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General calibration of TDR to assess the moisture of tropical soils using artificial neural networks

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SUMMARY

Determinations of soil moisture are important for various agricultural, environmental and hydrological applications, and accurate assessments are required. Artificial neural networks (ANNs) were applied in the present study to conduct general calibrations of time-domain reflectometry (TDR) probes using the physical characteristics of soil to estimate the moisture. The ANNs were trained and tested using data from five different soils. All of the combinations of physical properties, including the bulk density and sand, silt, clay and organic matter contents, were tested, and the inclusion of at least one of those network variables along with the apparent dielectric constant (K_a), which was assessed using the TDR device, were sufficient to calibrate all five of the soils simultaneously. The ANN selected for the general calibration has a hidden layer with 13 neurons and tan-sigmoid-type transfer function. The analysis of the statistical indexes values indicates that the ANNs were slightly better than the third-order polynomial equations (Topp-like equations), which were specifically fitted to each soil. The tests were conducted to assess the performance of the general calibrations that were applied to estimate the moisture of the soils excluded from the training process, although the ANNs have such a potential; the most representative variables in descending order of importance were as follows: organic matter, sand, clay, and bulk density. The soil silt content failed to stand out in this analysis and showed a lower performance. Based on the results, the organic matter content was the preferred variable for use along with the K_a in the ANNs applied to the general calibration of TDR (RMSE ranging from 0.0126 to 0.0237 g/g and r^2 ranging from 0.9083 to 0.9891). The sand content was also considered an advantageous variable because it was more easily assessed. The variables clay content and bulk density or the combination of several variables may also be used when available. As found by previous studies, the TDR calibration using ANN were better to sandy soils.

1. Introduction

There are various methods for assessing soil water content, including the gravimetric method, which is considered to be the standard method, and methods that use soil physical properties related to moisture to indirectly estimate the soil water content, including temperature, neutron thermalisation, electrical resistance, capacitance, spectrometry and time-domain reflectometry – TDR (Altendorf et al., 1999; Anderson and Croft, 2009; Antonucci et al., 2011; Calamita et al., 2012; Francesca et al., 2010; Imhoff et al., 2007; Noborio, 2001; Souza and Matsura, 2002).

The use of the TDR method has expanded and provided a relevant contribution for studies on the soil–water–plant–atmosphere relationship, enabling assessments of the soil moisture (Calamita et al., 2012; Graeff et al., 2010; Zehe et al., 2010) and its electrical conductivity (Moret-Fernández et al., 2012; Persson and Uvo, 2003; Skierucha et al., 2012), estimations of crop evapotranspiration (Schelde et al., 2011; Ward and Dunin, 2001) and analyses of the movement of water and solutes in soils (Kulasekera et al., 2011; Souza and Folegatti, 2010; Thomsen et al., 2000; Timlin and Pachepsky, 2002).

The TDR method has advantages over other methods that include improved accuracy, lack of soil sample destruction, real-time assessment of moisture and potential for continuity and automation of data collection. However, a key issue when using the TDR method is the difficulty of developing calibration equations for the different soil types of interest (Coelho et al., 2003; Imhoff et al., 2007; Staub et al., 2010; Zehe et al., 2010).

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The TDR method is based on the effect of moisture on the microwave propagation velocity in soils. Soil moisture (θ) may be estimated when the apparent dielectric constant (K_a) of the system has been established based on calibration equations (pedotransfer function) developed in the laboratory or in the field (Jones et al., 2002). Various types of mathematical models may be used in TDR calibrations. The third-order polynomial regression equation (Eq. (1)) proposed by Topp et al. (1980) is one of the most well-known and used (Comegna et al., 2013; Kaiser et al., 2010; Loiskandl et al., 2010; Nagare et al., 2011; Stangl et al., 2009).

$$\theta = a + bK_a + cK_a^2 + dK_a^3 \quad (1)$$

Other researchers (Jacobsen and Schjønning, 1993; Silva and Kay, 1997) have proposed calibrating the TDR by using the soil physical characteristics, including the bulk density and clay and organic matter contents, in addition to K_a, through an adaptation of third-order polynomial equation (Eq. (2)); however, the improvement in fit was considered small.

$$\theta = a + bK_a + cK_a^2 + dK_a^3 + e(\text{Bulk dry density}) + f\ \text{Clay} + g(\text{Organic matter}) \quad (2)$$

Persson et al. (2001) used artificial neural networks (ANNs) as a pedotransfer function (PTF) to model the relation between soil moisture and K_a and produced in a better performance than that of other tested equations. Subsequently, Persson et al. (2002) also applied ANNs to calibrate the TDR using other soil properties in addition to K_a, resulting in a general calibration for several types of soils. Using ANNs associated with soil physical characteristics enables the development of general calibrations that adequately estimate moisture without having to conduct specific calibration experiments for each type of soil (Arsoy et al., 2013; Persson et al., 2002).

Despite the good performance of ANNs to predict soil moisture, only very few studies have been conducted to provide TDR calibration using ANNs since the pioneer Persson et al. (2001) paper. Table 1 outlines the papers that have described this kind of studies. The soil density and clay content were the most frequently used input variables alongside K_a. Furthermore, all of the studies used multilayer perceptron (MLP) feedforward networks with only one hidden layer containing from 8 to 11 neurons. However, different training algorithms and activation functions were used. Once the ANN's architecture affects its performance, a promising research area consists in the evaluation and unification of training algorithms and methods (Arsoy et al., 2013), as well as the procedure to data standardisation, training epochs taken on training and the ANN's numbers of neurons and layers.

Studying the behaviour of tropical soils moisture, many researchers (van den Berg et al., 1997; Tomasella et al., 2000; Hodnett and Tomasella, 2002; Tomasella and Hodnett, 2004; Li et al., 2007; Minasny and Hartemink, 2011; Babangida et al., 2014) strongly encourages treating these soils separately from the temperate climate ones, deriving specific tropical soil PTFs. According to Tomasella and Hodnett (2004), physical and chemical differences between temperate and tropical soils might explain why PTFs derived for soils of temperate climate appeared to be inadequate for tropical soils (especially Latosols, Nitosols and related soils). The pronounced differences between temperate and tropical soils are usually explained by the micro-aggregated structure of Latosols and Nitosols, where Fe and Al oxides play an important role as binding agents of negatively charged clay minerals, creating stable micro-aggregates within the size range of silt to fine sand. As an example, kaolinitic tropical soils (about 60% in clay) show "unusual" properties when compared with typical temperate clayey soils, especially concerning to soil moisture behaviour: low available water capacity and almost 80% of the plant available water between −10 and −100 kPa. This behaviour resembles that of a typical temperate climate sandy soil, although the water contents are comparatively higher because of the clayey character of Latosols.

Based on the relevance of this topic and because no similar study has been found in the literature using tropical soils, the present study was conducted to fit the models based on ANNs to calibrate a TDR device to assess the moisture of different types of tropical soils found in Brazil.

2. Materials and methods

The present study consisted of fitting mathematical models based on ANNs to calibrate a TDR device using five types of tropical soils collected in the municipalities of Alegre, Aracruz, Guaçuí and Jerônimo Monteiro in the state of Espírito Santo, Brazil. The TDR was also calibrated using the fitted third-order polynomial equations (Topp-like equations) for comparison purposes (Topp et al., 1980).

The calibration consisted of mathematically correlating the apparent dielectric constant (K_a), which was measured using TDR probes, and the soil physical properties, including the water content. A TDR100 device with three-rod CS 610 probes (Campbell Scientific, Logan, UT, USA) was used.

2.1. Soil sampling and TDR measurements

The following five soil types were used: a clayey red-yellow Latosol (soil 1), medium texture Latosol (soil 2); Cambisol (soil 3); Alluvial soil (soil 4); and sandy soil (soil 5). Soil sampling was conducted at depths ranging from 0 to 10 cm. Three samples were collected from each soil, representing three replicates. Two types of samples were collected in the field to characterise the studied soils: disturbed samples and undisturbed samples. The granulometry (texture) and organic matter content were assessed in the laboratory using the disturbed samples according to the standard methods reported by Brazilian Corporation of Agricultural Research (EMBRAPA, 1997). The undisturbed methods were used to assess the bulk density according to the volumetric ring method. Table 2 outlines the descriptive characteristics of the studied soils.

Fifteen plastic containers of known mass that were approximately 30 cm long, 15 cm wide and 7 cm deep (approximately three-litre volume) were used in the experiment. The bottom surface of the containers had previously been perforated to enable

Table 1
Studies found in the literature on TDR calibration using artificial neural networks.

Author	Inputs	Network architecture	Transfer function	Training algorithm	Country
Persson et al. (2001)	K_a	1-8-1	Sigmoid	GD	Sweden
Persson et al. (2002)	K_a, bulk density, clay, organic matter	4-9-1	Sigmoid	GD	Denmark
Namdar-Khojasteh et al. (2010)	K_a, bulk density, clay	3-10-1	None informed	GDM	Iran
Arsoy et al. (2013)	K_a, bulk density, specific gravity, clay + silt	4-11-1	Tan-sigmoid	LM	Turkey

K_a: apparent dielectric constant; GD: gradient descent algorithm (backpropagation); GDM: GD with momentum; LM: Levenberg–Marquardt algorithm.