Calibration and study of physical-hydric relations of an Oxisol using a frequency domain reflectometry probe

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Abstract: The FDR Diviner 2000® probe is widely used to monitor soil moisture and to study physical-hidric relationships. The calibration equation provided by the manufacturer may not correctly reproduce the actual moisture value for the same type of soil with different bulk densities. In addition, it was postulated in this experiment that the capacitance probe can be used to determine the soil water tension and the initial soil water retention curve. Thus, the objectives were: to assess whether the calibration equation parameters of the Frequency Domain Reflectometry (FDR) probe changes with the bulk density variation; estimate the soil water tension using the FDR probe; and verify the effect of the probe calibration in determining the initial soil water retention curve for the Red Oxisol at three bulk density levels (1.2, 1.4 and 1.6 Mg m^{-3}). The results showed that for the Red Oxisol the calibration equations of the Diviner 2000® probe changes according to bulk density variation, with a greater difference occurring in the 1.4 Mg m^{-3} bulk density, whose measurement error using the default equation can be up to 0.17 m^3 m^{-3}. In addition, the FDR probe can be used to estimate the soil water tension, if the soil is less than 1.4 Mg m^{-3} bulk density. Finally, the use of the capacitance probe to determine the initial water retention curve can only be performed by prior calibration of the equipment specifically for the desired bulk density.

Keywords: soil physics; soil moisture; soil compaction; instrumentation.

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1 Introduction

Determination of soil moisture is a routine practice in studies of soil science, irrigation, or for water management purposes. Its determination can be made quickly and accurately using the sensors currently available on the market. Among the sensors, perhaps the most widespread, are Frequency Domain Reflectometry probes, such as Diviner 2000®, which is a capacitance probe used for practical and scientific purposes. This equipment has the advantage of estimating the moisture along the soil profile in a few seconds, simply by installing an access tube to the desired depth. The sensor is of the capacitive type, and uses the soil dielectric constant as a basis for determining moisture. The sensor has two rings at its end that form a capacitor. The capacitor together with an oscillator forms a circuit that generates an oscillatory field to propagate through the soil through the access tube (Provenzano et al., 2016). The sensor measures the resonant frequency, which will vary depending on the amount of water in the soil around the access pipe.

The conversion of the frequency to a volumetric moisture value is done by a calibration equation, usually of the power type. The equipment manufacturer provides

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a default calibration equation inserted in its measurement system, however, its use for different soils is still a controversial topic. In some cases, research has shown that the standard equation can be used precisely (Araújo Primo et al., 2015). In other situations, it has been demonstrated that it is necessary to use a specific equation for the analyzed soil (Andrade Junior et al., 2007; Haberland et al., 2014), including following the textural variation of the soil profile (Haberland et al., 2014). What has not yet been verified is whether, for the same soil class, the response of the capacitance probe varies with compaction, represented by the soil bulk density.

In Brazil, specifically in the region of the cerrado of Mato Grosso, the Oxisol class occupies the largest territorial area (about 46%). These soils generally have a bulk density of 1.20 to 1.30 Mg m^{-3} in their natural condition. When cultivated, the surface layer is constantly tilled by mechanized management, but in a subsurface, where there is no-tillage, sometimes a compacted region is formed, where the bulk density can reach values greater than 1.40 Mg m^{-3}. This variation in the soil bulk density along the profile alters the physical-hydric properties of the soil. More compacted soils have less total porosity, the volumes of macropores are reduced substantially, becoming micropores. Consequently, the water retention curve also changes. It is to be expected, therefore, that the calibration equation of the capacitance probe will also change with the variation in bulk density.

The capacitance probe can also be used to monitor soil moisture for irrigation management in the field, in a greenhouse, or for scientific research that requires monitoring the moisture profile, such as in determining the soil hydraulic conductivity. In such cases, it is sometimes necessary to analyze the moisture value and the soil water potential value. However, when using indirect soil moisture measurement equipment, the soil water potential can be obtained by empirical equations, through its relationship with moisture (Araújo Primo et al., 2015). This work also sought to evaluate the correlation between the soil water tension and the relative frequency obtained by the Diviner 2000® probe, as a way to indirectly determine the water potential. In addition, we tried to evaluate the initial soil water retention curve using this same sensor, for a condition of the soil with different bulk densities. The retention curve is extremely useful and necessary in studies that involve water management in irrigated crops.

From the above, the objectives in this work were: I) to verify if the default calibration of the Diviner 2000® capacitance probe can be used to determine the volumetric moisture in Red Oxisol with different soil bulk density; II) check the relationship between the soil water tension and the relative frequency obtained with the Diviner 2000® probe; and III) and verify the effect of the Diviner 2000® probe calibration in determining the initial soil water retention curve with variation in soil bulk density.

2 Material and methods

The experiment was carried out at the Federal University of Mato Grosso, Rondonópolis campus (Latitude: 16.46ºS; Longitude: 54.58ºW; Altitude: 290 m), between August and October 2019. The experimental units consisted of buckets of Polypropylene approximately 0.303 m in diameter and 0.369 m in total height. The soil in each unit was inserted up to a height of 0.30 m. The treatments were three levels of soil bulk density: 1.2; 1.4 and 1.6 Mg m^{-3} (Megagram por cubic meter) with three replications, totaling nine experimental units.

The soil used was the Red Oxisol, collected in the 0.0 - 0.20 m deep layer and later sieved in 3.0 mm mesh. The soil has 40% sand, 40% clay and 20% silt, whose textural class is Clay-Loam (USDA). The physical properties of the soil used in the experiment are listed in Table 1. The average soil moisture (determined by the gravimetric method) was θ_m = 7%. To establish the desired bulk densities, the dry soil mass required for each soil bulk density level was calculated based on the Equation 1:

$$\rho_d = \frac{W_d}{V} \quad (1)$$

in which:

ρ_d = soil bulk density (Mg m^{-3});

W_d = is soil dry mass (Mg);

V = is total soil volume (m^3).

The values were corrected to compensate for the moisture that the soil had. To facilitate the compaction process, the soil of the highest density treatment (1.6 Mg m^{-3}) was moistened for better accommodation in the buckets. For the other treatments, moistening was not necessary.

Table 1 Physical properties of the soil used in the experiment

Soil depth, m	Sand, %	Silt, Mg m^{-3}	Clay, mm d^{-1}	Bulk density	Particle density	Saturated hydraulic conductivity
0 – 0.20	40	20	40	1.22	2.59	600

For each treatment, the soil compaction process was carried out in layers, each 1/3 of the height of the buckets, using a disk with a diameter similar to that of the bucket, and over it weights to compress the soil. After adding all the soil to the bucket, an access tube was inserted in the center of the bucket with the aid of an auger. The total volume of soil considered was 17800 cm³, which corresponds to the volume of the bucket minus the volume occupied by the access tube.

To assess the soil water tension, a tensiometer was installed in each experimental unit, whose capsule was positioned 10 cm deep in relation to the soil surface. Subsequently, the soil was saturated for a period of three consecutive days, after which the measurements began. Figure 1 shows the general view of the experiment.

Frequency measurements with the Diviner 2000® probe took place at three depths along the tube, 10 cm apart, and the final value used was the average of the three measurements. The measured frequency (raw counts) was converted into a relative frequency as described in the equipment manual (Sentek, 2000):

$$RF = \frac{Fa - Fs}{Fa - Fw} \qquad (2)$$

where, RF = relative frequency;

F_a = frequency reading on a Polyvinyl chloride tube (PVC) fully suspended in the air (179428 counts);

F_s = frequency reading in PVC pipe in the soil;

F_w = frequency reading in sealed PVC tube immersed in water (128625 counts).

After measuring the frequency, the soil + bucket set was weighed using a portable digital scale, accurate to 5 g (Figure 2). With the current mass of the soil and the mass of dry soil contained in each treatment, the soil moisture was calculated. This methodology is similar to that described by Haberland et al. (2014). Finally, the soil water tension is also measured using a digital densitometer. All measurements were made daily.

Figure 1 Experiment overview, showing the buckets with the access tubes and tensiometers installed.

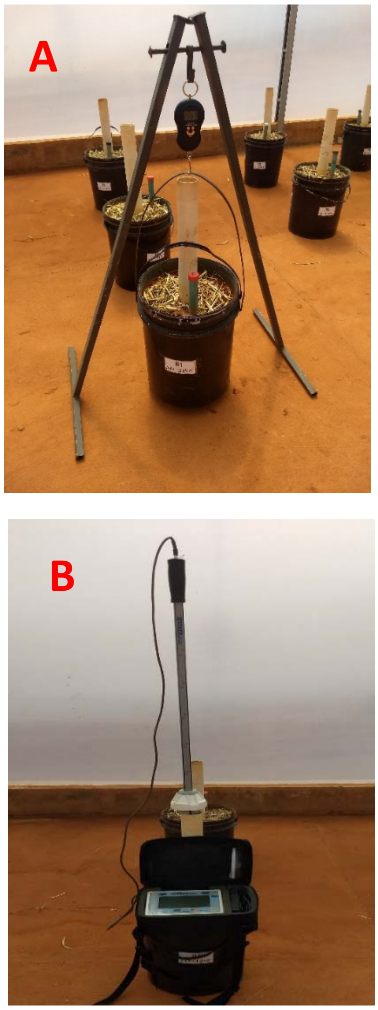

Figure 2 Weighing of experimental units - using digital scale and metal support (A; Relative frequency measurement using the Diviner 2000® capacitance probe (B).

To obtain the calibration equations, soil moisture obtained by weighing was related to the relative frequency, with subsequent adjustment of the potential model ($\theta v = ax^b$) to the data. The same procedure was adopted to obtain the relationships between soil tension and relative frequency to generate the initial water retention curve.

The difference between the volumetric soil moisture obtained with the default equation provided by the manufacturer and the adjusted equation for the different bulk densities, were compared by the paired t test, at the level of 5% probability.

For each level of soil bulk density, the Root Mean Square Error (*RMSE*) was calculated between the two methods of measuring soil moisture, according to the equation:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=0}^{n}(\theta - \theta_p)^2} \quad (3)$$

Whereθ is the soil moisture (m^3 m^{-3}) measured by weighing and θp represents the soil moisture (m^3 m^{-3}) measured by the Diviner 2000® probe.

3 Results and discussion

Figure 3 shows the relationship between volumetric moisture measured by weighing and the relative frequency obtained with the Diviner 2000® probe, for different bulk densities. In addition, the default calibration equation provided by the manufacturer and the custom equations for each bulk density level are described in Table 2. In all three bulk density levels, the moisture values obtained by weighing and by the capacitance probe, were statistically different from each other (Table 3).

Initially, at the density of 1.2 Mg m^{-3}, which represents a non-compacted soil, the general tendency was to underestimate the volumetric moisture using the default equation provided by the manufacturer. The average difference between the two methods was 0.08 m^3 m^{-3} or 8% over the entire measurement range. For the other two levels of bulk density, the largest discrepancies occurred in the density of 1.4 Mg m^{-3}, whose average difference between the forms of measurement was 0.13 m^3 m^{-3}. The bulk density of 1.6 Mg m^{-3} was the one with the lowest measurement error, with an average difference of 0.02 m^3 m^{-3} (Table 3).

It is also important to note that the discrepancies between the measurement methods are more evident as the soil moisture increases, as can be seen from Table 3. The difference between the maximum values reaches 0.16 m^3 m^{-3} for bulk density of 1.4 Mg m^{-3}. For this same density, the minimum values measured by the two methods differed by 0.12 m^3 m^{-3}.

The discrepancies between the moisture measurement methods for the different bulk densities can also be seen in Figure 4. Note the difference between the regression line adjusted to the data obtained with the default calibration equation for the three soil density levels and the straight line 1: 1. Again, the discrepancy is greater for the bulk density of 1.4 Mg m^{-3} and less for 1.6 Mg m^{-3}. It is also possible to observe the approximation of the data to the 1: 1 line using the custom calibration equation.

The discrepancies observed previously would imply major errors in determining moisture in scientific experiments that require this physical soil variable. As an example, in Figure 5 is the soil moisture measured in the field with the Diviner 2000® probe, using the default calibration equation and the custom equation. This measurement was carried out in an experiment to determine the field capacity in the same place where soil was collected for calibration of the capacitance probe. Thus, the value of the field capacity determined with the default equation would be 0.07 m^3 m^{-3} less than the actual value measured by gravimetry, resulting in calculations and misinterpretations about water processes in the soil.

Parvin and Degré (2016) evaluated in the laboratory the soil moisture FDR sensors models 10HS and 5TM (Decagon Devices), in a Luvisol with an induced bulk density of 1.35 to 1.50 Mg m^{-3}. These authors found that with the increase in the soil bulk density, the raw signal (ie, the response generated by the sensors) generated by the sensors increased linearly, even though the soil was in the same moisture. This would result in an overestimation of soil moisture with the evaluated sensors. Parsons and Bandaranayake (2009) found the same tendency to increase the sensor signal with increased bulk density (ranging from 1.1 to 1.6 Mg m^{-3}), using FDR ECH2O EC-5 sensors (Decagon Devices), resulting in errors in determining soil moisture. For the Diviner 2000® capacitance probe, there are no reports yet on the influence of bulk density on the equipment's calibration equation.

According to some authors (Gupta and Jangid, 2012; Parvin and Degré, 2016) the dielectric properties of the soil vary with bulk density, clay content and salinity. The basic principle of operation of capacitive sensors is the incorporation of soil as part of the capacitor and the variation of the dielectric constant of the soil-water-air mixture is used to estimate soil moisture. This would explain why the response of the sensors can vary depending on the condition of the soil.

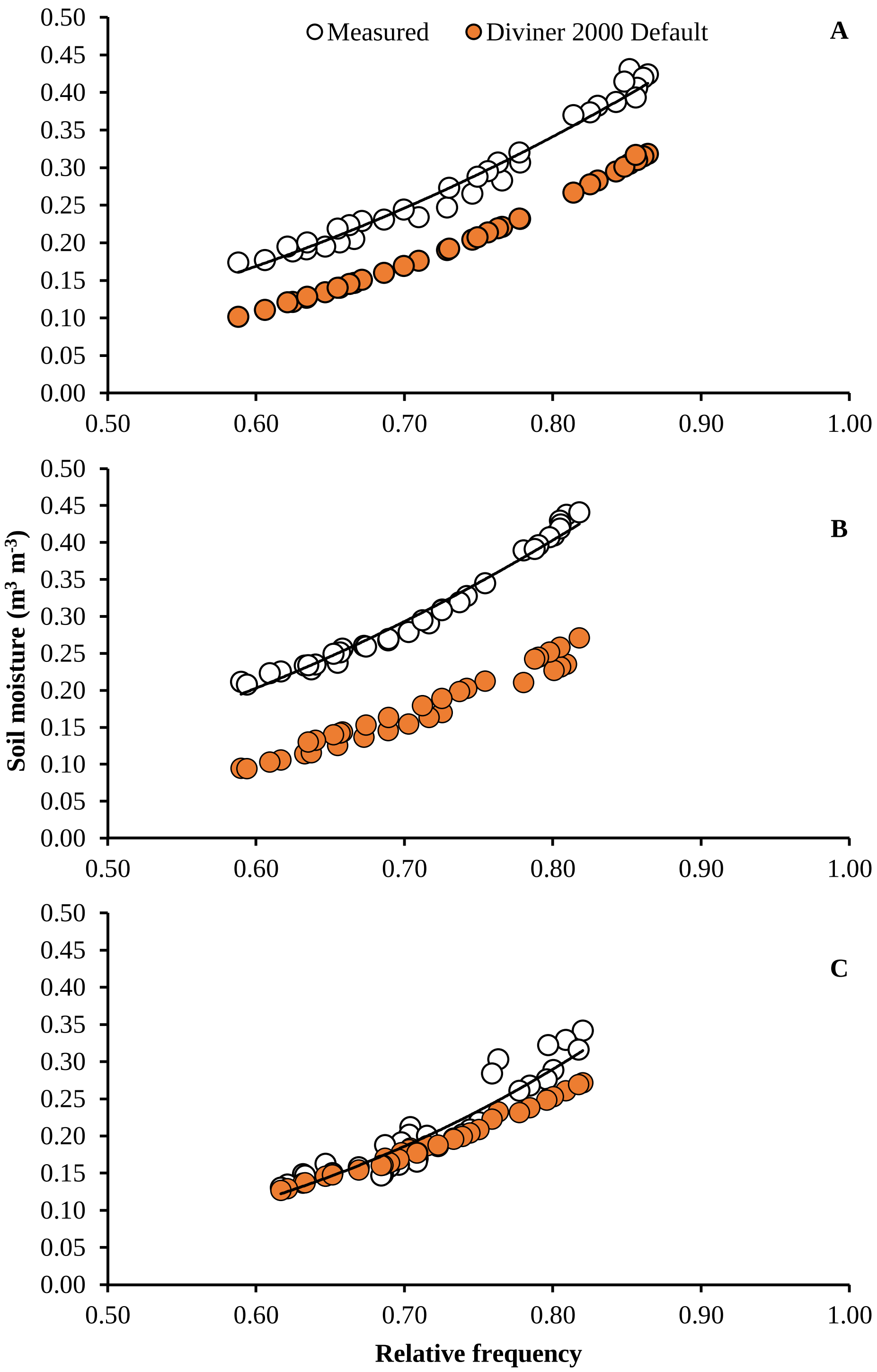

Figure 3 Relationship between soil moisture (m^3 m^{-3}) measured by weighing and the relative frequency obtained with a Diviner 2000® capacitance probe in an Oxisol with a bulk density of 1.2 (A), 1.4 (B) and 1.6 Mg m^{-3} (C).

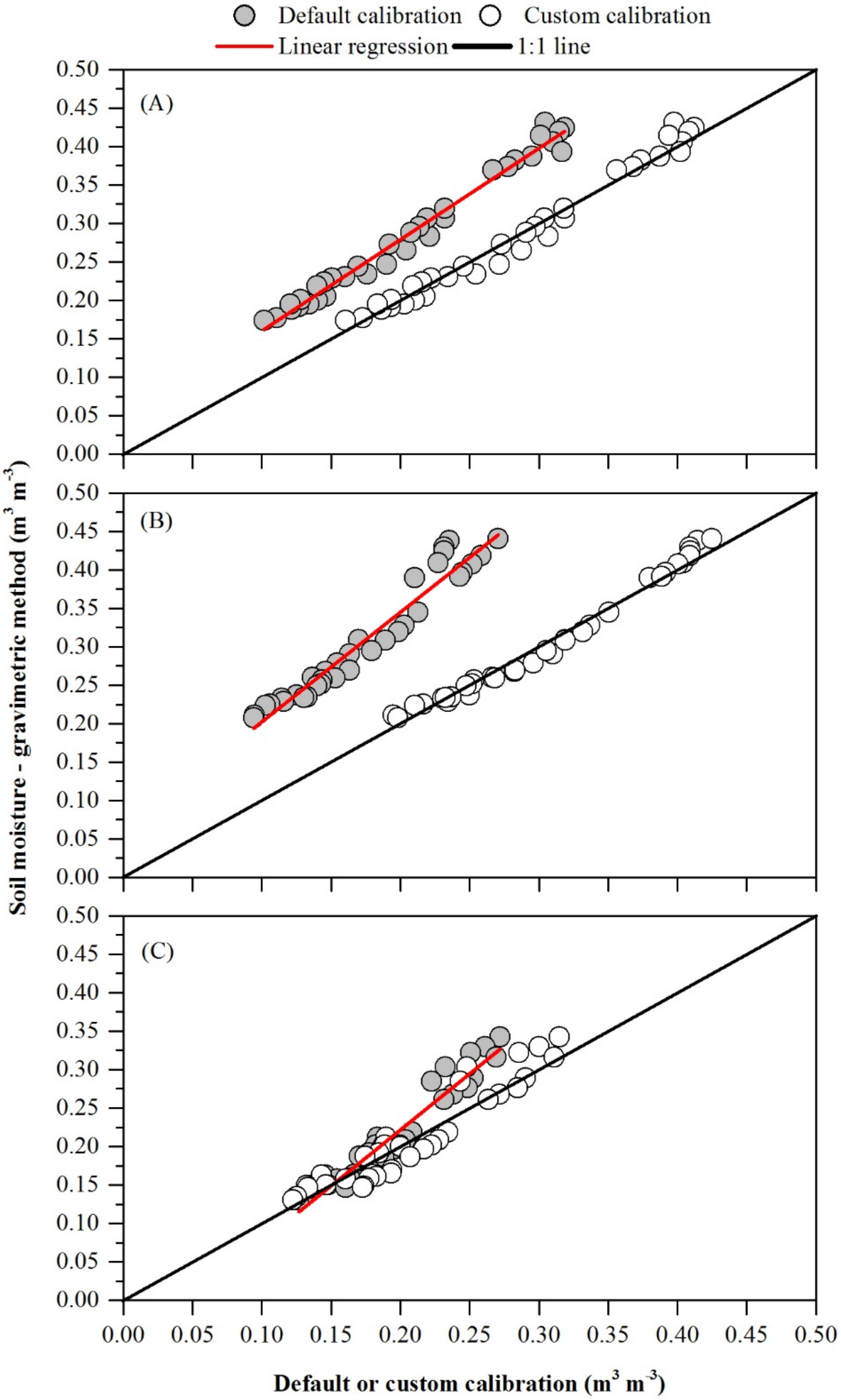

Figure 4 Regression between the soil moisture obtained by weighing and obtained with the capacitance probe using the default calibration, for the Oxisol with bulk densities of 1.2 (A), 1.4 (B), and 1.6 (C) Mg m^{-3}

Table 2 Calibration equation of the Diviner 2000® capacitance probe as a function of soil bulk density, with respective coefficients of determination (R^2) and RSME

Soil bulk density (Mg m^{-3})	Custom calibration	R^2	RSME	Default calibration
1.2	$v = 0.5890RF^{2.4467}$	0.9764	0.08	
1.4	$v = 0.6862RF^{2.3851}$	0.9758	0.14	$v = 0.494RF^{3.0175}$
1.6	$v = 0.6072RF^{3.3165}$	0.8766	0.03	

Table 3 Maximum, minimum and average values of soil moisture ($m^3 m^{-3}$) obtained by the gravimetric method and with the Diviner 2000® probe for different soil bulk densities

Soil bulk density ($Mg m^{-3}$)	v gravimetric ($m^3 m^{-3}$)			v Diviner 2000 ($m^3 m^{-3}$)		
	Máximum	Minimum	Average	Máximum	Minimum	Average
1.2	0.43	0.17	0.29a	0.32	0.10	0.21b
1.4	0.44	0.21	0.31a	0.27	0.09	0.17b
1.6	0.34	0.13	0.21a	0.27	0.13	0.19b

Note: Averages followed by the same letter on the line do not differ statistically from each other by the paired t-test at 5% probability.

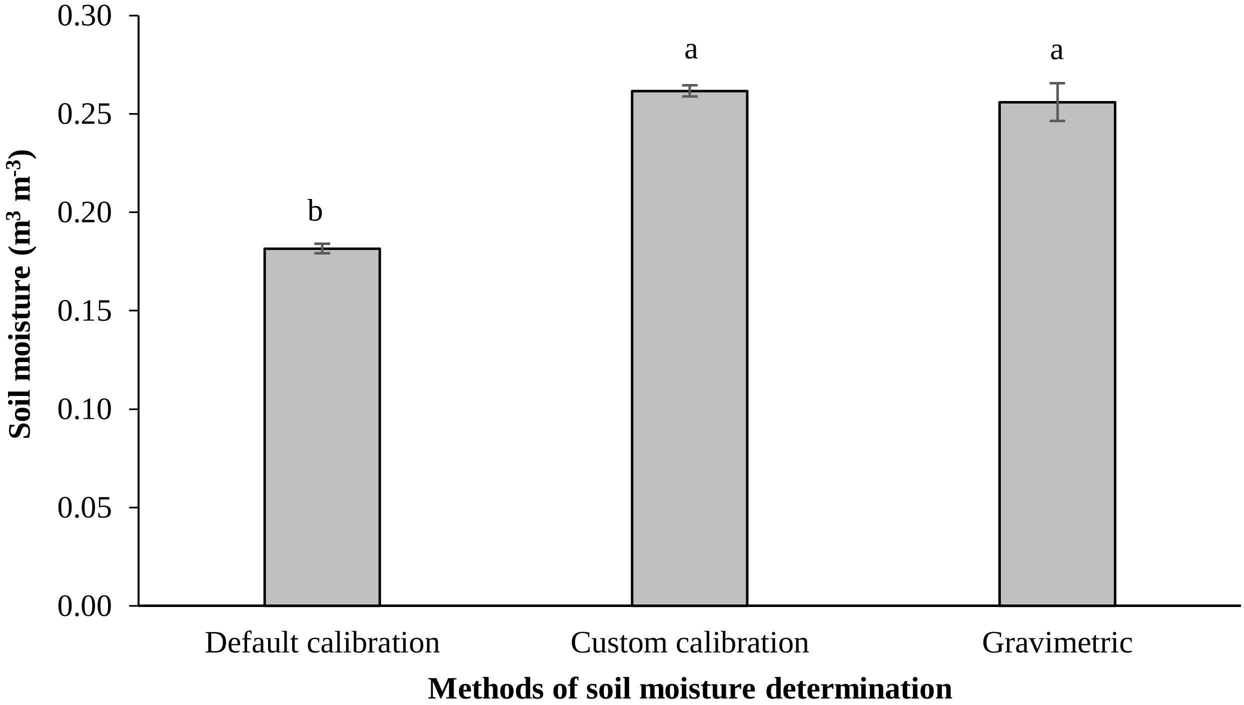

Figure 5 Soil moisture measured in the field with the Diviner 2000® capacitance probe using the default calibration equation and the custom calibration equation

Note: Measurement performed to determine field capacity. Soil bulk density: 1.20 $Mg m^{-3}$. Bars indicate standard deviation. Means compared with reference (Gravimetric) by paired t-test (p<0.05).

The relationship between the soil water tension and the relative frequency obtained a high adjustment for the densities of 1.2 and 1.4 $Mg m^{-3}$. The bulk density of 1.6 was the one that obtained the greatest measurement variation and did not obtain a significant equation (Figure 6). As in the previous case, each level of soil bulk density obtained an independent response. The greatest amplitude of variation of the relative frequency occurred in the initial density of 1.2 $Mg m^{-3}$ with values of 0.59 to 0.88, followed by the bulk density of 1.4 (0.61 to 0.84) and 1, 6 $Mg m^{-3}$ (0.68 to 0.82). This smaller variation for the density of 1.6 $Mg m^{-3}$, would help to explain the biggest measurement errors obtained at this level of compaction (Figure 6C).

The equations obtained with these relationships can facilitate data acquisition in studies that require measurements of soil water tension along soil depth and time, as in the case of determining the hydraulic conductivity by the instantaneous profile method (Almeida et al., 2018). In the literature, there is only the work of Almeida et al. (2018) who used self-made capacitive sensors (rectangular shape, 15 cm long) to evaluate the possibility of using these sensors to replace tensiometers in the instantaneous profile method. These authors concluded by the advantage of using sensors to replace the tensiometer, making the method less laborious.

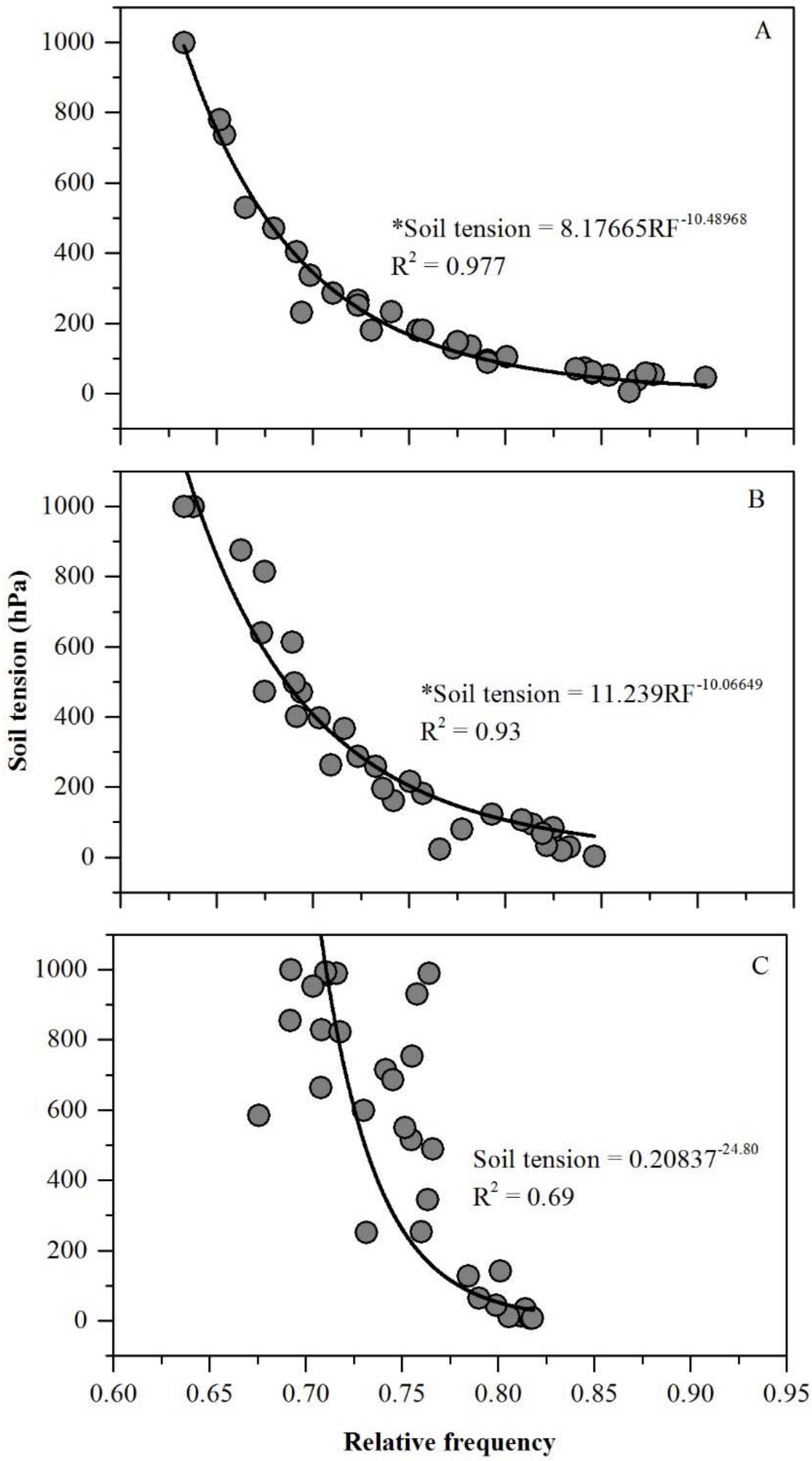

Figure 6 Relationship between soil water tension (hPa) and relative frequency in an Oxisol with bulk density of 1.2 (A), 1.4 (B) and 1.6 Mg m^{-3} (C). * significant at% 5 probability.

Regarding soil water retention, the difference in results is observed when moisture was obtained by gravimetry and when it was obtained using the Diviner 2000® probe with the default calibration equation and with the custom equations (Figure 7). The custom equations for each soil bulk density are described in Table 4. The differences between the retention curves are smaller for the bulk density of 1.6 Mg m^{-3}. At this level of compaction, the smallest variations in moisture occurred throughout the experiment (between 0.34 to 0.15), as shown in Figure 7C. This tendency is natural in compacted soils, due to changes in the distribution of pores, substantially reducing macropores, with an increase in micropores.

With the previously adjusted equations (Table 4), the estimated field capacity value at 330 hPa was calculated, whose results are shown in Table 5. Considering the default calibration equation, the differences in relation to the gravimetric method were 0. 06 and 0.10 $m^3 m^{-3}$ for bulk densities of 1.2 and 1.4 Mg m^{-3}, respectively. However, for the bulk density of 1.6 Mg m^{-3}, the values were numerically equal. Using the custom calibration equations, the differences were 0.01, 0.02 and 0.03 $m^3 m^{-3}$, for the bulk densities of 1.2, 1.4 and 1.6 Mg m^{-3}, respectively.

Retention curves are extremely useful for irrigation management, whether in experiments (Nunes et al., 2016) or in field conditions. As demonstrated previously, for the Red Oxisol, they must be used specifically for each level of soil bulk density. The presented equations, although specific to the Red Oxisol, can be very useful in studies relating the effect of soil compaction. As an example, Nunes et al. (2016) evaluated the effect of compaction and soil water on corn root development. For that, it was necessary to use different water retention equations for each bulk density level (ranging from 1.0 to 1.8 Mg m^{-3}).

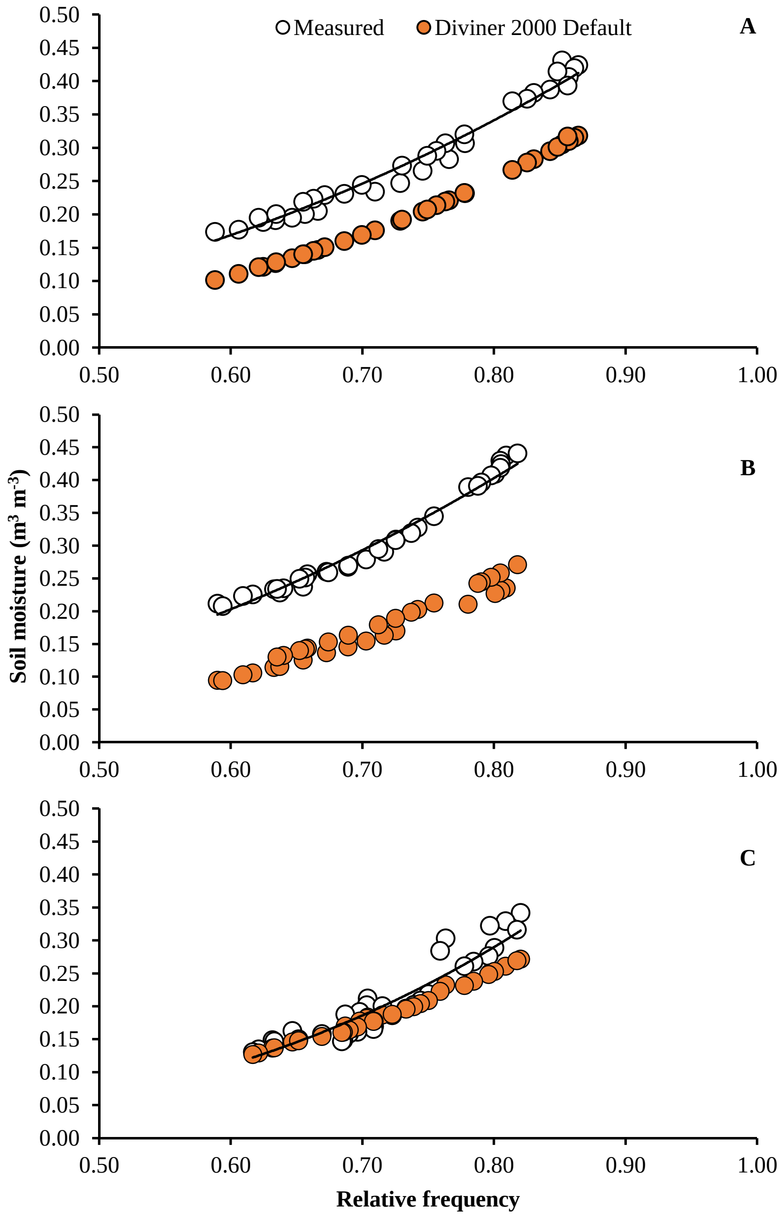

Figure 7 Relationship between soil moisture ($m^3 m^{-3}$) measured by weighing and soil water tension (hPa) in an Oxisol with bulk density of 1.2 (A), 1.4 (B) and 1.6 Mg m^{-3} (C).

Table 4 Equation parameters ($\theta v = ax^b$) of the initial water retention curve in Red Oxisol with bulk density of 1.2, 1.4 and 1.6 Mg m^{-3} obtained by different methods

Soil bulk density, Mg m^{-3}	Method	Parameters		R^2	RMSE
		a	b		
1.2	Gravimetric	0.943	-0.247	0.902	-
	Default calibration	0.775	-0.265	0.890	0.072
	Custom calibration	0.849	-0.215	0.890	0.0177
1.4	Gravimetric	0.781	-0.186	0.819	-
	Default calibration	0.568	-0.210	0.786	0.110
	Custom calibration	0.766	-0.166	0.786	0.026
1.6	Gravimetric	0.473	-0.152	0.798	-
	Default calibration	0.334	-0.085	0.669	0.029
	Custom calibration	0.395	-0.093	0.699	0.034

Note: Equation parameters significant at 5% probability.

Table 5 Soil moisture values (m^3 m^{-3}) in field capacity determined by custom equations for the Red Oxisol with bulk density of 1.2, 1.4 and 1.6 Mg m^{-3}

Soil bulk density (Mg m^{-3})	Soil tension hPa	Default calibration m^3 m^{-3}	Custom calibration m^3 m^{-3}	Gravimetric method m^3 m^{-3}
1.2	330	0.17	0.24	0.23
1.4	330	0.17	0.29	0.27
1.6	330	0.20	0.23	0.20

4 Conclusions

For the Oxisol (40% clay; 40% sand; 20% silt), the calibration equation of the Diviner 2000® capacitance probe changes with the change in soil bulk density. On average, the default calibration equation underestimates soil moisture by 28%, 44% and 9% for the bulk densities of 1.2, 1.4 and 1.6 Mg m^{-3}, respectively. The capacitance probe can be used to estimate the soil water tension, if the soil has a bulk density between 1.2 and 1.4 Mg m^{-3}. Finally, the use of the probe to determine the initial water retention curve, can only be carried out by prior calibration of the equipment specifically for the desired bulk density level.

Thus, in general, the FDR probe calibration is done considering only the soil class, without taking into account its physical condition, represented by the bulk density. We recommend that probe calibration also consider soil bulk density, otherwise the study of physical-hydric relationships will be subject to large measurement errors.

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References

Almeida, E. L., A. S. Teixeira, O. C. Rocha Neto, R. A. Oliveira Leão, and F. J. F. Canafístula. 2018. Use of capacitive sensors with the instantaneous profile method to determine hydraulic conductivity. *Revista Ciência Agronômica*, 49(2): 353-362.

Andrade Junior, A. S., C. R. Da Silva, and R. Daniel. 2007. Calibração de um sensor capacitivo de umidade em Latossolo Amarelo na microrregião do Litoral Piauiense. *Revista Brasileira de Ciências Agrárias*, 2(4): 303-307.

Araújo Primo, J. T., T. G. F. Silva, S. M. S. Silva, M. S. B. Moura, and L. S. B Souza. 2015. Calibração de sondas capacitivas, funções físico-hídricas e variação do armazenamento de água em um argissolo cultivado com palma forrageira. *Revista Ceres*, 62(1): 20-29.

Gupta, V. K., and R. A. Jangid. 2012. The effect of bulk density on emission behavior of soil at microwave frequencies. *International Journal of Microwave Science and Technology,* 2011: 160129.

Haberland, J., R. Gálvez, C. Kremer, and C. Carter. 2014. Laboratory and field calibration of the Diviner 2000 probe in two types of soil. *Journal of Irrigation and Drainage Engineering*, 140(4): 04014004.

Nunes, J. A. S., E. M. Bonfim-Silva, and T. J. A. Silva. 2016. Bulk density and water tensions in the soil on corn root production. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 20(4): 357-363.

Parsons, L. R., and W. M. Bandaranayake. 2009. Performance of a new capacitance soil moisture probe in a sandy soil. *Soil Science Society of America Journal*, 73(4): 1378–1385.

Parvin, N., and A. Degré. 2016. Soil-specific calibration of capacitance sensors considering clay content and bulk density. *Soil Research*, 54(1): 111–119.

Provenzano, R., G. Rallo, and H. Ghazouani. 2016. Assessing field and laboratory calibration protocols for the Diviner 2000® probe in a range of soils with different textures. *Journal of Irrigation and Drainage Engineering*, 142(2): 04015040.

Sentek. 2000. Diviner 2000® User Guide Version 1.21. South Australia: Sentek Pty Ltd.