precision with which we know the mean value becomes greater. This does not mean that the precisely known mean value is accurate. Although related, precision is not equivalent to SD or variance. Statistically speaking, precision may be defined for a given probability level, SD value, and number of samples taken. By *in place* we mean in a field area considered to be uniform. Accuracy refers to how close the value of water content, indicated by the measurement process, is to the actual value of water content measured directly in the field. In the context of a uniform field area or support volume, we may compare the mean water content from the several sensor readings to the mean water content of several direct measurements to assess accuracy. These definitions may be applied to determinations of θ_v, S, and ΔS.

It is important to recognize the sources of variability in soil water determinations using sensors. There are at least four sources of variation not controlled by the user. One is the instrument's internal variability evidenced by electronic noise, circuit temperature dependencies, and the like. A second source is the inherent spatial variation in soil water content within the domain at the scale of interest (for us that is crop water uptake at the scale of whole-plant root systems and the size of the domain might be a field plot). A third source is interference from soil properties such as temperature, bulk electrical conductivity, bulk density, etc., that are variable on the scale of the whole sensing volume of the sensor. Such interferences vary in time and space and so introduce variability in the water content values recorded. A fourth source, not widely accepted as important yet, is the variation due to the interaction between the sensing system and the variability of soil properties at scales smaller than the whole sensing volume of the sensor (and much smaller than the scale of interest for crop water use or most hydrologic concerns). This was first proposed by Evett and Steiner (1995), who studied a capacitance-type EM soil water sensor. More evidence for the fourth source of variability is beginning to appear in the literature on electromagnetic field interactions with composite materials (e.g., Panteny et al., 2005) and in the literature on soil water sensing with EM sensors (Logsdon, 2009). There may be other sources of variation, such as improper access tube installation, that are within the user's control.

The objectives of this study were to: (i) compare the accuracy and variability (spatial and temporal) of point water contents and profile water storage values determined by five methods (the NMM and four EM sensors) in a uniform field soil using soil-specific calibrations to find which methods correctly assess the true water status (its variability in space and time and its value) as determined by gravimetric sampling; and (ii) determine the relative usefulness of the six methods for spatial and temporal variability studies, including the number of access tubes or gravimetric sampling points needed to determine the profile water content in a uniform field area to within a given precision at a specified probability level. Relative difference plots were used for the spatial analysis, leaving a detailed look at semivariograms to a subsequent study.

Materials and Methods

Three field experiments were conducted at the USDA-ARS, Conservation and Production Research Laboratory (CPRL) at Bushland, TX (35°11′ N, 102°6′ W, 1170 m elevation above mean sea level) in 2003, 2004, and early 2005. Irrigation water treatments were intentionally varied in space and time to discern the capability of each sensor to determine differences in water stored in the profile. The study was designed so that comparisons would be of mean profile water contents in two adjacent but differently irrigated field plot areas, or so that comparisons would be of patterns in space and time in these plots (e.g., relative difference rankings). This design obviates the need for sampling with all the different systems well within the spatial correlation length for water content, which in any case varies between the systems. We did not compare the results from an individual NMM access tube with the results from an individual EM sensor access tube or individual gravimetric sampling location. If we had done so, then we would have sampled as closely together as possible without causing interference of one sampling system with another. The sampling system used here is relevant to many field plot studies in which it is necessary to compare the plot mean water contents or differences in soil water storage between or among plots. The results also should be applicable to a broader range of studies including those of spatial variability of water content and crop water use.

Experiments were conducted on a Pullman soil (a fine, mixed, superactive, thermic Torrertic Paleustoll). In the two adjacent

fields used, the Pullman soil is very uniform, which is characteristic of large expanses of irrigated soils in the southern High Plains (Taylor et al., 1963; Unger and Pringle, 1981). These are the fields that have been used for studies of crop water use for >20 yr at the CPRL (e.g., Howell et al., 2006), and they were chosen for their uniformity. The intent was to have uniform soils on which different irrigation treatments could be imposed to create differences in soil water storage. To maximize uniformity, the areas studied were no greater than 100 m in extent and were chosen based on prior uniform cropping and irrigation history. The intent was to have uniform soils for which the concept of a field mean soil water content or profile water storage value would be appropriate (minimum spatial variability and drift).

In early 2003, parallel linear transects were established in the east–west direction across a winter wheat (*Triticum aestivum* L.) field for the first experiment (Fig. 1). Each transect included 10 access tubes for a particular device spaced at 10-m intervals along that transect. The transects were separated normal to their axes by 2.5 m so that gravimetric sampling could be done using a tractor in the alleys between transects. Gravimetric soil samples were collected using a hydraulic soil coring machine (Model 15-TS GSRT, Giddings Machine Co., Windsor, CO) to 2-m depth in similarly parallel transects of 10 locations spaced at 10-m intervals. Transects for gravimetric sampling were located parallel to those for access tubes (Fig. 1). Each time a transect was gravimetrically sampled, a new transect location was established such that sampling was always separated from the previous sampling or from access tubes by at least 1.0 m. All of the data that we present are representative of several samples over time, so if the gravimetric samples were taken closer to one or two of the sensors at one sampling time, the next time they were closer to another one or two sensors (Fig. 1). This eliminated the bias that might have occurred if data from only one sampling time were compared and the gravimetric samples were taken closer to one sensor than another.

We used the NMM (Model 503DR1.5, Campbell Pacific Nuclear International, Concord, CA), three capacitance-type EM soil water sensing systems (Model PR1/6 Profile Probe, Delta-T Devices Ltd., Cambridge, UK; and models EnviroSCAN and Diviner 2000, Sentek Environmental Technologies, Kent Town, SA, Australia) and a Trime T3 tube probe (IMKO Micromodultechnik GmbH, Ettlingen, Germany), which is a quasi time domain reflectometry (TDR) device. The instrumental variability of these sensors and of the NMM in uniform, repacked soil columns has been studied by others (e.g., Paltineanu and Starr, 1997; Kelleners et al., 2004) and by us (Evett et al., 2006) and is small compared with the variability of field water content. Still, multiple readings in place were taken with the EM and TDR devices to minimize the influence of any instrumental variability, but not with the NMM.

Access tubes for the Diviner 2000 and EnviroSCAN were polyvinyl chloride (PVC) plastic tubes with 5.1-cm i.d. and 5.6-cm o.d., 2 m long, obtained from Sentek. The EnviroSCAN and Diviner sensors were read in the same PVC access tubes. The EnviroSCAN system features a plastic backbone on which sensors may be placed at 10-cm intervals and through which a communications cable runs to the sensor-string head. We placed sensors so as to be centered at depths of 15, 35, 55, 75, 95, 115, 135, 155, 175, and 195 cm. To take field readings, we placed the sensor string in an access tube and took three sets of readings at these depths. We then lifted the string by 10 cm, inserted a plastic device to hold the string at that elevation and repeated the three sets of readings with the sensors centered at depths of 5, 25, 45, 65, 85, 105, 125, 145, 165, and 185 cm. By so doing, we obtained readings at center depths ranging from 5 to 195 cm in 10-cm increments in each access tube. We took three replicate sets of readings with the Diviner 2000 in each access tube in 10-cm increments to its maximum depth of 160 cm.

The PR1/6 probe has sensors permanently fixed in the monolithic plastic probe rod at nominal depths of 10, 20, 30, 40, 60, and 100 cm. Given the access tubes from the manufacturer, we found that measurements were actually centered at 7-, 17-, 27-, 37-, 57-, and 97-cm depths. The access tubes were epoxy-fiberglass with an inside diameter of 26 mm and outside diameter of 28 mm. Because the sensor electrodes were not axially symmetrical, three immediately consecutive sets of readings were taken in place, with 90° rotation of the probe about its long axis between readings.

The NMM was used with a depth control stand (Evett et al., 2003) for measurements centered at the 10-cm depth and in 20-cm increments below, with the deepest measurement

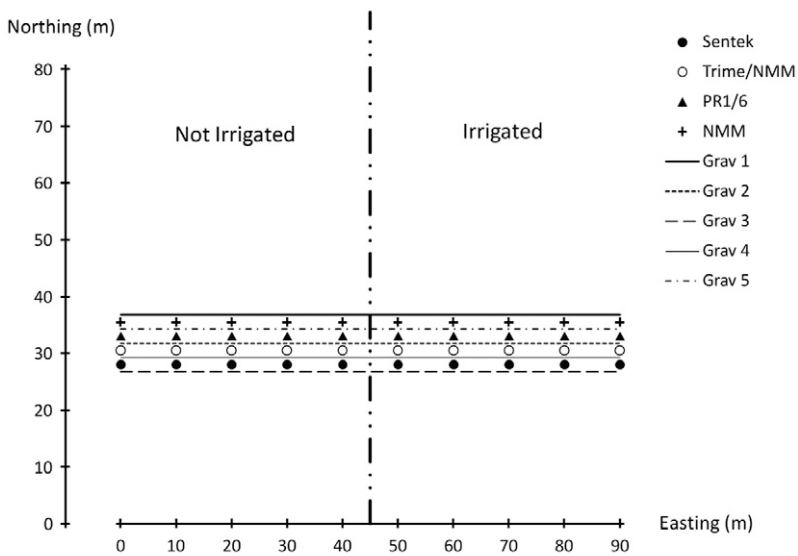

FIG. 1. Diagram of the transects of access tubes in the winter wheat field in 2003 showing relative positions of the tubes for the PR1/6, neutron moisture meter (NMM) and Trime T3 (both used in the same access tubes), and the Sentek devices (EnviroSCAN and Diviner 2000, both used in the same access tubes). The NMM was read in the Trime plastic access tubes and in metal access tubes. North–south spacing between access tube transects was 2.5 m. Also shown are east–west lines illustrating the first five transects of gravimetric sampling (Grav), at 1.25 m from the access tubes. All gravimetric samplings were done at the same eastings as for the access tube positions. Eastings are relative to the westernmost access tube positions. The last four gravimetric samplings were done on east–west transects that were offset 1.0 m from the lines shown. Sampling 6 was offset to the east of Sampling 5. Sampling 7 was offset to the west of Sampling 2. Sampling 8 was offset to the east of Sampling 4. Sampling 6 was offset to the east of Sampling 3. The vertical line separates the unirrigated and irrigated sides of the field, which sloped at 0.5% to the east. Tubes were numbered 1 through 10 from east to west.

centered at a depth of 230 cm. Counts were taken for 60 s to minimize random noise. Other NMM methods used are decribed by Hignett and Evett (2002) and Evett (2008). Readings were taken in both the electroplate-galvanized steel access tubes normally used for the NMM and in the Trime access tubes, which had practically the same inside diameter.

We also used a Trime T3 tube probe, which is a cylindrical probe with two waveguides oriented vertically on opposite sides of a cylindrical plastic body. We measured the length of waveguide that is in contact with the access tube to be 17.5 cm. The probe is suspended from a cable and lowered to the desired depth (the cable is limited to 3-m length) inside a polycarbonate plastic access tube (41-mm i.d., 44-mm o.d.). Using a depth control stand, we made measurements at 17.5-cm depth intervals with the topmost measurement centered at 8.75 cm below the soil surface, resulting in readings centered at depths of 8.75, 26.25, 43.75, 61.25, 78.75, 96.25, 113.75, 131.25, 148.75, 166.25, 183.75, 201.25, and 218.75 cm. The T3 probe was matched with the Trime-FM field measuring device, which sends a fast rise time pulse through a coaxial cable to the probe and outputs a "pseudo" transit time that is related to water content. After the first set of readings, the probe was rotated 90° about its long axis and another set of readings was taken.

The EM sensors were calibrated for volumetric water content in the laboratory for the A, Bt, and Btka horizons of the Pullman soil (soil collected immediately adjacent to the fields used in this study) in repacked soil columns as reported by Evett et al. (2006). Because the soil columns used to calibrate the EM sensors were not large enough in diameter to contain all of the neutron flux when the soil was air dry, the NMM could not be calibrated in the laboratory so it was field calibrated (Evett et al., 2006). Laboratory calibrations have been applied to field soils quite often (e.g., Starr and Paltineanu, 1998), but there is always the question of how applicable such calibrations really are. For example, a field calibration in California of most of the instruments used in the present study showed that calibrations changed markedly with depth (Mazahrih et al., 2008). The California soil was drip irrigated in an arid environment and probably had increasing salinity with depth, causing the calibration changes. Since bulk electrical conductivity (σ_a) varies with depth due to clay and water content (and temperature) changes, not salinity, in the Pullman soil at Bushland (Evett et al., 2005), and since we know that σ_a affects the calibration of EM sensors, we did separate calibrations for the soil layers that differed the most in clay content. Temperature and σ_a effects were not included in the calibrations of Evett et al. (2006) because those data would not normally be available with the EM sensors used.

Access tubes were installed using the installation kits available from the manufacturers and according to manufacturer best practice recommendations. In some cases, the kits were insufficient to complete installation in hard, dry clay soil, so additional equipment was devised and built to complete the installations (Evett and Cepuder, 2008; Laurent and Evett, 2008). Data on the time required to install each kind of access tube were taken, and notes were made of any problems with the installation. Since it is common to blame problems with sensor readings from within access tubes on the tube installation (lack of tight fit, voids or disturbed soil outside the access tube caused by installation practices, etc.), we were careful to follow the manufacturers' recommendations and to use manufacturer tools, which involved installing tubes with cutting edges and augering from within the tubes. In this study we could not destructively remove the tubes to inspect the quality of the installation because this would have entailed destroying the field plots with soil pits, so we assessed the quality of installation using the same installation tools and procedures to install the same access tubes into a clay loam soil (similar to the Pullman) in a field calibration study in California in which we later dug soil pits to directly sample the soil next to the access tubes (Mazahrih et al., 2008). Inspection of the soil surrounding each access tube and of the soil contact with the access tubes revealed tight fits of the access tubes with the soil and no soil disturbance. Thus, we are confident that any variability in EM sensor readings was not due to problems with the access tube installations.

Measurements were first taken on 12 Mar. 2003 and continued at intervals until the final set of measurements in the wheat field on 21 Nov. 2003 (Table 1). After the first three sets of measurements, irrigations were begun on one half of the field to examine the differences among sensors in profile water storage estimates made in the unirrigated and irrigated halves. After irrigation, eight more sets of measurements were made.

Gravimetric samples were taken to 2-m depth using a hydraulic-push machine and two pushes of a 1.5-m-long sampling tube with a 3.1-cm i.d. bit. The inner diameter of the tube above the bit was larger than the bit diameter to reduce friction of the core moving within the tube. Cores were extruded into a plastic tray and sectioned into 10-cm lengths that were put into individual soil cans, weighed, dried for 24 h at 105°C, and reweighed. The water mass lost on drying was converted to volume and divided by the core section volume to calculate volumetric water contents for each 10-cm depth increment.

For the second experiment, 20 access tubes for each device were installed in an irrigated soybean [*Glycine max* (L.) Merr.] field at Bushland, TX, in 2004 (Fig. 2). Ten tubes were in east–west linear transects in an area that was irrigated (weekly or more often) to replenish 100% of the water used by the crop (replenishment to field capacity, 0.33 m^3 m^{-3}) as measured by a weighing lysimeter (Howell et al., 1995). The remaining 10 access tubes

Table 1. Experiment 1 dates (and serial day of the year, DOY) of transect measurements made using electromagnetic and neutron moisture meter (NMM) sensors and gravimetric sampling in a winter wheat field at Bushland, TX, in 2003; X indicates that a measurement was made with the sensor or method listed. A parenthetical number after an X indicates the DOY of the measurement when it varied from that on which most other methods were used. Irrigation of one half of the field began after 30 Apr. 2003.

Date (DOY)	NMM	EnviroSCAN	Diviner	PR1/6	Trime	Gravimetric
12 Mar. (71)	X	X (72)	X (72)	X (72)	X	–†
29 Apr. (119)	X	X	X	X	X	–
30 Apr. (120)	X	X	X	X	X	X (121)
21 May (141)	X	X	X	X	X	X
11 June (162)	X	X	X	X	X	X (161)
15 Aug. (227)	X	X	X	X	X	X
27 Oct. (300)	X	X	X	X	–	X
5 Nov. (309)	X	X	X	X	X	X(311)
10 Nov. (314)	X	X	X	X	X	X
19 Nov. (323)	X	X	X	X	X	X
21 Nov. (325)	X	X	X	X	X	X

† Measurements were not taken for the device or method and day indicated.

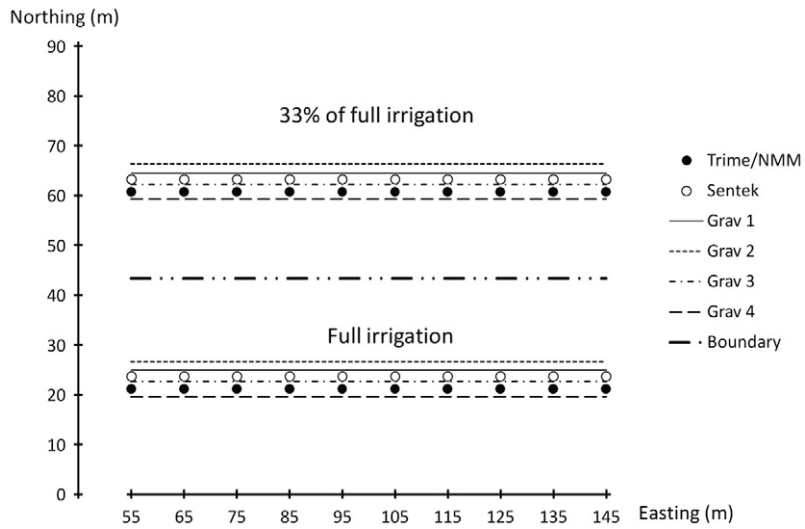

FIG. 2. Diagram of access tube and gravimetric sampling locations in the soybean and soybean fallow field in 2004 and 2005, showing relative positions of the tubes for the neutron moisture meter (NMM) and Trime T3 (both used in the same access tubes), and the Sentek devices (EnviroSCAN and Diviner 2000, both used in the same access tubes). North–south spacing between access tube transects was 2.3 m. Also shown are east–west lines illustrating the four transects of gravimetric sampling done in 2005. All gravimetric samplings were done at the same eastings as the access tube positions. Eastings are relative to the west end of the field. Northings are relative to the southern boundary of the full-irrigation plot. The transects were centered in the field in the east–west direction and in the north–south direction in each irrigation treatment plot (full irrigation and 33% of full irrigation, the boundary between them is shown). Tubes were numbered 1 through 10 from east to west in the 33% treatment and from 11 to 20 from west to east in the 100% treatment.

were installed in separate east–west transects in an adjacent area that received 33% of that amount but at the same irrigation times. Measurements were taken four times before harvest on 18 Oct. 2004 (Table 2). To avoid damage to the soybean crop, gravimetric samples were not taken in 2004. Measurements with the NMM were made in the plastic access tubes of the Trime T3 sensor, and the Trime T3 was read while centered at the same depths as the NMM. The Sentek EnviroSCAN and Diviner 2000 were read in the same access tubes.

The third experiment used the same access tubes as the second, but occurred in the January to April period of 2005 when the field was fallowed and wetted by winter precipitation (Table 2). Gravimetric samples were taken between transects as in 2003. Because of its poor performance in earlier laboratory studies (Evett et al., 2006) and in the 2003 field studies, the Delta-T PR1/6 was not included in the 2004 and 2005 studies.

Profile water contents were calculated as the depth of water in the surface to 100-cm depth range by numerical integration of the depth of water in all depth increments. Although some sensors were used to depths below 100 cm, the profile water contents were calculated to the 100-cm depth so that comparisons could be made of all sensors, one of which was not capable of readings below that depth. The depth of water in each depth increment was calculated from the water content at each depth multiplied by the corresponding depth increment.

Field means and sample SDs of profile water contents were calculated. The number (n) of sensors required to obtain the field plot mean water content to a specified probability (α) and precision (d) levels were calculated using the standard normal distribution ($u_{\alpha/2}$) and

$$n = \left(\frac{u_{\alpha/2}\mathrm{SD}}{d} \right)^2 \qquad [3]$$

Equation [3] is valid for normally distributed values that are independent of one another and for the population SD estimated from a large number of samples. Note that calculating n iteratively with the t distribution would produce more accurate values, which would in any case be larger than those we calculated. The iterative process can fail for small SD compared with d, however, as sometimes occurred in this study. The relative difference in profile water contents was calculated using Eq. [2], and the mean relative differences with error bars for maxima and minima at each location were ranked and plotted.

Results and Discussion

Experiment 1: Winter Wheat Field, 2003

The standard deviations of the profile water content before irrigation began were considerably different among the six methods (Table 3). Considering only the three sampling dates before irrigation began, the SD of profile water content for all 10 access tubes was roughly the same as that for either side of the field for the NMM, EnviroSCAN, Diviner 2000, and gravimetric data. In particular, the small SD values for the NMM and gravimetric methods (0.69 and 0.62 cm, respectively, for all 10 access tubes) quantify the uniformity of the initial profile water content in this field, which is illustrated in Fig. 3. In contrast, before irrigation began, the Trime T3 sensor exhibited an SD value ~50% larger (0.97 cm), and SD values for the profile water content for the capacitance sensors exceeded 2.0 cm, with that for the PR1/6

TABLE 2. Dates (and serial day of the year, DOY) of transect measurements made using electromagnetic and neutron moisture meter (NMM) sensors and gravimetric sampling in an irrigated soybean field at Bushland, TX, in 2004 and during the subsequent fallow period in 2005; X indicates that a measurement was made with the sensor or method listed. A parenthetical number after an X indicates the DOY of the measurement when it varied from that on which most other methods were used.

Date (DOY)	NMM	EnviroSCAN	Diviner	Trime	Gravimetric
Experiment 2					
10 Aug. 2004 (223)	–†	X	X	X	–
18 Aug. 2004 (231)	X	X	X	X	–
2 Sept. 2004 (246)	X	X	X	X	–
10 Sept. 2004 (254)	X	X	X	X	–
Experiment 3					
20 Jan. 2005 (20)	X	X	X	X	X(21)
3 Mar. 2005 (62)	X	X	X	X	X(63)
24 Mar. 2005 (83)	X	X	X	X	X
12 Apr. 2005 (102)	X	X	X	X	X(103

† Measurements were not taken for the device or method and day indicated.

sensor exceeding 5.0 cm. By Day 120, the winter wheat had dried the field to a profile water content only slightly larger than the 18-cm value typically found at 1500 kPa in this soil (Fig. 3). The mean profile water content measured gravimetrically to 100-cm depth on Day 121 was 0.9 cm smaller than that determined by the NMM on Day 120, and neither method showed much variation from a mean value of 19.8 cm across the field.

After irrigation began, the profile water contents reported by the six methods differed considerably, particularly in the degree of water content variability and the shape of the profile, including over- and underestimation of the water content at different depths (e.g., Fig. 4). The SD values of volumetric water content at each depth (Fig. 5) and of the profile water content (Table 3) indicate further differences between the six methods. The smallest variability of water content was reported by the NMM, with the variability of the Trime T3 results somewhat more variable, particularly on the unirrigated side of the field, but still representing the profile water content in much the same way as the NMM (e.g., Fig. 4). In this field, the depth to the $CaCO_3$–enriched (caliche) layer was ~120 cm. As shown by the NMM and gravimetric results, inherent soil water variability was larger in the caliche horizon below 120 cm than in the Bt and A horizons above 120 cm (Fig. 3 and 4). The larger variability below 120 cm is due to the presence of soil-filled prairie dog burrows in the softer caliche soil. These are commonly found in soil pits dug at the Bushland research station. The burrows contain soil that has washed in from the overlying Bt and A horizons, and they typically exhibit smaller bulk density than the overlying and surrounding soil. Depending on the presence or absence of macropore flow, typically occurring in soil cracks in this soil, the soil in burrows may exhibit larger or smaller water content than the surrounding soil. While overall the EM sensors exhibited more variability than the NMM, the three capacitance sensors exhibited the most variability as well as a tendency to severely underestimate water content above the 50-cm depth in the dry side of the field.

For the period after irrigation, the mean SD values for the five tubes in the irrigated side and for the five tubes in the unirrigated side are reflective of the variability associated with each device,

Table 3. Mean SD values before and after irrigation began in 2003 for water content in the soil profile from the surface to 100-cm depth using electromagnetic and neutron moisture meter (NMM) sensors for all 10 access tubes, the five access tubes in the irrigated half of the field, and the five access tubes in the unirrigated (dry) half of the field. Also shown are numbers of access tubes, *N*, required to determine field mean profile water content to a precision of 1 cm at the $\alpha = 0.1$ probability level ($\mu_{\alpha/2} = 1.64$) using the SD values determined after irrigation began as calculated using Eq. [3]. Finally, mean values and mean SD across all measurement locations and dates in 2003 of water content (*S*, cm) in the soil profile from the surface to 100-cm depth are shown. Data are for three capacitance sensors (Delta-T PR1/6, Sentek EnviroSCAN, and Sentek Diviner 2000), for the Trime T3 tube probe quasi time domain reflectometry device, for the NMM (read in steel access tubes), and for gravimetric measurements.

Parameter	PR1/6	EnviroSCAN	NMM	Diviner	Trime	Gravimetric
	cm					
Before irrigation began						
SD all	5.81	2.26	0.69	2.28	0.97	0.62
SD irrigated	3.54	2.06	0.70	1.93	0.53	0.43
SD dry	7.48	2.00	0.68	2.06	1.31	0.68
After irrigation began						
SD irrigated	2.14	1.37	0.60	1.66	0.94	1.42
SD dry	6.93	2.71	0.47	2.81	1.89	0.87
N (irrigated)	12.4	5.0	1.0	7.4	2.4	5.4
N (dry)	129.2	19.7	0.6	21.3	9.6	2.0
All dates	Mean difference from gravimetric					Gravimetric
Water content all	1.4	−2.6	−0.2	−4.4	−4.4	24.9
Water content irrigated	0.7	−2.1	−1.5	−4.6	−5.4	29.8
Water content dry	2.1	−3.1	1.1	−4.3	−3.3	20
SD all	7.97	6.84	4.06	6.18	4.39	5.42
SD irrigated	2.52	1.56	0.62	1.59	0.82	1.31
SD dry	7.08	2.51	0.53	2.38	1.72	0.85

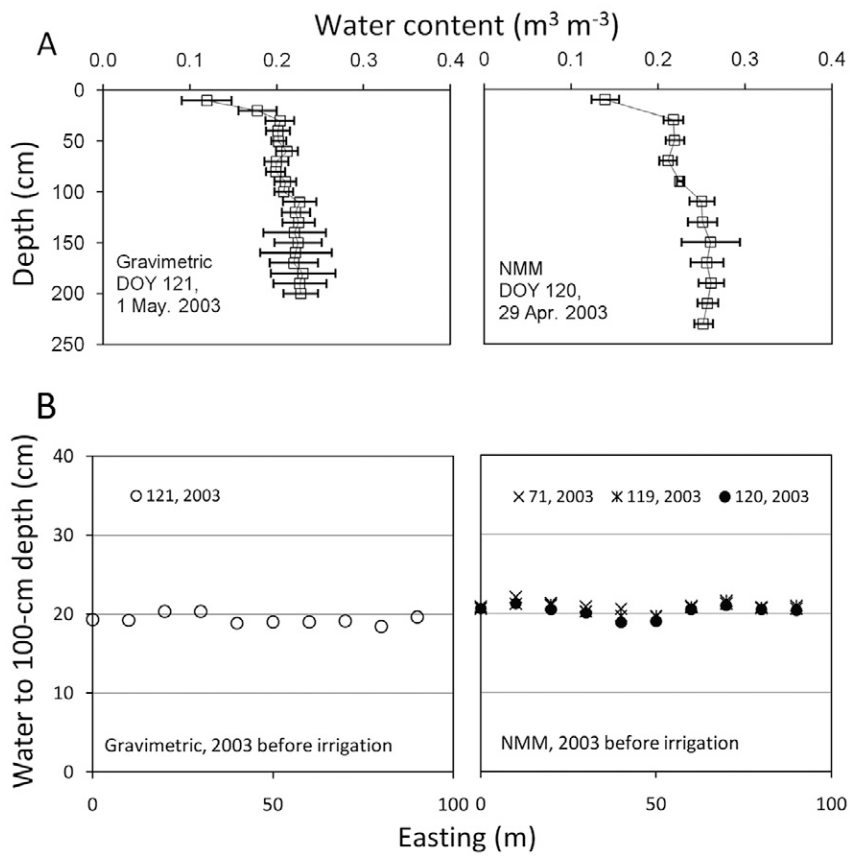

Fig. 3. (A) Mean profile water content by depth measured gravimetrically and by neutron moisture meter (NMM) on Day of the Year (DOY) 121 and 120 of 2003, respectively, just before irrigation began, with 1 SD bars, and (B) depth of water at each transect location for all days of measurement before irrigation began in 2003 as sensed with the NMM and measured gravimetrically.

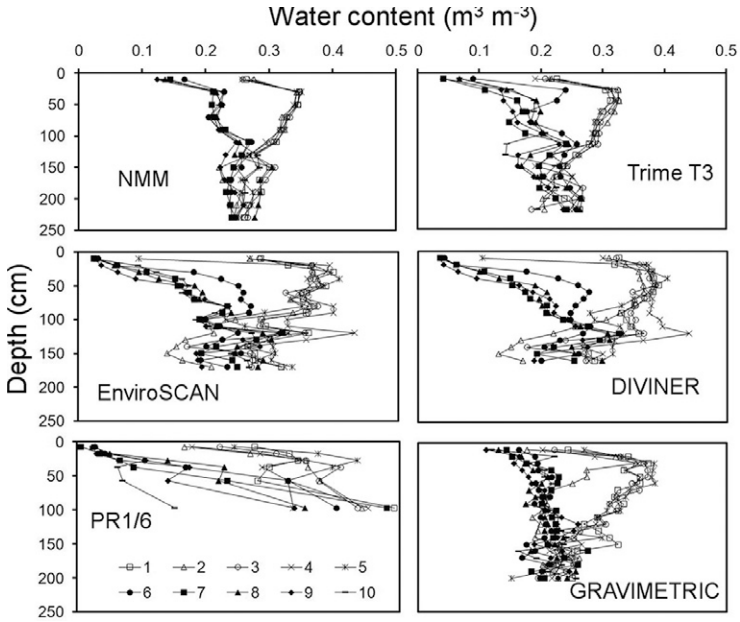

Fig. 4. Profile water contents for 10 transect locations for each of five sensor systems in a winter wheat field on 5 Nov. 2003 compared with gravimetric measurements. Half of the field (five transect locations) was irrigated. Sensing methods were frequency domain (EnviroSCAN, Diviner 2000, and PR1/6), quasi time domain reflectometry (Trime T3), and the neutron moisture meter (NMM). Heavy lines represent unirrigated sites (6–10), thinner lines represent irrigated sites (1–5).

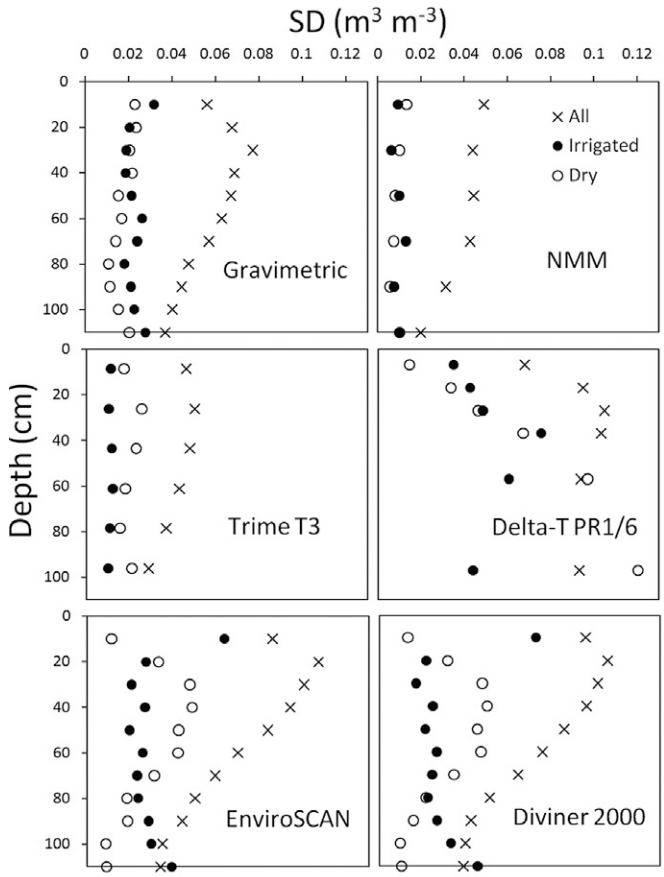

Fig. 5. Season-long mean SD of soil water content by depth for six methods of soil water determination used in the field in 2003 at Bushland, TX. Sensing methods were frequency domain (EnviroSCAN, Diviner 2000, and PR1/6), quasi time domain reflectometry (Trime T3), and the neutron moisture meter (NMM).Standard deviations were computed for all 10 access tubes, for the five access tubes in the wet (irrigated) side of the field, and for the five access tubes in the dry (unirrigated) side of the field.

including any instrumental variability (Table 3). For all 10 access tubes, the mean SD values for each sensor were larger because they reflected the increase in variation caused by irrigating one half of the field (Fig. 4), so they were excluded from Table 3. It is important to note, however, that the increase in SD for the combined data (all 10 access tubes) is influenced by the facts that (i) some sensors are more sensitive to the change from drier to wetter conditions than are others, and (ii) calibration inaccuracies can inflate or deflate the overall SD. For example, the populations of SD values do not appear to differ (values do not differ appreciably at any depth) between irrigated and unirrigated sides of the field for the NMM, and they do not appear to differ much for the gravimetric samples (Fig. 5). The difference is a little more for the Trime; even larger differences can be seen for the three capacitance sensors. Thus, the increase in SD caused by combining data from irrigated and unirrigated sides of the field is only partly due to the increase in the SD of actual water content. It is also enhanced by the way in which some of the sensors are affected by the variability in water content at scales smaller than their sensing volumes, which can increase the SD. Also, it is important to see how inaccuracies in calibrations can inflate or deflate SD values if water contents are misestimated. An example is the Trime, with which water contents were underestimated on the wet end but not so much on the dry end, making the estimated difference in water content between irrigated and unirrigated sides of the field less than actual. This resulted in the overall SD being smaller for the Trime than for the NMM, even though the SD values for the irrigated side alone and the unirrigated side alone were larger for the Trime than for the NMM. If the Trime calibration had been more accurate, the SD values for the combined data from all 10 access tubes would have been larger than those from the NMM.

For either the dry or irrigated sides of the field, the NMM exhibited the smallest SD of water content, with values approximately one half of those from gravimetric samples. The NMM showed little difference in SD between the dry and irrigated sides of the field. By contrast, scatter in the EM sensor data was particularly evident for the dry side of the field in the 20- to 60-cm depth range. The exception to this was the Delta-T PR1/6, which exhibited more scatter as depth increased to 100 cm on the dry side. Overall, the PR1/6 exhibited larger SD values than any other method.

The numbers of access tubes required to determine the field mean profile water content (0–100 cm) to within 1 cm at a 90% probability level were calculated using Eq. [3] and the mean SD for each method and each side of the field after irrigation began (Table 3). This meant that at least 35 values (5 positions in space × 7 samplings) of profile water content were used in determining the SD, a reasonable number. For this precision and probability level, the ratio of numbers of EM sensor access tubes or gravimetric corings to the number of NMM access tubes required for the irrigated side of the field was 12.8, 5.2, 7.6, 2.5, and 5.6 for the PR1/6, EnviroSCAN, Diviner, Trime, and gravimetric methods, respectively. In the dry side of the field, the ratios were 218, 33, 36, 16, and 3.4 for the PR1/6, EnviroSCAN, Diviner, Trime, and gravimetric methods, respectively.

The mean difference between sensor-estimated and gravimetrically determined profile water contents in 2003 was smallest for the NMM (Table 3). The relatively small difference between means of PR1/6 readings and gravimetric measurements masks the fact that PR1/6 readings were considerably smaller than gravimetric values early in the season and larger late in the season (Fig. 6), which may be an effect of seasonal temperature change since the PR1/6 was shown previously to be sensitive to temperature changes in this soil (Evett et al., 2006).

For the PR1/6 and Trime sensors, the greater scatter exhibited by the EM methods in the dry side of the field, particularly in the zone of active root water uptake (depths <150 cm), may be partially due to soil variability near the access tubes since SD values for these sensors were larger for this side of the field before irrigation began. Some of the larger variability in the dry side of the field after irrigation began, however, is probably related to the relatively smaller measurement volumes of these sensors compared with that of the NMM. For example, the NMM when read in the Trime access tubes showed nearly equal variability between the two sides after irrigation (SD values of 1.05 and 1.14 cm for the irrigated and dry sides, respectively; data not shown). As noted above, the sample size of the EM methods is probably in the range within which soil water content becomes more variable as sample size decreases. For example, from the data of Paltineanu and Starr (1997) and Evett et al. (2006), the measurement volume of the Diviner 2000 sensor is, at most, approximately 470 cm^3 in dry soil and 235 cm^3 in saturated soil, and that of the EnviroSCAN sensor is probably very similar. The smaller diameter Delta-T PR1/6 may have a larger measurement volume since the axial sensitivity tests of Evett et al. (2006) showed that it had an axial sensitivity approximately 20% larger than that of the Diviner 2000; and the lower frequency PR1/6 would be expected to have a correspondingly larger sampling volume since frequency is inversely related to EM field penetration. The size of the gravimetric samples, approximately 76 cm^3, was much smaller than the sample volumes of the EM sensors, yet the SD of the gravimetric water contents and ΔS values was smaller than those from all EM sensors on the dry side and smaller than all but the Trime data on the irrigated side. This is evidence that (i) a mechanism other than soil water variability at the scale of EM sensing is causing the relatively greater variability of values from the EM sensors, and that (ii) this mechanism acts at scales smaller than the sensing volumes of the EM sensors since the degree of variability in soil water content, measured gravimetrically at scales smaller than the sensing volume of the EM sensors, is itself smaller than that evidenced by estimates of soil water content from the EM sensors.

Comparison of data from the Trime and NMM read in the same plastic access tubes revealed a consistent linear correlation, with slopes averaging 0.97, intercepts averaging −0.07 $m^3\ m^{-3}$, coefficients of determination ranging from 0.68 to 0.84, and RMSE values ranging from 0.025 to 0.031 $m^3\ m^{-3}$ (Table 4). As the soil became thoroughly wetter in the irrigated side, the coefficients of determination became consistently >0.8 because the range of water contents was increased (Fig. 7), not due to any decrease of scatter in the data (RMSE values did not trend smallerer during the same time, Table 4). The mean 0.07 $m^3\ m^{-3}$ difference between the Trime and NMM data was due to a combination of consistent underestimation of water content by the Trime sensor of ~4.4

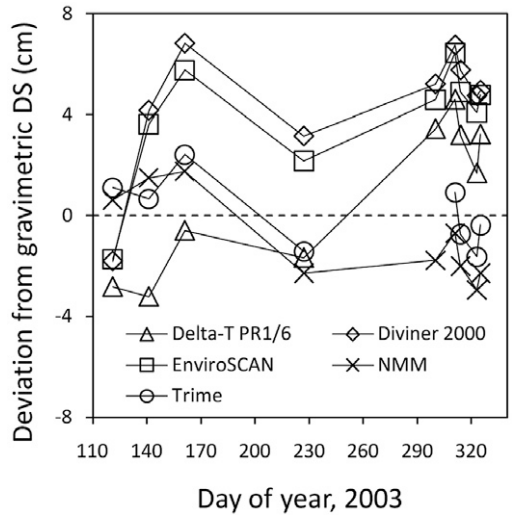

Fig. 6. Deviations from the difference in soil water storage (DS) between irrigated and dry sides of a field measured gravimetrically, and the differences in storage as sensed by frequency domain (EnviroSCAN, Diviner 2000, and PR1/6), quasi time domain reflectometry (Trime T3), and the neutron moisture meter (NMM). Data are for eight measurement dates in 2003 in a winter wheat field.

Table 4. Linear correlations between water content at individual sampling depths in the top 100 cm of soil for the Trime T3 sensor (S_{T3}) and that for the neutron moisture meter (S_{NMM}) for measurements in 2003 using the model $S_{T3} = a + b(S_{NMM})$ with 70 samples for each day.

Day of year	b	a	r^2	RMSE
				cm
119	1.013	0.075	0.680	0.026
120	1.020	0.079	0.710	0.025
141	0.895	0.043	0.580	0.031
162	0.785	0.013	0.660	0.025
227	0.911	0.034	0.780	0.027
309	1.022	0.080	0.840	0.026
314	1.009	0.087	0.820	0.027
323	1.042	0.097	0.810	0.027
325	1.072	0.104	0.800	0.028

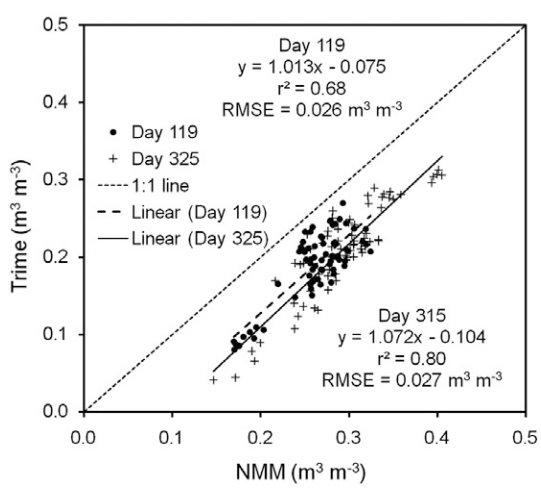

Fig. 7. Examples of the correlation between water contents measured by the Trime T3 tube probe and the neutron moisture meter (NMM) at equivalent depths in the Trime plastic access tubes in 2003. Day 119 was before irrigation of half the field began, and Day 315 was after one half of the field was thoroughly wetted.

cm in 100 cm or 0.044 m^3 m^{-3} (Table 3) and overestimation of water content by the NMM due to the H in the plastic access tubes, from which a correction factor of −0.026 m^3 m^{-3} can be deduced for the NMM when read in the Trime's polycarbonate plastic access tubes.

We believe that the difference in variability between EM sensor data and NMM and gravimetric data was in part due to the tendency of EM fields to permeate the parts of the soil with larger permittivity and electrical conductivity (both due to larger water content) rather than equally permeating all soil volumes. Logsdon (2009), using an EM sensor with steel probe rods inserted into heterogeneous soil columns, provided supporting evidence for this behavior. Furthermore, investigating electric dipole antennas, Hollinger et al. (2001) found that an EM field becomes coupled with interfaces across which material electrical parameters change, resulting in important changes in the amplitude radiation pattern; they noted that such parameter changes could "be due to minor increases of the pore water salinity and/or the clay fraction." For the Trime T3, this behavior may have been mitigated because this sensor acts as a waveguide, in essence forcing the wave front to pass through volumes of soil with smaller water content and thus including those volumes in the determination of travel time, resulting in smaller SD values than for the other EM sensors. The capacitance sensors do not act as waveguides; they are essentially antennas that radiate a field (the fringing field) into the soil outside the access tube. Further evidence that microscale structure of soil electrical properties influenced the EM sensor readings is that the readings became more variable as the soil dried even though it is well known that the sensing volume of EM sensors increases as soil dries. By contrast, increasing the volume of gravimetric sampling decreases the variability of water content values. We can only conclude that soil drying accentuated the differences in the electrical properties of soil peds both inside and at ped surfaces, thus enhancing the coupling of the EM field with this microscale variability.

Relative Differences and Spatial Variability

Ranking of the mean relative difference, $\overline{\delta_i}$, of a soil property is typically used to assess both the variation in space (uniformity) and in time of the property. One possible outcome is identification of a location in the field where the mean is reliably close to the field mean. In so doing, an implicit assumption is made that there is no imposed difference with time across the field. We used $\overline{\delta_i}$ rankings for somewhat different, but related, purposes. In particular, we were more interested in the spatial variation aspect of these plots than in the time variation; and we specifically wanted to examine imposed differences in water content. In our 2003 experiment, we purposefully imposed a difference in soil profile water content with time by repeatedly irrigating one half of a uniform field, resulting in a (gravimetrically determined) mean water content on the irrigated side of 31.1 cm of water in the surface to 100-cm depth layer, slightly less than the field capacity, and a mean water content of 20.0 cm on the unirrigated side, a little larger than the permanent wilting point of ~18 cm (Fig. 8). Thus, the ranking of $\overline{\delta_i}$ values should show that the five locations in the irrigated side of the field were uniformly wetter than the five locations in the unirrigated side of the field. If water content were uniform in each side of the field, then $\overline{\delta_i}$ values would vary little for each side (low SD for each side).

To assess the variation on each side of the field, we fitted linear regressions to the $\overline{\delta_i}$ data for each side, lower slopes indicating more uniformity. The most spatially uniform $\overline{\delta_i}$ values for the two sides of the field were computed from the NMM data, as indicated by the small slope values. The NMM data also showed the least variability with time (smallest limit bar

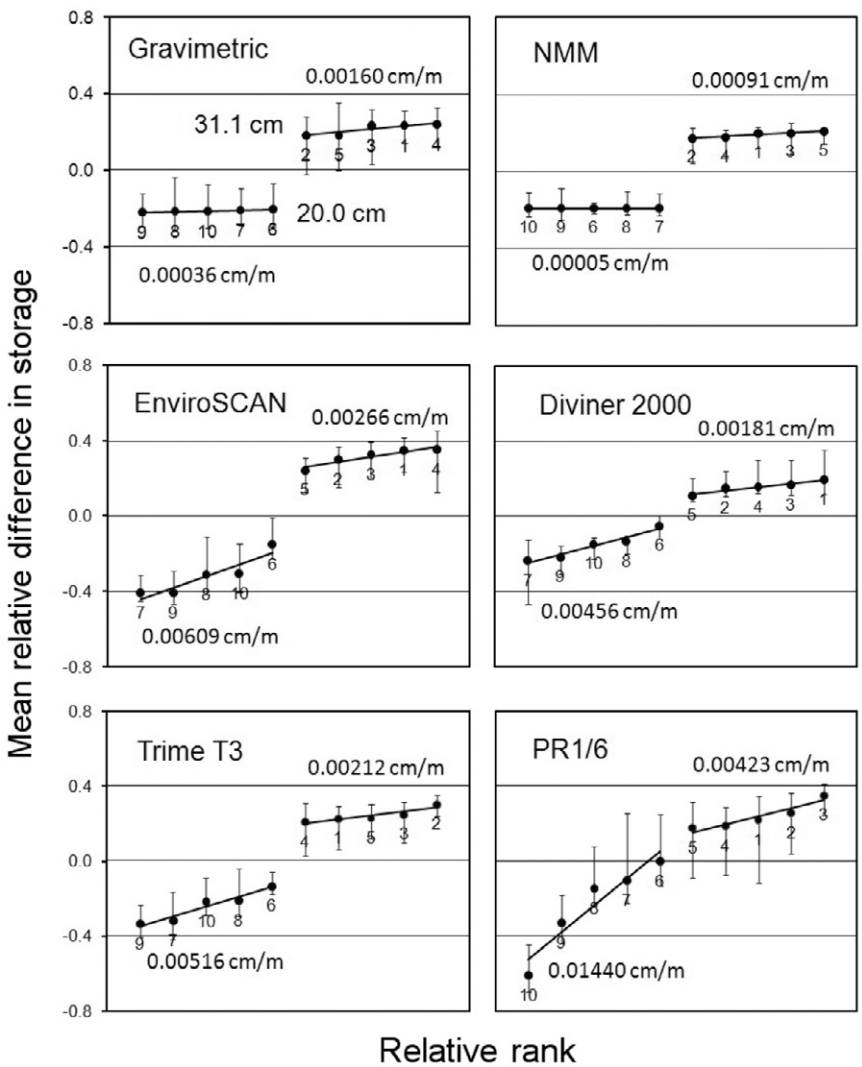

FIG. 8. Ranking of the mean relative difference of storage in 10 access tubes for eight measurement dates after irrigation of winter wheat began in 2003. Data are shown for gravimetric measurements, the neutron moisture meter (NMM), the Trime T3 probe, the EnviroSCAN and Diviner 2000 capacitance probes, and the Delta-T PR1/6 capacitance probe. The limit bars indicate the minimum and maximum values of the relative difference at each of the 10 access tube locations. Slope values are changes of water content (cm of water depth in 100 cm of soil) per meter of distance. These are not trends, but rather indicate a rate of spatial variability.

ranges). The next most spatially uniform were the gravimetric data (Fig. 8), which, as expected, also showed considerably more variation with time because the sampling location changed every time. Data from the Trime T3 probe, which was read in the same access tubes as the NMM, showed spatial variation in the data, particularly on the dry side, that was not evident in the gravimetric or NMM data. Similar variability was apparent in data from the three capacitance sensors, with Location 6 being sometimes not clearly different from the irrigated side of the field. Although the EnviroSCAN and Diviner 2000 were read in the same access tubes, the Diviner 2000 showed less variability but also a less clear distinction between irrigated and dry sides of the field than did the EnviroSCAN. Data from the PR1/6 did not clearly differentiate between irrigated and unirrigated sides of the field. Variability with time also was larger for the four EM sensors compared with the NMM data, as is shown by the range of maximum and minimum values of relative difference (limit bars in Fig. 8).

Linear regression of EnviroSCAN vs. Diviner readings showed strong correlations between the two for dates both before irrigation began and afterward (Fig. 9), which showed that these two sensors responded reproducibly to some property of the soil–access tube system, which we believe was not water content alone. This belief is based on two facts: (i) the two sensors were inaccurate, even when using soil-specific calibrations; and (ii) the sensors showed spatial variation of the profile water content that did not exist at the scale of gravimetric measurement (75 cm^3), which is smaller than the measurement volumes of these two EM sensors. The correlation between the two sensors is not surprising since they share the same basic design and similar measurement volumes. The main difference is that the Diviner has a larger base operating frequency, which should reduce its sensitivity to σ_a in the conductive Pullman soil (see Evett et al., 2006). Evidence for reduced sensitivity to σ_a is seen in the smaller SD values for the Diviner, in the fact that the Diviner was more accurate when the factory calibrations were used for both sensors (water content not overestimated as much at the high end, Fig. 9), and in the fact that the (nonexistent) spatial variation was less pronounced for the Diviner. Nonetheless, both sensors overpredicted water contents in the Pullman soil when using the factory calibrations. The soil-specific calibrations of Evett et al. (2006) reduced the overprediction and brought the correlation of readings from the two devices to close to the 1:1 line (Fig. 9).

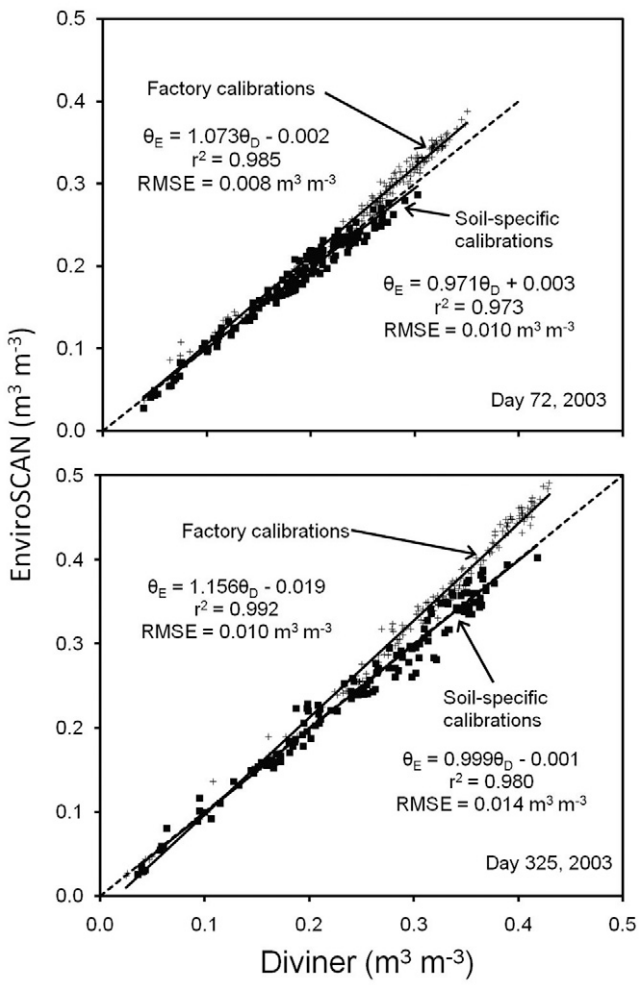

Fig. 9. Correlations of water contents reported by the EnviroSCAN and Diviner systems using both factory calibrations and the soil-specific calibrations of Evett et al. (2006) for Day 72 in 2003 before irrigation began and for Day 325 in 2003 after irrigation. Solid lines are regression lines. Dashed lines are the 1:1 lines.

Experiments 2 and 3: Soybean Field, 2004 and 2005

Variability

Two sets of measurements were acquired during the active irrigation season (10 and 18 Aug. 2004), and two sets were acquired as the field was allowed to dry before harvest (2 and 10 September). Four sets of measurements were taken in the fallow field in early 2005. Gravimetric sampling was done only in 2005 so as not to disturb the crop in 2004.

In 2004, the SD of profile water contents for all 20 access tubes was exaggerated by the difference in water content between the 33 and 100% irrigation treatments (Table 5). The values of SD for either the 33 or 100% treatment were largest for the Diviner and EnviroSCAN in 2004 and largest for the Trime in 2005. Similar to the 2003 results, the SD values for the NMM were the smallest of any method at all times and the SD values for the gravimetric data were next smallest. Values of SD for the EM measurements were generally from two to six times larger than

Table 5. Mean SD values of profile water contents to 100-cm depth for electromagnetic and neutron moisture meter (NMM) sensors on Days of the Year (DOY) 223, 231, 246, and 254 (August–November) in 2004 and DOY 20, 62, 83, and 102 (early January–April) in 2005 with numbers, *n*, of profile water content samples necessary to determine the field plot mean profile water content to 100-cm depth with a precision of 1 cm at the $\alpha = 0.1$ probability level for the 33 and 100% irrigation treatment plots.

Parameter	Diviner	Trime	EnviroSCAN	NMM	Gravimetric
2004					
SD all	6.81	4.97	6.36	2.99	NA
SD 33%	5.95	3.02	5.41	0.98	NA
SD 100%	2.12	2.02	1.93	1.31	NA
n (33%)	95.2	24.5	78.7	4.6	NA
n (100%)	12.1	11.0	10.0	2.6	NA
2005					
SD all	1.54	2.26	1.47	0.44	0.69
SD 33%	0.83	0.94	1.05	0.45	0.67
SD 100%	1.58	2.08	1.51	0.35	0.56
n (33%)	1.9	2.4	3.0	0.5	1.2
n (100%)	6.7	11.6	6.1	0.3	0.8

those for the NMM or gravimetric measurements. During the irrigation season in 2004, the values of SD for the EM methods were approximately 50% smaller in the 100% irrigation treatment than in the drier 33% treatment, again showing increased variability even as the sampling volume increased in the drier soil. To detect a difference with a precision of 1 cm and the 90% probability level in the 100% irrigation treatment, the ratio of numbers of EM access tubes for profile water content samples to the number of NMM access tubes was 2.2, 2.6, and 2.4 for the EnviroSCAN, Diviner, and Trime methods, respectively. In the 33% treatment plot, the ratios were 30, 37, and 9.5 for the EnviroSCAN, Diviner, and Trime methods, respectively.

By early 2005, differences in water content between the two treatments had disappeared due to plentiful precipitation, which left the entire field wetter than during the irrigation season; mean and SD values of gravimetric samples were 0.370 ± 0.007 $m^3\ m^{-3}$ in the 33% irrigation treatment and 0.373 ± 0.006 $m^3\ m^{-3}$ in the 100% irrigation treatment. On average, the 100% treatment was only 0.3 cm wetter in the top 100 cm of soil as determined by gravimetric sampling in 2005, compared with 0.1 cm wetter by NMM, 1.7 cm drier by the EnviroSCAN, 2.9 cm wetter by the Trime, and 2.0 cm drier by the Diviner measurements (Table 6). The generally smaller SD values in early 2005 and the smaller SD values for the 100% irrigation treatment in 2004 both reinforce the observations in 2003 that the variability of actual soil water content was larger in drier soils, which agrees with the findings of others (e.g., Famiglietti et al., 1999; Hawley et al., 1982; Hupet and Vanclooster, 2002; Schmitz and Sourell, 2000). As in 2003, however, SD values for the NMM and gravimetric data in 2004 and 2005 were least affected by the relative wetness or dryness of the soils. Since the gravimetric sample volume was smaller than those of the EM sensors, the enhanced variability of apparent water content as observed with the EM sensors must be due to some mechanism that goes beyond simple variability of soil water content at the gravimetric sample volume of ~76 cm^3. The 2-cm overestimation of water content by the NMM was caused by its being read in the plastic access tubes of the Trime sensor. If the correction factor of −0.026 $m^3\ m^{-3}$ determined from the 2003 data were applied, the NMM would have underestimated water content overall by 0.5 cm compared with gravimetric data, making the NMM the most accurate sensor.

In 2005, to detect a difference with a precision of 1 cm at the 90% probability level in the 100% irrigation treatment, the ratio of numbers of EM and gravimetric profile water content samples to the number of NMM access tubes required was 18.6, 20.4, 35.3, and 2.6 for the EnviroSCAN, Diviner, Trime, and gravimetric methods, respectively. In the 33% treatment plot, the ratios were 5.4, 3.4, 4.4, and 2.2 for the EnviroSCAN, Diviner, Trime, and gravimetric methods, respectively; and the maximum numbers of access tubes required ranged from 12 for the Trime to six and seven for the EnviroSCAN and Diviner 2000, compared with one for gravimetric or NMM sampling. Nevertheless, the differences between the 100 and 33% treatments were small and dominated not by relative wetness or dryness but by other determinants of soil variability (probably bulk density), and the numbers of access tubes required were small compared with numbers determined for the 2003 and 2004 seasons.

The larger SD values for drier soils mean that more EM sensor access tubes will be needed in drier soils to obtain a plot-mean profile water content to a given degree of precision. This precision may not translate into accuracy, however, given the relative inability of the EM sensors to estimate the profile water contents accurately. Compared with gravimetrically determined profile water contents, the Trime system was least accurate and the Diviner was most accurate in early 2005. The NMM was most consistently different from gravimetric measurements due to being read in the plastic access tubes. Nevertheless, differences in soil water storage between the 33 and 100% treatment plots were most accurately determined by the NMM (error of 0.1 cm compared with the gravimetric data) (Table 6).

TABLE 6. Mean differences (cm) between profile water contents measured by electromagnetic and neutron moisture meter (NMM) sensors and by gravimetric sampling for Days of the Year 20, 62, 83, and 102 (early January–April) in 2005. Also shown are the mean differences (cm) between the differences in storage (storage in the 100% irrigation treatment minus storage in the 33% treatment) as measured by gravimetric sampling and by each system for three intervals in 2005 (Days 20–62, 62–83, and 83–102).

Parameter	Mean differences from gravimetric profile water content				Gravimetric profile water content
	Diviner	Trime	EnviroSCAN	NMM	
	cm				
Mean all	0.7	−8.0	−2.1	2.0	37.1
Mean 33%	1.7	−9.4	−1.2	2.0	37.0
Mean 100%	−0.3	−6.5	−2.9	2.1	37.3
100% − 33%	−2.1	2.9	−1.7	0.1	–

Relative Differences

Relative differences in soil water storage during the 2004 irrigation season were clearly differentiated between the 33 and 100% irrigation treatments by the NMM, and somewhat less so by the Trime system, which showed two to three times as much variability in storage at any location in the field (Table 5) and across the field (larger slopes in Fig. 10). The differences between the 33 and 100% irrigation treatments were also evident in data from the Diviner and EnviroSCAN systems, but less clearly than for the Trime system, and Locations 3 and 1 were not clearly different from zero mean relative difference. Behaviors of the Diviner and EnviroSCAN systems were nearly identical, including the ranking of sampling positions, and data were also more than twice as variable as the NMM data. In either the 33% or full irrigation treatments, variability in space was larger for the EM sensors than for the NMM, much larger in the drier 33% treatment for the capacitance sensors but also larger for the Trime T3 sensor. These results are similar to those found in 2003.

Variability across space and time was much less for all measurement methods in 2005 due to the uniformity of soil water content across the 33 and 100% treatments resulting from winter precipitation (Fig. 11). The overall spatial variability was nearly equal for gravimetric and NMM data but the NMM data showed more temporal stability, probably due to the fact that gravimetric samples were taken at different locations each time. Data from the EM sensors were approximately 10 times more variable in space, and data from both the EnviroSCAN and Diviner systems displayed tails at the dry end that indicated more variability of sensed data from these systems. Since the NMM and Trime T3 sensors were read in the same access tubes,

the Trime T3 showed variability that did not exist in the field at the scale of interest. The larger spatial variability of EM sensor data, when NMM and gravimetric data showed that the actual variability was much smaller at scales as small as 75 cm^3, can be ascribed to the interaction of the sensor EM field with variable capacitive and resistive elements at scales smaller than the measurement volumes of the EM sensors, all of which exceeded 75 cm^3. As shown by Logsdon (2009), this interaction could have biased the averaging of permittivity within the sensed soil volume.

For the EM sensors, the choice of access tube installation location could have a large effect on the assessment of profile water content changes with time. For example, comparison of Fig. 10 and 11 shows that Location 10 in the 33% irrigation treatment ranked near the dry end in 2004 and near the wet end in 2005 for both the EnviroSCAN and Diviner 2000 sensors. The same was true for Locations 4 and 5. While ranking for the NMM data also varied, the much smaller relative differences for the NMM indicate that the position in the field would have little impact on the assessment of profile water content. The behavior of the Trime sensor, which is based on travel time principles, represented a middle point between that of the capacitance sensors and NMM or gravimetric sampling. For the Trime, the ranking of locations was more consistent between 2004 and 2005 than for the capacitance sensors, but appreciable nonrealistic spatial variation was still indicated for both years.

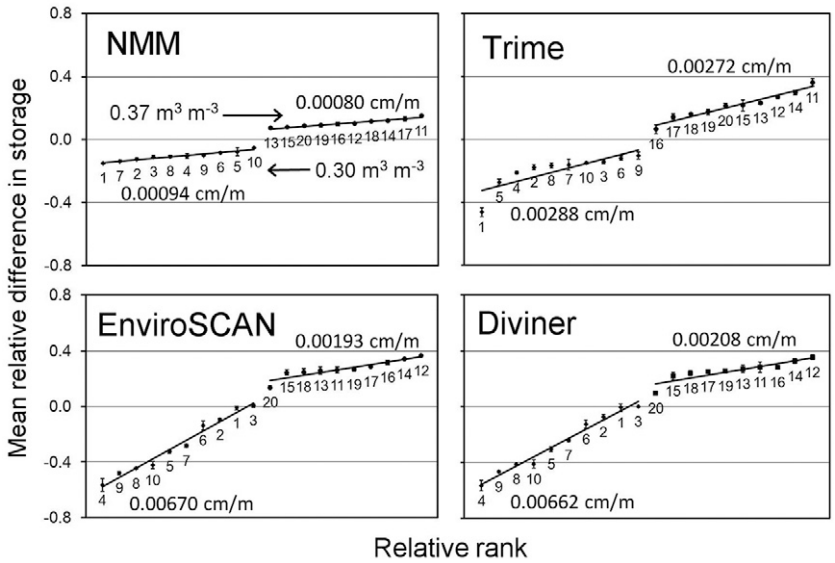

Fig. 10. Ranked mean (with time) relative differences in storage for the neutron moisture meter (NMM), Trime, EnviroSCAN, and Diviner sensors during the irrigation season in 2004 at Bushland, TX. Numbers are sequential for the position of the access tube in the transect. Bars indicate the smallest and largest relative difference for each location.

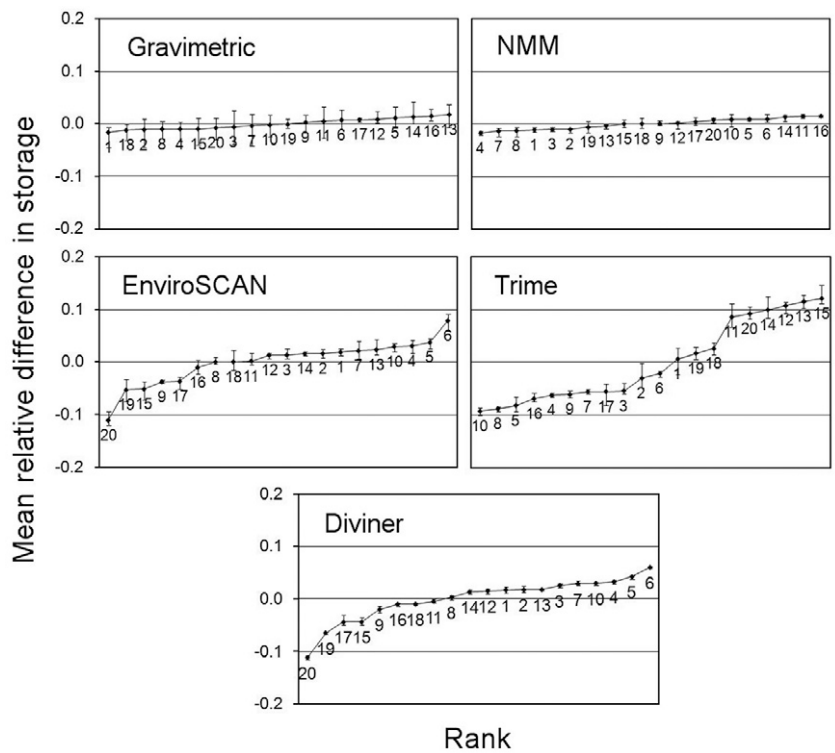

Fig. 11. Ranked mean (with time) relative differences in storage for the neuron moisture meter (NMM), Trime, EnviroSCAN, and Diviner sensors and for gravimetric water contents during the fallow season in early 2005 at Bushland, TX. Numbers are sequential for the position of the access tube in the transect. Bars indicate the smallest and largest relative difference for each location.

Summary

Statistical analysis showed that one to five NMM access tubes or gravimetric cores were needed to ascertain differences in stored soil water to 1-cm precision at the 90% confidence level in the several field plots and years in this study. From two to 72 more EM sensor access tubes were required to achieve the same level of confidence and precision; in general, so many more that the EM methods would be prohibitively expensive for our field experiments. In addition, although precision can be improved by more samples, this does not improve the accuracy of θ, S, or ΔS. The EM sensors were relatively inaccurate even though soil-specific calibrations were used. Moreover, the numbers of access tubes required for the EM sensors were strongly dependent on water content, increasing greatly for unirrigated or deficit-irrigated conditions compared with the numbers needed under well-watered conditions. Finally, ranked relative differences showed that the EM sensors exhibited more variation in profile water content in space, particularly under drier soil conditions, than actually existed as shown by gravimetric and NMM data. The spatial variation indicated by the NMM and gravimetric methods was small and closely similar. These results combine to indicate (i) that use of one or two EM sensor access tubes could not be relied on to provide a mean profile water content that was representative of the field plots in this study or of changes in profile water content with time, and (ii) that selection of access tube installation location(s) could have a large and unpredictable impact on subsequent water content estimates.

Our data show that at all water contents, but particularly at smaller water contents in the Pullman soil, the EM sensors were sensitive to a kind of soil property variability that is larger than the mean variability of gravimetric water content data for sample volumes of ~76 cm^3. We conclude that this variability is different in kind from mean volumetric water content because it occurs for the EM sensors, which all have measurement volumes larger than that of the gravimetric samples, when it does not occur for the gravimetric samples or for the NMM samples. We infer that this variability is due to site-specific (at each measurement point) variations in the way in which the EM field permeates and interacts with the soil at each measurement point where microscale variability in water content at scales smaller than the sensor sampling volume necessarily induces variable resistive and capacitive elements in this structured soil. Evidence for this was strong in all years, but particularly in the 2005 data when the larger spatial variability of the EM sensor data, in contrast to the much smaller variability of the NMM and gravimetric data at scales as small as 75 cm^3, would make sense if the variability were due to interaction of the sensor EM field with variable capacitive and resistive elements at scales smaller than the measurement volumes of the EM sensors, all of which exceeded 75 cm^3.

It is well known that soil water is nonuniformly distributed in soil peds, and that as structured soils dry, the ped surfaces become drier than the ped cores, with the reverse occurring during wetting. Also, peds that are farther from the larger cracks will dry and wet more slowly. In soils like the Pullman, containing superactive clays and exhibiting appreciable and increasing bulk electrical conductivity as they are wetted (Evett et al., 2006), the peds necessarily become a network of volumes and surfaces with unequal water contents and bulk electrical conductivities—in essence a network of capacitive and conductive (resistive) elements. Although the interaction of EM fields with such a network is poorly understood, it is known that a radiated field, such as is used by a capacitance sensor, will tend to be preferentially coupled with the more conductive elements of any conductive network (Hollinger et al., 2001; Schwank et al., 2006; Schwank and Green, 2007) and be influenced in important ways by the randomness of conductive and capacitive elements (Panteny et al., 2005; Logsdon, 2009). Logsdon (2009) showed that a heterogeneous arrangement of wetter and drier volumes in a soil affected the accuracy of another EM sensor, resulting in larger water content readings in a heterogeneous soil than for a uniform (on the small scale) mixed and repacked soil of the same mean water content. Our EM sensor results show overestimation of water content on the wet end and underestimation of water content on the dry end, even though we used soil-specific calibrations. This misestimation of water content is probably related to the biased interaction of the EM field with nonuniform water contents at the small scale, as shown by Logsdon (2009), rather than to errors in the calibrations done in uniform, repacked soil columns by Evett et al. (2006). Further evidence of this is the improved agreement in Fig. 9 when the soil-specific calibrations were used.

We infer from our data that the randomness of the conductive and capacitive elements at scales of ~76 cm^3 or more (EM sensor field sizes) has a much larger effect on the EM sensors than the randomness of mean volumetric water content at 75-cm^3 volume in the Pullman soil, resulting in increased variability in EM sensor readings above the variability due to mean volumetric water content variations in a 75-cm^3 sample volume alone. This increased variability was highly reproducible between two capacitance sensing systems, proving that the variability is a real outcome of soil property variability at these scales. This conclusion is supported by our earlier finding that variability of readings from another capacitance sensor used in plastic access tubes (Sentry 200 AP, Troxler Electronic Laboratories, Research Triangle Park, NC) was reproducible between four of those sensors and so had to be due to the variability of soil properties at scales smaller than the sensing volumes of the NMM or gravimetric sampling, which did not show the variability (Evett and Steiner, 1995). The impact of this microscale variability on soil profile water content estimates is to introduce a spatiotemporal variability of sensor response that, although caused by real phenomena at the microscale, is not caused by mean water content variability at the scale of the measurement volume. This apparent variability is unrealistic and irrelevant to most studies of soil profile water content spatiotemporal variability, of the availability of water to plants, and of ET.

Since the Pullman soil is similar to many soils in semiarid and arid regions, and because structured or macroporous, superactive (conductive when wet) soils exist in many more-humid climes (e.g., Logsdon, 2005, 2006), it is likely that similar problems will occur for EM sensors in those soils. In fact, microscale variability exists even in unstructured soils that are known for their uniformity, and this variability can translate into variability of measured soil water content (Baveye et al., 2002).

The results on variability show that the EM sensors do not produce data that are useful for the spatial analysis of the variability of profile soil water content based on one access tube per support volume. While increasing the number of access tubes for each support volume might allow data from such systems to be used for spatial analysis, our analysis indicates that this is unlikely; we believe that the number of access tubes required would be economically unachievable for most studies, and we believe that, due to accuracy issues, the data so obtained would not realistically represent the variability of water available for plant growth or hydrologic processes even with soil-specific calibrations.

The design of future EM sensors for use with access tubes should concentrate on ways to force the EM field to pass through all of the soil matrix. This may be done using waveguide approaches such as used by the Trime sensor or by using multiple electrodes, one or more of which serve as virtual grounds. Because of the microscale EM field interactions with variable conductive and capacitive elements, which we infer and others have demonstrated, approaches that use resonant electromagnetic fields are unlikely to fully succeed even if corrections for bulk electrical conductivity, EM frequency, and bound water (relaxation effects) are made as demonstrated by Schwartz et al. (2009a,b).

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