ORIGINAL ARTICLE

Calibration of TDR probe for the estimation of moisture in typical red Ferrallitic soils

Calibración de sonda reflectométrica para la estimación de la humedad de suelos ferralíticos rojos

http://opn.to/a/fdgG1

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ABSTRACT. The dielectric method to estimate soil moisture content is based in the existent closed relationship between dielectric permittivity and water content. The time-domain reflectometry (TDR) is an indirect technique to estimate the soil water content based on the mentioned relationship given by polynomials of different ranges inserted in the equipment. However, the absence of generalization of these models to transform the data of the sensors into readings of moisture content of different soils makes necessary the obtaining of the place-specific calibration curves. The objective of the present work consists on the calibration of a probe TDR 300 model 6430FS for its use in typical red Ferrallitic soils of Ciego de Ávila, Cuba.

Keywords: Dielectric method, gravimetric moisture, time domain reflectometry, empirical calibration equation.

RESUMEN. El método dieléctrico de estimación de la humedad de los suelos se fundamenta en la relación estrecha existente entre ésta y la permitividad dieléctrica de los mismos. La reflectometría del dominio en el tiempo (TDR, por sus siglas en inglés: Time Domain Reflectometry) es una técnica indirecta de estimación de la humedad del suelo basada en la relación mencionada dada por polinomios de diferentes rangos e insertados en estos equipos. Sin embargo, las ausencias de generalización de estos modelos para convertir los datos de los sensores en lecturas de humedad de suelos diferentes hacen necesaria la obtención de curvas de calibración sitio-específicas. El objetivo del presente trabajo consiste en la calibración de una sonda TDR 300 modelo 6430FS para su uso en suelos ferralíticos rojos típicos de la provincia Ciego de Ávila, Cuba.

Palabras clave: Método dieléctrico, humedad gravimétrica, reflectometría en el dominio del tiempo, ecuación empírica de calibración.

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Received: 12/09/2017
Approved: 11/06/2018

INTRODUCTION

Currently around 70% of the total drinking water of the Earth is used in agricultural work, 20% in industry and 10% in domestic tasks (Baroni *et al.*, 2007). In Cuba, according to González *et al.* (2015), 59.7% of the total volume of this liquid is used by agriculture. Being a limited resource on a planetary scale, the need for its efficient use is evident, with an emphasis on agriculture.

Most of the agricultural uses of water are based on the determination of its content in the soil. Its measurement should be one of the indicators in the evaluation of the need to apply water for irrigation (FAO, 2015). From the hydrological point of view, it is only possible to establish water balances in the soil if there is reliable information on the variation of water content of the storage variation in the profile considered (Cornelissen *et al.*, 2014; Lin *et al.*, 2016). In addition, the determination of water content variation in the soil is necessary for the calculation of recharge and flow, both saturated and unsaturated, through the soil and the unsaturated zone and allows knowing the main mechanisms of solute transport (Vereecken *et al.*, 2014; Miller y Chanasyk, 2015).

With just these considerations, the importance of the application of reliable, economical and environmentally friendly methods for the measurement of soil moisture and its variations, as well as the response of these variations to different contour conditions is obvious.

All methods of measuring soil moisture content use a physical property of a sample that varies with the water content in it: mass in the case of gravimetric method, resistance or conductivity in the case of electrical method, etc. In international practice and in Cuba, the gravimetric method continues to be the reference and most used in agricultural practice and engineering despite its obvious shortcomings (Zhao *et al.*, 2016). It is a laborious direct method, high consumer of time and energy as well as being destructive. Other methods are highly expensive or unreliable and have not been widely extended in agricultural and research practice. However, the dielectric method, based on the direct relationship between the volume of water in this medium and the value of its relative dielectric permittivity, recently stands out for its spreading and potential for the determination of soil moisture and the description of its physical state (Suchorab *et al.*, 2014; Lin *et al.*, 2016). Time domain reflectometry (TDR) probes are a practical example of this method. It is an indirect, rapid and non-destructive technique for estimating moisture content based on its direct relationship with the relative dielectric permittivity of soil (Chen, 2014; Zhao *et al.*, 2016). However, its applicability in specific soils has been questioned in several investigations (Ponizovsky *et al.*, 1999; Bravo-Espinosa *et al.*, 2009), since this type of equipment uses mathematical models (Topp *et al.*, 1980) of relationship moisture-permittivity dielectric of the soil. Those models privilege the role of water content in the system to the detriment of the influence of other properties of it such as mechanical composition and aggregates, content of organic matter, density, etc. That is why several authors emphasize the need for calibration models of these devices for each soil (Cichota, 2003; Zhao *et al.*, 2016).

In foreign literature, a large number of studies investigating the subject are reported (Bravo-Espinosa *et al.*, 2009; Zhao *et al.*, 2016). In Cuba, Ustariz (2017) reports the obtaining of specific calibration curves for a probe TDR in Ferrallitic soils of Artemisa and Pinar del Río Provinces. Likewise, López *et al.* (2006), present a study that characterizes a similar equipment in determinations of soil water content under organoponics conditions. On the other hand, Cabrera *et al.* (2017), obtained the empirical relationships between the dielectric permittivity of the soil and its moisture content in red Ferrallitic soils of Ciego de Ávila Province and discuss the suitability of time domain reflectometry for the estimation of this parameter in the same soils. The authors cited recognize the advantages of this technique for the estimation and monitoring of this soil parameter, although they warn about the necessary conditions to consider for their effective use.

The objective of this work is to obtain the calibration models of the TDR 300 Model 6430FS probe from Spectrum Technologies for typical red Ferrallitic soils of Ciego de Ávila Province.

METHODS

In the work, a soil classified as typical Ferrallitic red according to the last classification of soils in force in the country, (Hernández *et al.*, 1999), is studied. For this, soil samples from four fields of Ciego de Ávila Province were collected:

- Botanical Garden and Experimental Station "Juan Tomás Roig", from University of Ciego de Ávila "Máximo Gómez Báez", located at Km. 9 1/2 of the road to Morón.
- Cooperative of Agricultural Production (CAP) ¨El Tezón¨, located in Ceballos, Ciego de Ávila Municipality.
- Cooperative of Agricultural Production ¨La Carolina¨, Venezuela Municipality.
- For the typical red Ferrallitic soil (TRFS) study, the TDR 300 Model 6430FS probe from the US firm Spectrum Technologies shown in Figure 1 was used.

FIGURE 1. Probe TDR 300, model 6430FS, used in the determination of soil moisture content.

Simultaneous soil moisture measurements *in situ* were carried out in the soil layers 0.00-0.10; 0.10-0.20; 0.20-0.40 and 0.40-0.60 m with the help of the TDR probe and the soil samples for the gravimetric method. Soil apparent density was determined with the help of cylinder method, while soil mechanical fraction of less than 0.002 mm was obtained by Bouyoucos method (Vadiunina y Korchaguina, 1986).

To assess the effectiveness of the TDR equipment for different soil water contents, three moisture comparative profiles were obtained up to depths of 0,60 m with the help of both methods. In each field, four random points were selected. In each of them and from each depth, four soil samples were taken for the gravimetric analysis and the same number of readings of the probe. From the statistical analysis of these values, those excessively distant from the average values in each case were eliminated. The Microsoft Office Excel 2003 program was used to obtain the mathematical models.

RESULTS AND DISCUSSION

Some Characteristics of the Investigated Soil

Values of some of the physical properties of the TRFS investigated are shown in Table 1. Soil apparent density in the surface layer is relatively low given the capacity of organic matter and iron, to form stable microaggregates in this part of the profile. Its tendency is to increase with depth because of the decrease of the organic matter content and the process of compaction. This process manifests with greater force in the layer 0.20 - 0.40 m where the plough pan generally is present. However, these values are lower than those reported by Cid *et al.* (2011), which may be related to differences in organic matter content and soil management technologies. With typical solid phase density values, the total pore volume is high and characteristic of clay soils. The values of the mechanical fraction of less than 0.002 mm are high and tend to increase in the lower layers with the loss of aggregate stability due to the decrease in organic matter.

TABLE 1. Some Physical Characteristics of the TFRS Investigated

Depth (m)	Apparent Density (mg/m^3)	Solid Phase Density (mg/m^3)	Total Porosity (% V)	Fraction d < 0.002 mm (%)
0.00-0.10	0.97	2.62	62.97	71
0.10-0.20	1.01	2.67	62.17	70
0.20-0.40	1.10	2.71	59.40	73
0.40-0.60	1.08	2.72	55.37	78

Soil Moisture Profiles of Typical Red Ferrallitic Soil of Ciego de Avila Province

In Figure 2, three moisture profiles obtained simultaneously with the help of the TDR probe and by the gravimetric method are shown. The values used represent the means of the estimates made by both methods in the three selected fields of the province.

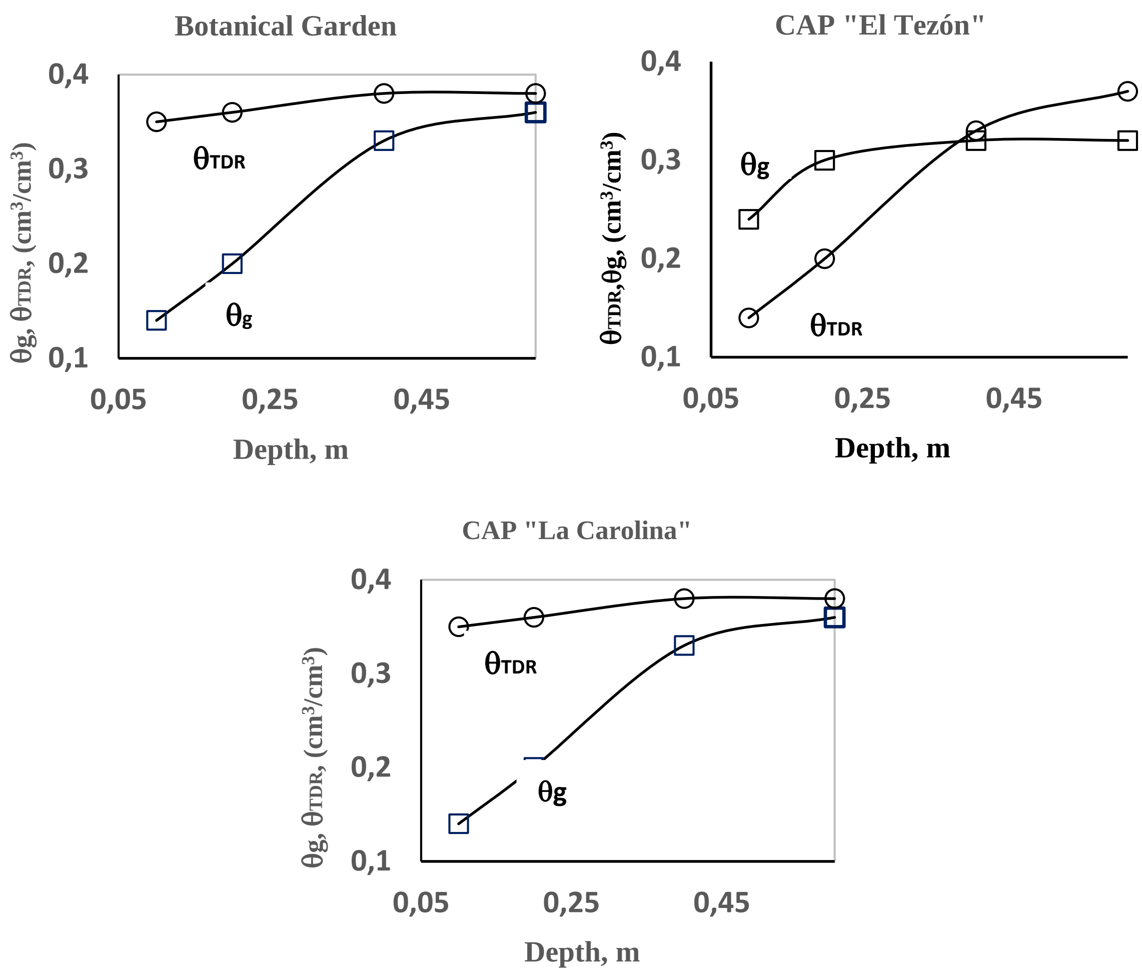

FIGURE 2. Moisture profiles of the investigated TFRS.

The curves are illustrative of the probe response to different contents of soil moisture and clay. For relatively low water content values, this device underestimates the actual value of the parameter. However, the opposite occurs for high values of this parameter. The graph corresponding to "La Carolina" stands out due to the high values of water content reported in correspondence with the rainy season and the high degree of soil wetting. Under these conditions, the TDR probe overestimates the liquid contents reaching values of up to 0,50 cm^3 / cm^3. A similar result is reported by Garcia and Oliveira (2001), when five different soils were investigated in Piracicaba Region, Brazil. For values of water content above 0.30 m^3 / m^3, the TDR probe overestimated these values in relation to those reported by gravimetric method. The authors agree with Robinson *et al.* (2003), when affirming that the results show that the use of TDRs in clay soils, tends to estimate inaccurate values that depend on the type of clays.

According to Zhao *et al.* (2016), several studies showed that the empirical equation of Topp *et al.* (1980), has a high precision for inorganic soils but is inapplicable for organic, fine-textured and clay soils (Dasberg and Hopmans, 1992; Yu *et al.*, 1997). In the opinion of the authors of this work, the inaccuracies of the mentioned model may be due, among other factors, to the fact that the dielectric permittivity characterizes as a whole the polycomponent and polyphase system that the soil is. Hence, its value is related, to a greater or lesser extent, with all the properties of the system and not only with a particular one, the water content, fact on which the aforementioned universal model is based. Considering this fact, Zhao *et al.* (2016), have proposed a new model that considers the additional effect on the dielectric permittivity of soil properties such as its type, bulk density, compaction energy, porous fluid conductivity and temperature.

In this way, the studies carried out indicate that generalizations such as those of Topp *et al.* (1980), are not as universal as expected. These facts suggest that the reliable determination of soil moisture content with the reflectometric technique requires site-specific equipment calibrations (Suchorab *et al.*, 2014; Almeidas *et al.*, 2017).

Calibration Models of the TDR 300 Model 6430FS for Typical Red Ferrallitic Soil of Ciego de Avila Province

It is necessary to take into account that empirical models are only functional relationships between variables and there is not necessarily a physical meaning for the found relationship. Because of that, they have limited applicability to the data that gave rise to them, and they may, adjust well eventually, to others from similar conditions.

Next, in Figure 3, calibration models (gravimetric moisture θg as a function of the TDR θT readings) are shown for a TDR 300 probe from the American firm Spectrum Technologies. These models were obtained in undisturbed typical red Ferrallitic soils of Ciego de Ávila Province with determinations of soil layers of 0.00-0.10; 0.10-0.20; 0.20-0.40 and 0.40-0.60 m depth.

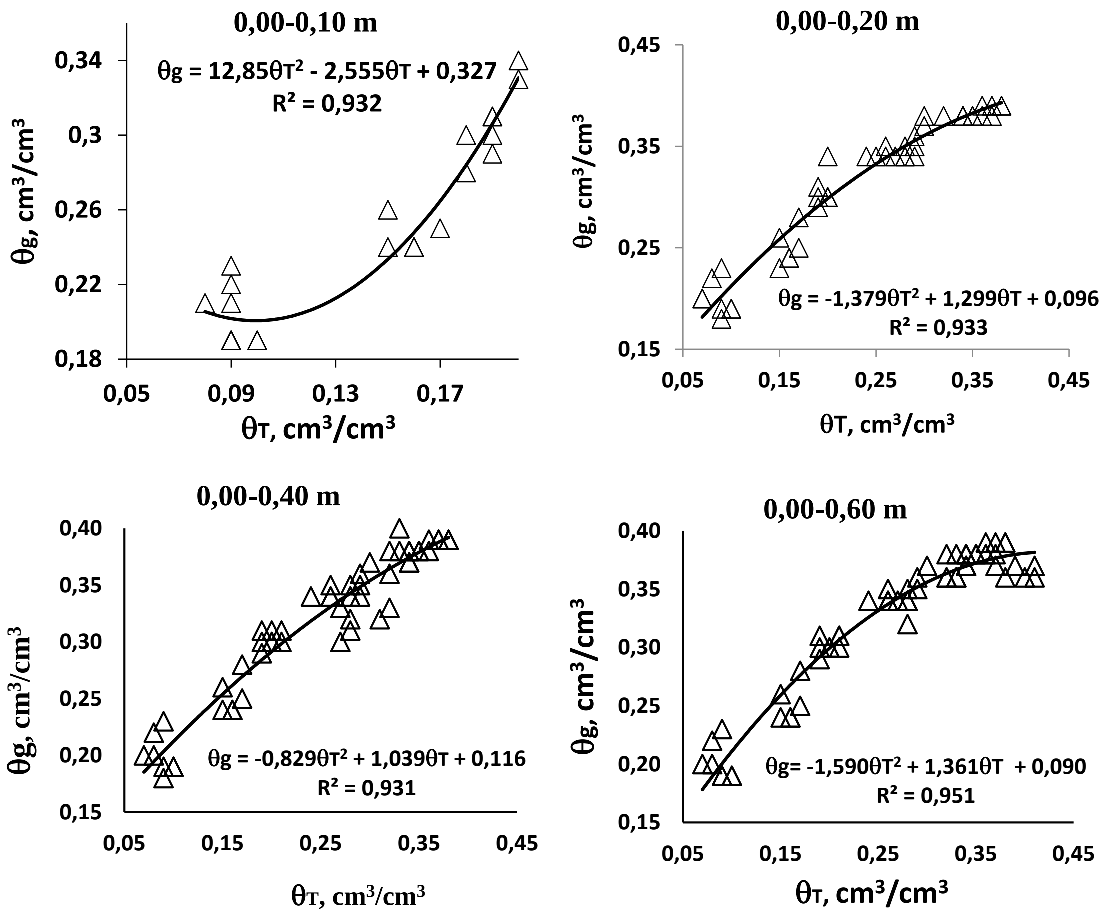

FIGURE 3. Calibration curves for different depths of the investigated TFRS.

As it is observed, all the models respond to polynomials of second degree with good adjustments according to the coefficients of determination located over 0.93. Ustariz (2017), reports a model linear for a TDR ML2X probe in Red Ferrallitic soil compacted from Artemisa Province with a good fit . At the same time that author affirms that the use of the internal equation of the probe for these study conditions would imply an underestimation of soil moisture in a 10% on average, compared to the use of the specific calibration with its negative implications, including the inadequate calculation of the irrigation sheet. In the same way, Vera *et al.* (2016), investigating clay loam soils in Murcia, Spain, also report linear relationships of soil water contents given by both measurement methods and point out possible overestimations of the parameter value between 55% and 200% if the specific equations for each site are not used. All the mentioned authors coincide in highlighting the importance of site-specific calibration of this equipment.

CONCLUSIONS

- The mathematical models inserted in the TDR 300 Model 6430FS probe cause significant inaccuracies in the estimation of the investigated TFRS moisture, which suggests the obtaining of the corresponding calibration curves.

- In the TFRS of Ciego de Ávila Province, the calibration models for the TDR 300 Model 6430FS probe respond to second-degree polynomials with satisfactory adjustments.

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NOTES

*The authors of this work declare no conflicts of interest.

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