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Field calibration of a capacitance soil water probe in heterogeneous fields

Dieter Geesing[A], *Martin Bachmaier*[B], *and Urs Schmidhalter*[A,C]

[A]Technical University of Munich, Department of Plant Science, Chair of Plant Nutrition, Am Hochanger 2, D 85350 Freising, Germany.
[B]Technical University of Munich, Department of Bio Resources and Land Use Technology, Crop Production Engineering, Am Staudengarten 2, 85354 Freising, Germany.
[C]Corresponding author; email: schmidhalter@wzw.tum.de

Abstract. Soil water research requires methods to perform accurate measurements. A capacitance probe gauge has characteristics that seem to make it an attractive replacement for neutron scatter gauges to measure soil water content, but there is evidence that capacitance systems should be calibrated for individual soils. Laboratory calibrations and many field calibration methods are costly and time-consuming, and controlled conditions and disturbed soil samples do not always reflect field conditions, and thus, they are inadequate for practical use. The objectives of the present study were (*i*) to test a simple field calibration method for a recently developed capacitive sensor even under highly variable soil texture conditions, and (*ii*) to validate this approach under various soil moisture conditions. Soil samples were taken 0.5 m from the access tube of the sensor and a whole field calibration and several site-specific calibrations were developed using 10–142 observations per site under different soil water regimes. A regression of soil water content estimated by sensor reading on water content obtained by core sampling showed no significant difference in the slope and intercept of the 1:1 line when the field calibration was applied. However, the precision of the calibration was only considerably increased if the estimations were based on site-specific calibrations developed on at least 35 observations per site. The precision and accuracy of the calibration equations were not affected when data were obtained only under wet or dry soil conditions. The method presented in this paper is a speedy and cheap way to calibrate capacitance probe sensors.

Additional keywords: soil water variability, site-specific calibration, portable capacitance probe, soil water monitoring.

Introduction

Many applications in fields such as hydrology, meteorology, and agriculture require mapping of soil moisture, since the amount and status of water in soils impacts crop growth and the fate of agricultural chemicals applied to the soil. This requires reliable techniques to perform accurate soil water content measurements with minimal soil disturbance. Many methods for soil moisture monitoring use permanently installed devices at selected sites in a field, and thus, their usefulness is limited because of the high spatial variability of soil moisture, in particular in areas with high soil textural variability.

In the 1950s the soil moisture neutron probe was introduced and quickly became a widely accepted non-destructive method of soil profile water content measurement (Gardner *et al.* 1991). Its radioactive source, however, requires licensing during transportation and storage, and the training of users on safety regulations. Thus, many uses, such as remote unattended sensing, are restricted when neutron probes are used. As an alternative to gravimetric or neutron scattering methods, techniques for automating continuous measurement of soil water content based on the dielectric behaviour of soil and water are being used. The technologies used include time domain reflectometry (TDR), frequency domain reflectometry (FDR), and capacitance methods (Gardner *et al.* 1991). The theory behind the technique and reviews of capacitance methods have been presented, for example, by Dean *et al.* (1987), Paltineanu and Starr (1997), Lane and Mackenzie (2001), and Starr and Paltineanu (2002).

Although portable capacitance-type soil moisture meters had been proposed in early works (de Plater 1955), a unique portable and commercially available instrument that is based on the capacitive method to assess soil moisture now exists (‘Diviner’, Sentek Pty Ltd, Kent Town, S. Aust.).

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There is ample evidence from other studies that capacitance systems should be calibrated for individual soils (Baumhardt *et al.* 2000; Lane and Mackenzie 2001; Morgan *et al.* 2001). Laboratory calibrations offer the advantage of a controlled bulk density but do not take the soil structure into account, and are laborious and time-consuming. Field calibrations as proposed by the manufacturer of the capacitance probe used for this study are tedious or have been conducted on little-differentiated soils with probes that were embedded in the soil (Ould Mohamed *et al.* 1997). Our preliminary studies (data not shown) indicated that the moisture changes were measured reliably by the portable capacitance sensor, whereas the absolute θ_v values were unrealistic and did not agree with data from gravimetric soil sampling. Since the present study is part of broader research that requires a multitude of soil water monitoring sites, a practical *in situ* calibration approach was needed. Thus, the objectives of this study are (*i*) to investigate the suitability of a rapid and cheap soil sampling method for field calibration of portable capacitance probes even under highly variable soil texture conditions, and (*ii*) to investigate the effect of the application of data obtained on wet or dry soils on the accuracy and precision of the calibration in the field.

The instrument presented in this paper is based on a high-frequency (100–150 MHz) capacitance system, where the dielectric properties of a medium describe the response of that medium to an alternating electric field. Gaudu *et al.* (1993) reviewed reported relations between the dielectric constant ε and the volumetric soil water content (θ_v) obtained using capacitance methods in soils. Most were derived empirically, and Gaudu *et al.* (1993) summarised these as strictly linear, linear over a limited range of θ_v, and non-linear over a wide range of θ_v. Empirical calibrations are a practical means of representing the bulk dielectric properties of soil, which arise from complex and poorly characterised interactions between the dielectric properties of the soil components, that is, solid particles of different composition, shape, and size, air, and free and bound water. Bell *et al.* (1987) conducted field calibrations using a capacitive soil moisture probe in 4 different soils. They found that the relation between the capacitance probe readout and the water content is not linear and is influenced by the type of soil. A linear approximation, however, is adequate for the restricted ranges of water content experienced in practice in many soils. Evett and Steiner (1995), using a capacitance system of similar design to that of Bell *et al.* (1987), also opted for linear calibrations. Tomer and Anderson (1995), using the same type of equipment, found that a second-order polynomial gave the best calibration in fine sand soils.

For a system comparable to the one presented in this paper from the same manufacturer, but permanently installed (‘EnviroScan’, Sentek), a nonlinear relation [θ_v (m^3/m^3) = 0.490$SF^{2.1674}$] between the soil volumetric water content and the scaled frequency (*SF*) was found (Paltineanu and Starr 1997). The *SF* represents the ratio of an individual sensor’s frequency response in soil (F_s) compared with sensor responses in air (F_a) and in nonsaline water (F_w) at room temperature (≈22°C):

$$SF = (F_a - F_s)/(F_a - F_w) \qquad (1)$$

Morgan *et al.* (1999) found that the manufacturer's calibration for the aforementioned EnviroScan system underestimates many fine sand soils of Florida and provided a different calibration for this soil type [θ_v (m^3/m^3) = 0.4514$SF^{2.1211}$]. The manufacturer’s calibration of the capacitance system as presented is $SF = 0.2746\theta_v^{\ 0.3314}$ (mm) for each 10-cm soil depth increment or:

$$\theta_v\ (\mathrm{m}^3/\mathrm{m}^3) = 0.4940SF^{3.0175} \qquad (2)$$

Materials and methods

To identify different sites, a 5-ha field in South Germany was intensively texture-mapped by auger sampling down to 90 cm soil depth, and 2 sites with different soil texture were chosen. Table 1 shows the average particle size distribution at the 2 sites. Site A is a dominantly silt-loamy Cambisol on colluvial material, and site B is a loamy Cambisol, with a considerable fraction of coarse fragments >2 mm.

As part of a broader study, 2 N-fertiliser levels (120 and 180 kg/N.ha) and 3 water supply treatments (irrigated, rain-sheltered, control) were assigned to plots in a completely randomised design at each site. Thus, the total number of plots, with 3 replications, was 36.

All experiments reported here used the ‘Diviner’ hand-held capacitance probe (Sentek). Each unit comprises a data display connected by cable to a portable probe rod with one sensor attached. Because each sensor responds slightly differently to air and water, the sensors are normalised (Eqn 1). The sensor is normalised by placing the probe into a sealed tube and subsequently holding the probe in the air and in a 10-L water bucket and by entering the respective raw counts.

The portable capacitance probe measures soil moisture content at regular intervals of 10 cm down through the soil profile. Readings are taken through the wall of a PVC access tube. The data stored in the display can be retrieved into a personal computer by a software application supplied by the manufacturer. The retrieved data can be displayed as charts using the manufacturer's software. The data can also be restored into a spreadsheet as scaled frequency or as volumetric water content after automatic transformation using the default or a customised calibration equation. The default equation supplied by the manufacturer is based on combined data gathered from a variety of different soils.

The capacitance probe access tubes were installed in each of the 36 plots. The installation of the access tubes took place while the soil surface was still frozen in the early morning hours of March to minimise soil compression by the tractor. The PVC pipes with an attached inward-tapered metal cutting edge were driven into the soil using a tractor-mounted hydraulic hammering head. The soil was removed from within the tube by a screw auger supplied by the manufacturer. After installation, tubes were cleaned inside with a nylon brush and the subsurface end of the tube sealed with an expandable bung. The careful installation of the access tubes provided a snug fit to the soil.

Soil water content was measured weekly from end of March to end of July 2000. On 18 May, 12 June, 26 June, and 5 July, at the same time as capacitance probe measurements were taken, the soil was also

Table 1. Size distribution of soil particles (texture) at the two experimental sites
The classification of soil particles follows the German system (Finnern *et al.* 1996)

	Soil depth (cm)	>2 mm (% soil)	<2 mm	<63 µm (% of fine earth fraction)	<2 µm
Site A	0–30	4.7 ± 2.7	32.9 ± 8.1	46.8 ± 6.3	20.4 ± 2.6
	30–60	2.8 ± 2.0	32.7 ± 10.5	46.3 ± 7.9	20.9 ± 3.4
	60–90	0.8 ± 1.1	20.8 ± 7.6	53.0 ± 4.4	26.2 ± 5.9
Site B	0–30	24.2 ± 14.7	46.5 ± 9.4	37.2 ± 5.3	16.3 ± 4.8
	30–60	25.9 ± 22.8	47.6 ± 18.8	33.2 ± 13.4	19.2 ± 7.5
	60–90	16.3 ± 18.9	43.6 ± 23.9	34.6 ± 15.2	21.8 ± 11.0

core-sampled. Samples were obtained with an auger of 4 cm inner diameter in 2 depths per hole, from 0 to 30 cm and from 30 to 60 cm. The first 15 cm and the last 5 cm of each auger sample were disposed of, thus obtaining soil samples from 15 to 25 cm and from 45 to 55 cm soil depth, since the centre of measurement has a 5-cm axially symmetric zone of accurate influence (Paltineanu and Starr 1997). The core samples were taken at locations 50 cm from the capacitance probe access tubes and, therefore, outside the main radial sensitivity range of 10 cm from the wall of the access tubes (Paltineanu and Starr 1997). Core-sampling in the close vicinity of the access tube would, however, have made further capacitive probe measurements impossible, and since the purpose of the present study was to validate the usefulness of a simple field calibration method for practical purposes rather than to improve the manufacturer's calibration, our approach was considered as the lesser of 2 evils.

Two samples were taken per depth at opposite sides from the access tube and bulked, put into a plastic bag, and immediately placed into an ice box. Soil samples were weighed, dried in an oven at 105°C for 24 h, and reweighed. Bulk density was derived from data obtained from 3 soil profiles inside the trial field and 2 soil profiles in a neighbouring field. The bulk density at site A was approximately 1.51 Mg/m^3 at 20 cm soil depth, 1.55 Mg/m^3 at 50 cm soil depth, and 1.56 Mg/m^3 at 80 cm soil depth, and at site B 1.64 Mg/m^3, 1.68 Mg/m^3, and 1.68 Mg/m^3, respectively. A comparison with data of sites with similar textural composition in adjacent fields suggests a coefficient of variation of the bulk density at each depth of <8%.

The relationship between *SF* of the capacitance readings at 20 and 50 cm soil depth and the volumetric soil water content of the gravimetrically measured samples (θ_v) of the equivalent soil depth was based on the model used for factory calibration:

$$\theta_v\ (m^3/m^3) = a\ SF^b$$

The exponential regression was fitted to the model using the SAS NLIN procedure for nonlinear regression (SAS Institute Inc. 1989). Even though *SF* is actually the dependent variable in this calibration, it was treated as the independent variable because the application of the equation is to derive θ_v from *SF* values from sensor frequencies measured in the field. We also chose the exponential function rather than another mathematical relation because this function was previously used by others (Paltineanu and Starr 1997) working with the aforementioned permanently installed capacitance sensors.

Linear regression equations were developed relating soil moisture content obtained by the thermogravimetric method to instrument readings transformed into θ_v by different calibration equations. The coefficients of these equations were statistically compared to those of a one-to-one (1:1) line (slope = 1, intercept = 0) using tests of hypothesis with SAS (SAS Institute Inc. 1989).

Calibration equations were also developed on a reduced number of observations, i.e. the data of one water regime treatment, one single sampling day, or after dividing arbitrarily each site into 3 groups with an equal number of plots (group A1, A2, A3 for site A; B1, B2, B3 for site B) for each site. A further data reduction was obtained by using only the data of one single sampling day and one group for the development of a calibration equation.

Usually, the customised calibrations based on a reduced number of observations were tested on the entire dataset of the field or site. In a second approach, the validity of these calibration equations was also tested by applying these calibrations to all data but the data used for developing the calibration.

Results

Volumetric soil water content (θ_v) of all 282 samples collected ranged from 0.04 to 0.50 m^3/m^3 (Table 2). At 20 cm soil depth, θ_v at site A ranged from 0.04 to 0.48 m^3/m^3, at site B the range was from 0.04 to 0.27 m^3/m^3 and, on average, θ_v was 0.06 m^3/m^3 less than at site A. At 50 cm soil depth, θ_v ranged from 0.22 to 0.50 m^3/m^3 at site A and from 0.09 to 0.38 m^3/m^3 at site B and θ_v was, on average, 0.17 m^3/m^3 less than at site A. Due to the different water regime treatments the moisture range may be regarded as the range normally experienced in these soils. At field level, the coefficient of variation of θ_v at the 4 sampling days was 39–50% at 20 cm soil depth, and smaller, i.e. 35–38%, at 50 cm soil depth. Variability of θ_v at 20 cm soil depth was generally higher at site A than at site B, but at 50 cm the opposite was true. Table 3 shows the calibration equations as developed from the entire dataset or from subsets of this study and the calibrations provided by the manufacturer or proposed by different authors.

At the silt-loamy site A, the volumetric soil water contents (θ_v) estimated by the use of the default calibration were generally less than the soil moisture contents based on the thermogravimetric method (Fig. 1). This is not consistent with the findings of Hanson and Peters (2000), who showed that readings of the EnviroScan system were generally much greater than neutron moisture readings on a silt-loamy site when based on the manufacturer's calibration.

For the coarse-textured site (site B), the readings of the portable capacitance system underestimated soil water content until a scaled frequency of around 0.65 (which corresponds to θ_v = 0.13 m^3/m^3). At a scaled frequency of around 0.8 (0.25 m^3/m^3) or greater, however, the soil water content of the coarse-textured site of this study was overestimated by the default equation. This is in agreement

Table 2. Soil water content variability at two sites of one field

Mean, maximum (max), minimum (min), coefficient of variation (CV), and standard deviation (s.d.) of soil water content obtained by core sampling at a silt-loamy site (site A) and a loamy site with a large proportion of coarse fragments (site B) of one field. Treat., water supply treatment: c, control; i, irrigation; r, rain-shelter

Depth (cm)	Date	Treat.	*N*	Mean ± s.d.	Max. (m^3/m^3)	Min.	CV (%)
Sites A and B							
20 + 50			282	0.23 ± 0.12	0.50	0.04	53.90
20			140	0.16 ± 0.10	0.48	0.04	60.84
50			142	0.29 ± 0.11	0.50	0.09	37.64
20	18 May		35	0.21 ± 0.10	0.43	0.05	48.17
	12 June		36	0.24 ± 0.09	0.48	0.06	39.01
	26 June		34	0.11 ± 0.04	0.22	0.05	39.57
	5 July		35	0.09 ± 0.04	0.23	0.04	49.55
50	18 May		35	0.33 ± 0.12	0.50	0.12	35.87
	12 June		36	0.30 ± 0.11	0.47	0.09	37.54
	26 June		36	0.29 ± 0.10	0.47	0.12	34.12
	5 July		35	0.23 ± 0.08	0.41	0.09	35.28
Site A							
20			70	0.19 ± 0.12	0.48	0.04	61.79
		c	22	0.19 ± 0.11	0.35	0.04	58.60
		i	24	0.24 ± 0.14	0.48	0.04	56.67
		r	24	0.14 ± 0.08	0.39	0.05	55.84
50			70	0.37 ± 0.07	0.50	0.22	18.96
		c	22	0.38 ± 0.08	0.47	0.22	21.04
		i	24	0.39 ± 0.07	0.50	0.25	17.95
		r	24	0.35 ± 0.06	0.46	0.24	16.86
20	18 May		17	0.26 ± 0.11	0.43	0.05	43.84
	12 June		18	0.30 ± 0.09	0.48	0.16	30.42
	26 June		18	0.12 ± 0.05	0.22	0.05	40.62
	5 July		17	0.09 ± 0.05	0.23	0.04	56.18
50	18 May		17	0.43 ± 0.04	0.50	0.37	8.58
	12 June		18	0.40 ± 0.05	0.47	0.29	13.64
	26 June		18	0.37 ± 0.06	0.47	0.22	16.98
	5 July		17	0.30 ± 0.05	0.41	0.22	16.60
Site B							
20			70	0.13 ± 0.06	0.27	0.04	44.80
		c	24	0.12 ± 0.05	0.22	0.05	45.98
		i	23	0.15 ± 0.06	0.27	0.05	42.62
		r	23	0.12 ± 0.05	0.22	0.04	42.52
50			72	0.21 ± 0.07	0.38	0.09	31.92
		c	24	0.21 ± 0.06	0.30	0.11	27.07
		i	24	0.24 ± 0.07	0.38	0.09	31.70
		r	24	0.17 ± 0.05	0.27	0.09	27.34
20	18 May		18	0.16 ± 0.05	0.22	0.05	30.03
	12 June		18	0.18 ± 0.05	0.27	0.06	27.90
	26 June		16	0.10 ± 0.04	0.17	0.05	37.28
	5 July		18	0.08 ± 0.03	0.17	0.04	40.38
50	18 May		18	0.22 ± 0.06	0.31	0.12	27.27
	12 June		18	0.21 ± 0.08	0.38	0.09	36.28
	26 June		18	0.21 ± 0.06	0.30	0.12	27.65
	5 July		18	0.17 ± 0.06	0.30	0.09	32.35

Table 3. Calibration equations ($\theta_v = aSF^b$) supplied by the manufacturer (default) and by other studies compared with the calibrations of this study developed from various datasets obtained in one field

Date is sampling date; group, data subset within site or site and sampling date

Dataset or reference	a	b	N	R^2	RMSE	a	b	N	R^2	RMSE
			Field							
Default	0.4940	3.0175								
Paltineanu and Starr (1997)	0.4900	2.1674								
Morgan *et al*. (1999)	0.4514	2.1211								
Field	0.4619	2.3419	282	0.78	0.06					
			Site A					*Site B*		
Site A	0.5183	2.1367	140	0.93	0.04					
Site B						0.3311	1.9368	142	0.88	0.03
18 May	0.5330	2.0277	34	0.94	0.03	0.3267	1.8177	36	0.88	0.02
12 June	0.5212	1.9454	36	0.86	0.03	0.3577	2.0494	36	0.78	0.03
26 June	0.4992	2.1704	36	0.94	0.04	0.3224	1.8639	34	0.92	0.02
5 July	0.4475	1.9811	34	0.94	0.03	0.2972	1.8994	36	0.92	0.02
Group A1	0.5114	1.9857	48	0.91	0.04					
Group A2	0.5245	2.2526	44	0.93	0.04					
Group A3	0.5200	2.1897	48	0.94	0.03					
Group B1						0.3312	1.7913	48	0.88	0.03
Group B2						0.3215	1.7405	47	0.87	0.03
Group B3						0.3254	2.0964	47	0.87	0.02
18 May group A1	0.5238	1.8421	12	0.95	0.02					
18 May group A2	0.5362	2.0600	10	0.95	0.04					
18 May group A3	0.5370	2.1535	12	0.94	0.03					
18 May group B1						0.3219	1.4712	12	0.92	0.02
18 May group B2						0.3187	1.7289	12	0.90	0.02
18 May group B3						0.3301	2.0832	12	0.82	0.02
5 July group A1	0.4192	1.7750	12	0.95	0.02					
5 July group A2	0.4524	2.0454	10	0.95	0.03					
5 July group A3	0.4678	2.1130	12	0.93	0.03					
5 July group B1						0.2975	1.8792	12	0.92	0.02
5 July group B2						0.2926	1.7254	12	0.90	0.03
5 July group B3						0.2491	1.6979	12	0.82	0.02
Control plots	0.5158	2.2588	44	0.94	0.04	0.3232	1.8537	48	0.91	0.02
Irrigated plots	0.5264	2.0214	48	0.90	0.04	0.3476	1.8934	47	0.91	0.03
Sheltered plots	0.5039	2.0931	48	0.95	0.03	0.2907	1.7734	47	0.82	0.02

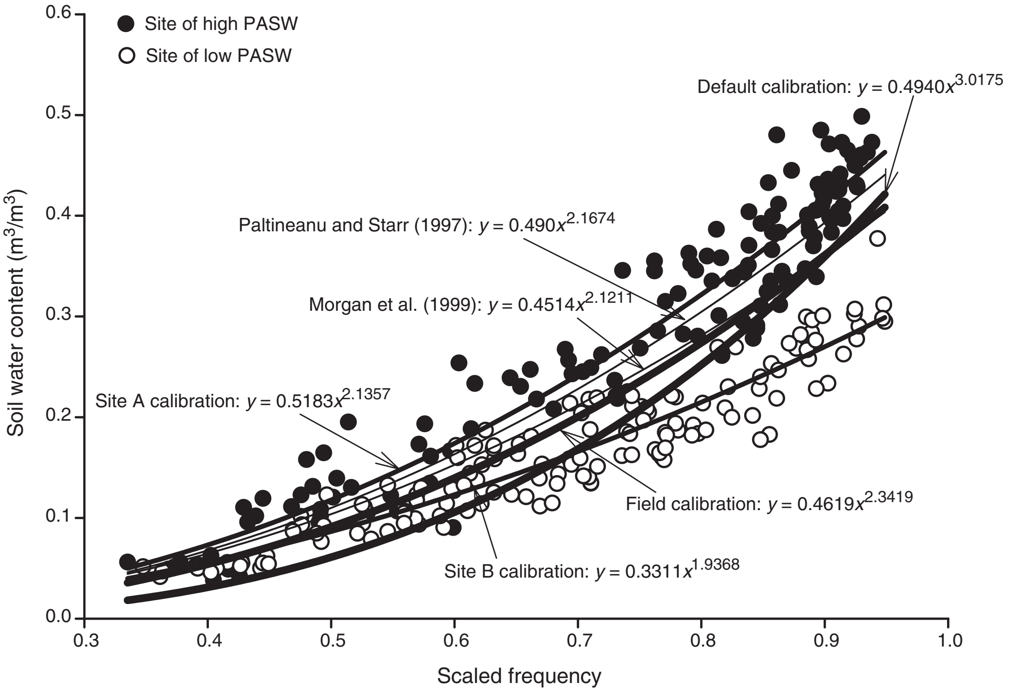

Fig. 1. Whole field and site-specific calibrations of Diviner capacitance probe compared with the calibrations supplied by the manufacturer and compared with the customised calibrations proposed by Paltineanu and Starr (1997), and by Morgan *et al.* (1999). PASW, plant available soil water.

with the findings of Morgan *et al.* (1999), who demonstrated that on some sandy soils of Florida soil water content is underestimated by the default calibration of the EnviroScan system, especially in the low soil water content range.

The calibration equation of this study developed from the combined data of both sites (field equation) provided a curve that compromised between the datasets of the 2 sites (Fig. 1). As a result, the soil water content of site A was constantly underestimated, while the θ_v of site B was constantly overestimated. Thus, soil water content estimated by this field calibration did not provide accurate values either, but its bias was more consistent.

Differences between estimated values from the default or the field equation and the estimations based on site-specific calibrations were substantial. At the dry range of site A and the wet range of site B, these differences exceeded 0.10 m^3/m^3.

When the estimated θ_v is linearly regressed on the gravimetrically obtained θ_v, both the field equation and the application of the site-specific equations for each site resulted in curves that did not significantly differ from the 1:1 line (Fig. 2*b*, *c*). The use of site-specific equations provided, however, a much smaller scatter and thus a smaller RMSE. The regression curve based on estimates using the default equation deviated significantly from the 1:1 line (Fig. 2*a*), mainly due to its poor performance at site B. At site A, the slope of the regression curve was not significantly different from unity, but it was shifted with an intercept significantly different from 0.

At the field level, the equations provided by Paltineanu and Starr (1997) and by Morgan *et al.* (1999), developed for the EnviroScan sensors, performed better than the default equations and performed more or less equally well as the field calibration of this study. At site A, the equation from Paltineanu and Starr (1997) appeared to be even more appropriate than the field equation of the present study. All 3 calibrations were, however, unacceptable for the sandy soil, even the calibration for sandy Florida soils of Morgan *et al.* (1999).

The site-specific calibrations of this study that were developed on a reduced number of observations, i.e. a subset of around 35 observations (group A1, A2, A3, B1, B2, B3), also performed satisfactorily (Table 4). It did not matter whether data stemmed from only one water regime treatment, one single day, or from a reduced number of plots per site. However, the data of 5 July from both sites, the data of 12 June from site B, and the data of the irrigated plots of site B produced slopes of the linear regression equations between capacitance probe reading and gravimetrically obtained soil water content that were statistically different from the 1:1 line.

A further reduction in the number of observations for the development of the calibration had varying results. The

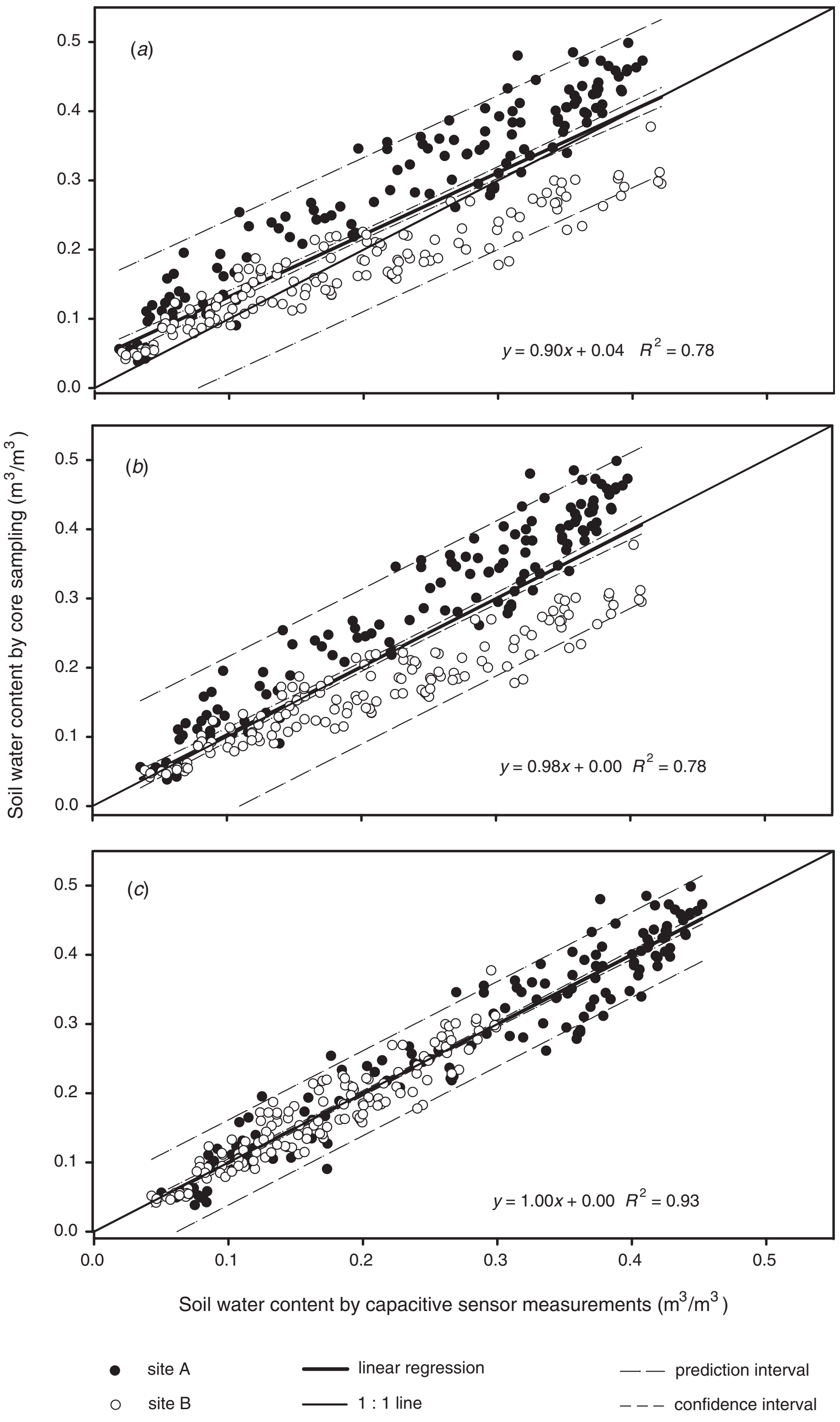

Fig. 2. Soil water content estimated by Diviner readings using (*a*) the default calibration, (*b*) a whole field calibration, and (*c*) site-specific calibrations plotted against soil water content obtained by core sampling.

Table 4. Linear regressions of soil water content derived from capacitive sensor readings based on different calibration equations on soil water content obtained by core sampling

RMSE, root mean square error; group, data subset within site or site and sampling date

Calibration equation	Field					Site A					Site B				
	Slope	Intercept	*N*	R^2	RMSE	Slope	Intercept	*N*	R^2	RMSE	Slope	Intercept	*N*	R^2	RMSE
Default	0.90	0.04	282	0.78	0.06	1.01^{B}	0.06	140	0.92	0.03	0.62	0.05	142	0.88	0.03
Paltineanu and Starr (1997)	0.94	-0.01^{A}	282	0.78	0.06	1.06	0.00^{A}	140	0.93	0.04	0.65	0.02	142	0.88	0.03
Morgan *et al*. (1999)	1.03^{B}	-0.01^{A}	282	0.78	0.06	1.15	0.00^{A}	140	0.93	0.04	0.71	0.01^{A}	142	0.88	0.03
Field	0.98^{B}	0.00^{A}	282	0.78	0.06	1.11	0.02	140	0.93	0.04	0.68	0.03	142	0.88	0.03
Site A	0.89	-0.01^{A}	282	0.78	0.06	1.00^{B}	0.00^{A}	140	0.93	0.04	0.62	0.01^{A}	142	0.88	0.03
Site B	1.43	-0.03	282	0.78	0.06	1.61	-0.02	140	0.93	0.04	1.00^{B}	0.00^{A}	142	0.88	0.03
Site A + B	1.00^{B}	0.00^{A}	282	0.93	0.03										
18 May						0.99^{B}	-0.01^{A}	140	0.93	0.04	1.03^{B}	-0.01^{A}	142	0.88	0.03
12 June						1.02^{B}	-0.02	140	0.93	0.04	0.91	0.01^{A}	142	0.88	0.03
26 June						1.04^{B}	0.00^{A}	140	0.93	0.04	1.03^{B}	0.00^{A}	142	0.88	0.03
5 July						1.18	-0.02	140	0.93	0.04	1.11	0.00^{A}	142	0.88	0.03
Group A1						1.04^{B}	-0.02	140	0.93	0.04					
Group A2						0.98^{B}	0.01^{A}	140	0.93	0.04					
Group A3						0.99^{B}	0.00^{A}	140	0.93	0.04					
Group B1											1.02^{B}	-0.01^{A}	142	0.88	0.03
Group B2											1.06^{B}	-0.02^{A}	142	0.88	0.03
Group B3											0.99^{B}	0.01^{A}	142	0.88	0.03
18 May group A1						1.03^{B}	-0.03	140	0.93	0.04					
18 May group A2						0.98^{B}	-0.01^{A}	140	0.93	0.04					
18 May group A3						0.97^{B}	0.00^{A}	140	0.93	0.04					
18 May group B1											1.13	-0.04	142	0.88	0.03
18 May group B2											1.07	-0.02	142	0.88	0.03
18 May group B3											0.98^{B}	0.01^{A}	142	0.88	0.03
5 July group A1						1.30	-0.04	140	0.93	0.04					
5 July group A2						1.16	-0.01^{A}	140	0.93	0.04					
5 July group A3						1.12	0.00^{A}	140	0.93	0.04					
5 July group B1											1.12	0.00^{A}	142	0.88	0.03
5 July group B2											1.17	-0.02	142	0.88	0.03
5 July group B3											1.38	-0.02	142	0.88	0.03
Control plots						1.00^{B}	0.00^{A}	140	0.93	0.04	1.03^{B}	-0.01^{A}	142	0.88	0.03
Irrigated plots						1.00^{B}	-0.01^{A}	140	0.93	0.04	1.16	-0.01^{A}	142	0.88	0.03
Sheltered plots						1.04^{B}	-0.01^{A}	140	0.93	0.04	0.95^{B}	-0.00^{A}	142	0.88	0.03

[A] Not significantly different from 0 at $P = 0.05$.

[B] Not significantly different from 1 at $P = 0.05$.

Table 5. Linear regressions of soil water content derived from capacitive sensor readings based on different calibration equations on soil water content obtained by core sampling

Data used to develop the calibrations are excepted. RMSE, root mean square error; group, data subset within site or site and sampling date

Calibration equation	Site A					Site B				
	Slope	Intercept	*N*	R^2	RMSE	Slope	Intercept	*N*	R^2	RMSE
18 May	0.96[B]	–0.01[A]	106	0.92	0.04	1.03[B]	–0.01[A]	106	0.87	0.03
12 June	1.01[B]	–0.02	104	0.93	0.04	0.88[B]	0.01	106	0.87	0.02
26 June	1.05[B]	0.00[A]	106	0.92	0.04	1.05[B]	–0.01[A]	108	0.86	0.03
5 July	1.20	–0.02	106	0.92	0.03	1.12	0.01	106	0.86	0.03
Group A1	1.04[B]	–0.02	100	0.93	0.04					
Group A2	0.97[B]	0.01[A]	104	0.93	0.03					
Group A3	0.99[B]	0.01[A]	100	0.92	0.04					
Group B1						1.00[B]	–0.01[A]	102	0.87	0.02
Group B2						1.08	–0.02	103	0.88	0.02
Group B3						0.96[B]	0.0233	103	0.87	0.03
18 May group A1	1.03[B]	–0.03	130	0.93	0.04					
18 May group A2	0.97[B]	0.00[A]	132	0.93	0.04					
18 May group A3	0.96[B]	0.00[A]	130	0.93	0.04					
18 May group B1						1.11	–0.05	132	0.87	0.03
18 May group B2						1.07	–0.02	132	0.87	0.02
18 May group B3						0.98[B]	0.01	132	0.87	0.03
5 July group A1	1.32	–0.04	130	0.93	0.04					
5 July group A2	1.16	–0.01	132	0.93	0.04					
5 July group A3	1.12	0.00	130	0.93	0.04					
5 July group B1						1.12	0.00[A]	132		0.03
5 July group B2						1.18	–0.02	132		0.03
5 July group B3						1.37	–0.02	132		0.03
Control plots	1.00[B]	0.01[A]	96	0.92	0.04	1.05[B]	–0.01[A]	94	0.86	0.03
Irrigated plots	0.99[B]	–0.01[A]	92	0.94	0.04	1.09	–0.01[A]	95	0.87	0.02
Sheltered plots	1.05[B]	–0.01[A]	92	0.91	0.04	0.97[B]	–0.00[A]	95	0.87	0.02

[A] Not significantly different from 0 at $P = 0.05$.
[B] Not significantly different from 1 at $P = 0.05$.

regression of estimated on gravimetrically obtained soil water content of the entire set of data of 18 May from site B, for example, provided a calibration that did not significantly differ from the 1:1 line. Two of the 3 calibrations developed on one of the subsets of the data of this day and site (18 May group B1, B2, or B3) each containing 10–12 observations, resulted in regression curves that deviated substantially from the 1:1 line.

When the validity of an equation was tested on all data except the data used to develop the equation, the quality of the customised calibrations was, except for group B2, comparable to the performance of the calibrations that included the data used for developing the calibrations (Table 5).

Discussion

The sphere of influence of the capacitance probe is small, with a main radial sensitivity range of 10 cm (Paltineanu and Starr 1997) from the access tubes. The core samples for the present study were intentionally taken outside this range because, otherwise, further probe measurements would have been impossible and the installation of access tubes is tedious. Thus, small-scale heterogeneity of soil texture and of soil moisture is a cardinal source of error. While profiles only 0.5 m apart may be quite similar in form, in detail there may be many differences. The use of data from core sampling obtained outside the sphere of main sensitivity, but still in vicinity of the access tube, for the calibration of the probes is, therefore, based on some assumptions. Firstly, it is assumed that the soil moisture content within a distance <50 cm is spatially dependent. The second assumption is that both the spatial discontinuity caused by short scale variability and sampling errors are random. Their impact on the customised calibration equation becomes less as the number of observations taken to develop the customised calibration increases. In the present study all calibration curves of the present study show scattering of points caused by sampling errors or as the result of short-scale variability. However, as the number of observations used to develop a calibration equation grows the influence exerted by outliers decreases.

In fact, the validity of the method of the present study seems to be limited by the number of observations used to develop the equation rather than by the soil moisture range covered by the dataset. A generally good performance of the equations could also be observed when developed on data subsets (Table 4) that did not cover the entire range of soil water content that can be potentially experienced at either site, i.e. only control plots, irrigated plots, or sheltered plots, and even when tested on data that were not used to develop the equation (Table 5). This is an interesting finding. It suggests that the usefulness of the presented method is not necessarily limited to conditions as provided by the field trial of the present paper where covering and irrigation created an artificially large range of soil water content data.

Bulk density (ρ_b) is an additional source of uncertainty as a factor affecting the dielectric constant ε (Perdok *et al.* 1996; Gardner *et al.* 1998) but above all because it governs the relation between mass wetness (θ_m) and θ_v. In this study, ρ_b had been derived from a limited number of soil profiles inside the trial field and in neighbouring fields, and it was assumed to be the same for a given plot and at a given soil depth if the soil texture was similar to the soil texture of the soil profile at this depth. This assumption is, however, not necessarily true for all sampling points, especially in heterogeneous fields. For example, at the coarse-textured site at 60 cm soil depth, the standard deviation of ρ_b was estimated to be 0.17 Mg/m^3. At θ_v = 0.3 m^3/m^3 this standard deviation corresponds to ±0.05 m^3/m^3 of volumetric water content or a potential range of 0.10 m^3/m^3.

Since we had some difficulty installing PVC tubes at the coarse-structured site, one might conjecture that the scaled frequency values from the sandy site were more variable due to possible soil disturbance and air gaps between the tube and soil that would introduce large errors. However, the RMSE was generally smaller at site B than at site A. This might be explained by flatter calibration curves for coarse-textured soils and thus, a smaller impact of erroneous frequency measurement on the resulting θ_v value.

The present study was conducted on the portable Diviner system and results were compared with findings from the EnviroScan system. Admittedly, results from EnviroScan system measurements and Diviner measurements do not necessarily have to be the same. In our preliminary studies (data not shown), EnviroScan measurements and Diviner measurements that were taken within 10 min at the same depths in the same access tubes installed on various soils were compared. A linear relationship between the θ_v measurement of the EnviroScan (θ_{ES}) and the θ_v of the Diviner (θ_D) was found:

$$\theta_{ES}\ (\mathrm{m^3/m^3}) = 0.89\ \theta_D\ (\mathrm{m^3/m^3}) + 2.27 \quad R^2 = 0.88, N = 260$$

However, the 2 systems apply an identical method, with comparable installation procedure, and both systems are provided from the same manufacturer, and on the other hand, since little published work exists on the portable capacitance systems presented here, a comparison of both systems may to a certain extent be justified.

Conclusion

The usefulness of capacitance sensors is affected by an unsuitable calibration. In this study, the use for practical water monitoring purposes in the field of the calibration supplied by the manufacturer and the calibration proposed by Paltineanu and Starr (1997) gave satisfactory results on a fine-textured site in a heterogeneous field. On a coarse-textured site, these 2 calibrations, and also the calibration suggested by Morgan *et al.* (1999) for sandy Florida soils, gave unacceptable results. The calibration developed for this study on the pooled data of both sites strongly underestimated the soil water content of the fine-textured site, and strongly overestimated the soil water content of the coarse-textured soil, although on the field level, it performed better than the manufacturer's calibration and the calibration proposed by Paltineanu and Starr (1997). This underscores the importance of site-specific calibrations in heterogeneous fields.

This study shows a speedy and cheap method to calibrate capacitance probe sensors. Despite concerns about different zones of influence and the impact of small-scale changes in soil water content, especially in heterogeneous soils, the results demonstrate that the presented calibration method provides reasonable calibration equations for portable capacitance sensors in heterogeneous fields if a large number of monitoring sites are needed. The method requires knowledge of the bulk density, and in this study, at least 35 observations per site were needed to develop an accurate calibration.

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