Assessment of pedotransfer functions for estimating soil water retention curves for the amazon region Avaliação de funções de pedotranferência para estimar curvas de retenção de água do solo na região amazônica

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DIVISÃO 2 - PROCESSOS E PROPRIEDADES DO SOLO

Comissão 2.2 - Física do solo

ASSESSMENT OF PEDOTRANSFER FUNCTIONS FOR ESTIMATING SOIL WATER RETENTION CURVES FOR THE AMAZON REGION[1]

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SUMMARY

Knowledge of the soil water retention curve (SWRC) is essential for understanding and modeling hydraulic processes in the soil. However, direct determination of the SWRC is time consuming and costly. In addition, it requires a large number of samples, due to the high spatial and temporal variability of soil hydraulic properties. An alternative is the use of models, called pedotransfer functions (PTFs), which estimate the SWRC from easy-to-measure properties. The aim of this paper was to test the accuracy of 16 point or parametric PTFs reported in the literature on different soils from the south and southeast of the State of Pará, Brazil. The PTFs tested were proposed by Pidgeon (1972), Lal (1979), Aina & Periaswamy (1985), Arruda et al. (1987), Dijkerman (1988), Vereecken et al. (1989), Batjes (1996), van den Berg et al. (1997), Tomasella et al. (2000), Hodnett & Tomasella (2002), Oliveira et al. (2002), and Barros (2010). We used a database that includes soil texture (sand, silt, and clay), bulk density, soil organic carbon, soil pH, cation exchange capacity, and the SWRC. Most of the PTFs tested did not show good performance in estimating the SWRC. The parametric PTFs, however, performed better than the point PTFs in assessing the SWRC in the tested region. Among the parametric PTFs, those proposed by Tomasella et al. (2000) achieved the best accuracy in estimating the empirical parameters of the van Genuchten (1980) model, especially when tested in the top soil layer.

Index terms: parametric PTFs, point PTFs, soil physics, soil water.

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RESUMO: ***AVALIAÇÃO DE FUNÇÕES DE PEDOTRANFERÊNCIA PARA ESTIMAR CURVAS DE RETENÇÃO DE ÁGUA DO SOLO NA REGIÃO AMAZÔNICA***

O conhecimento da curva de retenção de água (CRA) é essencial para compreender e modelar os processos hidráulicos no solo. No entanto, a determinação direta do CRA consome tempo, e o custo é alto. Além disso, é necessário grande número de amostras, em razão da elevada variabilidade espacial e temporal das propriedades hidráulicas do solo. Uma alternativa é o uso de modelos, que são chamados de funções de pedotransferência (FPT), que estimam a CRA por meio de propriedades do solo de fácil determinação. O objetivo deste estudo foi testar a acurácia de 16 FPT, pontuais ou paramétricas, existentes na literatura, em diferentes solos do sul e sudeste do Estado do Pará, Brasil. As FPT testadas foram propostas por Pidgeon (1972), Lal (1979), Aina & Periaswamy (1985), Arruda et al. (1987), Dijkerman (1988), Vereecken et al. (1989), Batjes (1996), van den Berg et al. (1997), Tomasella et al. (2000), Hodnett & Tomasella (2002), Oliveira et al. (2002) e Barros (2010). Utilizou-se um banco de dados contendo textura (areia, silte e argila), densidade do solo, carbono orgânico, pH do solo, capacidade de troca catiônica e CRA. A maioria das FPT testadas não demonstrou boa acurácia para estimar as CRA. As FPT paramétricas apresentaram melhor desempenho do que as FPT pontuais em estimar a CRA dos solos na região. Entre as FPT paramétricas, as propostas por Tomasella et al. (2000) obtiveram melhor acurácia em estimar os parâmetros empíricos do modelo de van Genuchten (1980), principalmente, quando testadas na primeira camada do solo.

Termos de indexação: FPT paramétricas, FPT pontuais, física do solo, água no solo.

INTRODUCTION

The term pedotransfer function (PTF) was first introduced by Bouma (1989) to describe the statistical relationship between easy-to-measure soil properties, such as particle size distribution, bulk density (Bd), soil organic carbon (SOC), and so on, and difficult-to-measure soil hydraulic properties, such as the SWRC, hydraulic conductivity, etc. According to Vereecken et al. (2010), the PTFs can be classified into two types: parametric PTFs that estimate the empirical parameters of the SWRC (Vereecken et al., 1989; Wösten et al., 1999; Navin et al., 2009; Gould et al., 2012) and point PTFs that are used to estimate soil water content at different matric potentials (Gupta & Larson, 1979; Saxton et al., 1986; Reichert et al., 2009). Papers published in recent years highlight the usefulness of parametric PTFs (Vereecken et al., 2010) because they directly provide the required hydraulic parameters to be used in mathematical models that describe the movement of water and solutes in soil, as well as the soil-plant-atmosphere interactions.

The main techniques used to develop PTFs are described in Pachepsky & Rawls (2004); however, most of the models are based on regression analyses (Tomasella & Hodnett, 1998; Tomasella et al., 2000; Cresswell et al., 2006; Reichert et al., 2009).

In Brazil, Arruda et al. (1987) were pioneers in relating soil particle size distribution to soil water content. Later, Tomasella & Hodnett (1998) produced functions for Amazonian soils to estimate the empirical parameters of the SWRC proposed by Brooks & Corey (1964). Using data from reports of soil surveys of various locations in Brazil, Tomasella et al. (2000) developed PTFs to estimate the empirical parameters of the van Genuchten SWRC model. In the State of Pernambuco, Brazil, Oliveira et al. (2002) developed PTFs to estimate soil moisture at field capacity (FC) and at the permanent wilting point (PWP). In that same year, Giarola et al. (2002), employing multiple regression analyses, developed PTFs relating soil particle size distribution and content of Fe and Al oxides to the volumetric water content at FC and PWP. The SWRC and the soil resistance to penetration curve were estimated by Silva et al. (2008) using PTFs having soil particle size distribution and soil carbon content as predictive variables. Reichert et al. (2009), using soil texture, SOC, Bd and soil particle density data, developed PTFs to predict soil volumetric moisture at specific matric potentials. Recently, Barros et al. (2013) presented PTFs to estimate the empirical parameters of the van Genuchten model for soils of northeastern Brazil.

The use of PTFs requires some care. PTFs developed for soils of a certain region may not be appropriate in other regions (Tomasella et al., 2003). These differences may influence the accuracy of the estimated parameters or water content. Therefore, the choice of an adequate PTF for a particular region and, or, for particular soil types is essential for the accuracy of the estimations. Recently, some studies have tested the accuracy of PTFs for estimating various soil properties (Abbasi et al., 2011; Botula et al., 2012; Moeys et al., 2012). In this context, the aim of this study was to assess the performance of some PTFs to estimate soil water retention at different matric potentials and also the empirical parameters of the van Genuchten (1980) model for soils of the Brazilian Amazon.

MATERIAL AND METHODS

Geographical study area

The study was conducted in the southeast of the State of Pará, Brazil, in three locations, corresponding to the municipalities of Nova Ipixuna, Parauapebas, and Pacajá, with coordinates of 4º 36' S, 49º 26' W; 5º 45' S, 49º 56' W; 3º 40' S, and 50º 56' W, respectively (WGS 84 coordinates). The locations have a tropical rainforest climate (Kottek et al., 2006). Average annual rainfall is 1,700 mm, with a pronounced dry season lasting 4-5 months, from June to October. Average annual relative humidity is 80 % (INMET, 2012). The landscape is composed of undulating to strongly undulating plateaus developed on the crystalline rocks of the Brazilian shield (Paleoproterozoic era). There is great diversity of rock types in the study area, with predominance of magmatic rocks (granites, granodiorites) in the municipalities of Nova Ipixuna and Pacajá, and metamorphic rocks (gneisses, etc) in Parauapebas (Issler & Guimarães, 1974).

The predominant soils are Typic Hapludult, Typic Hapludox, Typic Ferrudalf, Xanthic Hapludox, Inceptisol, and Aqult (Soil Survey Staff, 2010). The natural vegetation of the region includes Dense Submontane Rain Forest, Open and Mixed Broadleaf Forests, Dense Sub-montane Forests, Plateau, and Valley (DEOF, 2011).

Sampling and data analysis

Samples were collected at three depths (0-5; 10-15, and 40-45 cm), with four replicates for depth, in 27 profiles, for a total of 67 layers, evaluating variations of horizons in the profiles (14 layers with incomplete data were discarded). Bulk samples were collected to determine soil texture, soil organic carbon (SOC), soil pH, and cation exchange capacity (CEC). Undisturbed samples were collected to determine bulk density (ρ_b) and the SWRC (Table 1).

Soil texture was determined according to the method of Gee & Bauder (1986), with three laboratory replicates per sample. Soil particle sizes were separated according to the U.S. Department of Agriculture classification system: very fine sand (0.05 - <0.1 mm), fine sand (0.1 - <0.25 mm), medium sand (0.25 - <0.5 mm), coarse sand (0.5 - <1 mm), very coarse sand (1 - <2 mm), total sand (0.05 - <2 mm), silt (0.002 - <0.05 mm) and clay (<0.002 mm). A wide variation of data for soil texture is observed, ranging from very clayey to coarse sandy soils; there are, however, no silt soils (Figure 1).

After homogenization, about 1 g of air-dried soil was ground and sieved through a 0.2 mm mesh. Each sample was then transferred to a small tube, placed in a desiccator to remove possible moisture, and weighed before dry combustion analysis was carried out to determine SOC. Soil pH was determined by potentiometry at a soil:water ratio of 1:2.5.

The CEC was obtained by the sum of exchangeable cations, where Ca^{2+} and Mg^{2+} were extracted with potassium chloride and the contents of K^+ and Na^+ were extracted with Mehlich-1 solution (H_2SO_4 + HCl). Calcium and Mg^{2+} were determined by atomic absorption spectrometry and K^+ and Na^+ by flame photometry. Potential acidity (H+Al) was extracted

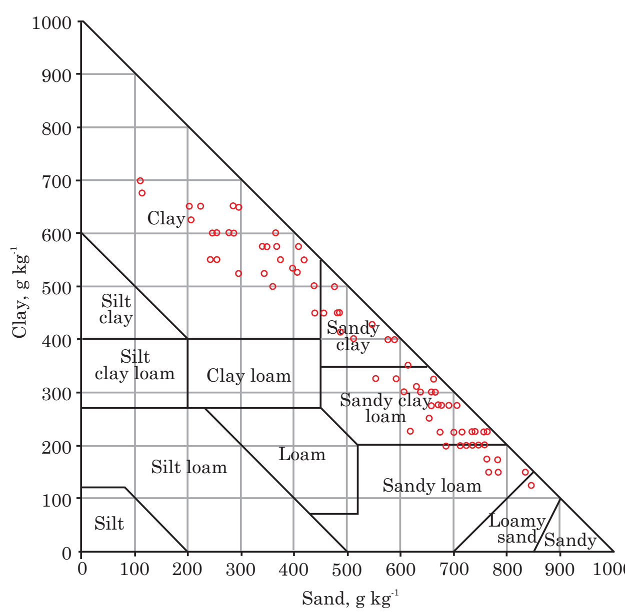

Figure 1. Textural classification of the soils used to evaluate the PTFs (n = 67).

Table 1. Descriptive statistics for soils from 67 layers used to test the selected PTFs

Statistic	ρ_b	Clay	Silt	Sand	SOC	CEC	pH	θ_s	θ_r	α	n
	Mg m^{-3}	g kg^{-1}				cmol$_c$ kg^{-1}		m^3 m^{-3}		cm^{-1}	
Average	1.36	390	80	530	11	3.6	5.7	0.48	0.10	0.08	1.29
Minimum	0.98	130	34	110	3	1.3	3.9	0.33	0,01	0.01	1.07
Maximum	1.63	700	210	850	23	7.8	8.1	0.63	0.33	0.90	1.62
SD	0.14	170	49	200	5	1.7	1.0	0.07	0.11	0.19	0.16
Number	67	67	67	67	67	27	27	67	67	67	67

ρ_b: Bulk density; SOC: soil organic carbon; CEC: cation exchange capacit; θ_S and θ_r: saturation and residual volumetric water content (adjusted), respectively: α and *n*: empirical parameters of the van Genuchten (1980) model; SD: standard deviation.

with calcium acetate at pH 7.0 and determined by titration with 0.05 mol L^{-1} NaOH.

The ρ_b was determined using cylinders of 5 × 5 cm (diameter and height) according to the method described in Blake & Hartge (1986). To determine the SWRC, the samples were subjected to nine matric potentials: 0, -1, -3, -6, -10, -33, -100, -300, and -1500 kPa, according to the method described in Klute (1986). The water content measured at each potential was the mean of four replicates. Each SWRC was then fitted to the van Genuchten (1980) model: $\theta(\psi) = (\theta_s - \theta_r)(1 + (\alpha^*\psi)^n)^{-m} + \theta_r)$, using the RETC program (van Genuchten et al., 1991) with the parameter m = 1-1/n, as proposed by Mualem (1976).

Description of the PTFs

Sixteen PTFs were selected for testing. Eight PTFs are parametric (Table 2) and were proposed by Vereecken et al. (1989), "Vereecken PTFs"; van den Berg (1997), "van den Berg-1 PTFs"; Tomasella et al. (2000) - level 1, 2, 3, and 4, "Tomasella PTFs"; Hodnett & Tomasella (2002), "Hodnett PTFs"; and Barros (2010), "Barros PTFs". The other nine are point PTFs (Table 3) and were proposed by Lal (1979), "Lal PTFs"; Aina & Periaswamy (1985), "Aina PTFs"; Batjes (1996), "Batjes PTFs"; van den Berg et al. (1997), "van den Berg-2 PTFs"; Pidgeon (1972), "Pidgeon PTFs"; Arruda et al. (1987), "Arruda PTFs"; Dijkerman (1988), "Dijkerman PTFs"; and Oliveira et al. (2002), "Oliveira PTFs". These point PTFs can predict either volumetric or gravimetric water content (Table 3).

Data for pH and CEC were measured only for the first layer. The PTFs that required pH and CEC as predictors (van den Berg-1 and Hodnett PTFs) were compared to the Tomasella PTFs for the samples representing the first layer (0-5 cm), and these results were discussed separately from those that had been estimated by the other PTFs.

Indicators used to assess the accuracy of the PTFs

The indices used to evaluate the accuracy of the PTFs were the mean error (ME), the root mean square error (RMSE), and the coefficient of determination (R^2), represented by equations 1, 2, and 3 below, respectively. In addition, the confidence index (CI) was calculated according to Camargo & Sentelhas (1987), as described in equations 4-6. CI is the product of the Willmott (w) index, given by equation 5, and the Pearson correlation coefficient (r), given by equation 6.

$$ME = \frac{1}{n}\sum_{i=1}^{n}(O_i - E_i) \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - E_i)^2} \quad (2)$$

$$R^2 = \sum_{i=1}^{n}(E_i - \bar{O})^2 / \sum_{i=1}^{n}(O_i - \bar{O})^2 \quad (3)$$

$$Cl = r * w \quad (4)$$

$$W = 1 - \frac{\sum_{i=1}^{n}(E_i - \bar{O})^2}{\left[\sum_{i=1}^{n}\left(|E_i - \bar{E}|\right) + \sum_{i=1}^{n}\left(|O_i - \bar{O}|\right)\right]^2} \quad (5)$$

$$r = \frac{\sum_{i=1}^{n}(E_i - \bar{E})(O_i - \bar{O})}{\left[\sum_{i=1}^{n}(E_i - \bar{E})^2 + \sum_{i=1}^{n}(O_i - \bar{O})^2\right]^{0,5}} \quad (6)$$

in which n represents the number of observations, O_i the observed (measured) water content values, E_i the estimated (predicted) water content values, and $\bar{E}$ and $\bar{O}$ the mean values of estimated and measured water content.

The *ME* represents the systematic error in the regression model. The remaining error is attributed to the variance of the model (Baker, 2008). The closer the *ME* value is to zero, the better the performance of the PTF. Likewise, PTF performance also increases when the calculated RMSE approaches zero (Pachepsky & Rawls, 2004). The R^2 indicates how the variance of the estimated variable is explained by the variance of the observed variable. The predictive capacity of the PTFs increases with the increase in R^2. The *CI* values were interpreted as proposed by Camargo & Sentelhas (1987): *CI* > 0.85 = optimum PTF accuracy; *CI* from 0.85 to 0.76 = very good; *CI* from 0.75 to 0.66 = good; *CI* from 0.65 to 0.61 = average; *CI* from 0.60 to 0.51 = tolerable; *CI* from 0.50 to 0.41 = bad; and *CI* ≤ 0.40 = very bad.

RESULTS AND DISCUSSION

The soil samples showed high amplitude of soil bulk density (ρ_b), soil texture (clay and sand content), and SOC values, as well as a wide range of values for the parameters of the van Genuchten (1980) model. In general, the soil types in the study location are sandy clay and sandy clay loam (Figure 1), which reflects the low residual water content values (θ_r), i.e., low capacity for retaining water at high matric potentials.

Assessment of parametric PTFs for the total data set (all depths)

Assessment of the parametric PTFs for the whole data set (Table 4) shows that the four Tomasella PTFs have better capacity in estimating the parameters of the van Genuchten (1980) model than the other PTFs. There is also a slight advantage for the Barros PTFs compared to the Vereecken PTFs. A more detailed analysis of the Tomasella PTFs shows that a reduction in predictive capacity is observed as the PTF level increases (Table 4, Figure 2). The PTFs that showed the best performance, with a *CI* classified as "good" for eight of the nine selected potentials, were the Tomasella PTFs, levels 1 and 2 (L_1 and L_2, Figure 2). The performances of these two PTFs were similar. The L_1 PTF, which uses Bd, clay, silt, fine and coarse sand fractions, and so-called "equivalent moisture" (water content measured at -33 kPa) as predictors, had a slightly higher *CI* than the L_2 PTF, whose predictors are identical to those of the L_1 PTF, with the exception of Bd, which is replaced by SOC. The L_3 and L_4 PTFs showed unsatisfactory *CI* performance (Figure 2). Equivalent moisture does not enter as a predictive variable in these two PTFs, which use only texture, Bd, and SOC as predictive variables. Overall, it is observed that the PTFs that use more variables to estimate the SWRC parameters have higher

Table 2. Parametric PTFs selected for estimating the parameters of the van Genuchten (1980) function

Tomasella et al. (2000) - Level 1 (L_1)
θ_s = [82.19 + (-0.018 Sil) + (23.23 Eqm) + (-28.67 Bd) + (0.005 CS Sil) + (-0.003 CSCl) + (0.003 FS Cl) + (-0.0008 CS^2)]/100
θ_r = [-13.36 + (0.25 Sil) + (0.34 Cl) + (39.91 Eqm) + (7.68 Bd) + (-0.005 Sil^2) + (-0.001 Cl^2)]/100
lnα = [264.46 + (1.21 Cl) + (-378.61 Eqm) + (- 328.35 Bd) + (0.005 CS FS) + (0.07 CS Sil) + (0.09 FS Cl) + (0.06 CS^2)]/100
n = [219.09 + (-152.96 Eqm) + (-0.029 CS Sil) + (-0.04 FS Cl) + (-0.010 CS^2) + (0.003 FS^2)]/100
Tomasella et al. (2000) - Level 2 (L_2)
θ_s = [41.65 + (57.44 Eqm) + (1.93 SOC) + (-0.003 CS FS) + (0.005 CS Sil) + (-0.005 CS Cl) + (-0.004 Sil Cl)]/100
θ_r = [-1.67 + (0.28 Sil) + (0.26 Cl) + (49.04 Eqm) + (-0.82 CO) + (0.002 FS Cl) + (-0.008 Sil^2)]/100
lnα = [-235.26 + (1.44 Cl) + (216.15 Eqm) + (0.06 CS FS) + (0.139 CS Sil) + (0.03 FS Cl) + (-0.05 Sil Cl) + (0.03 CS^2)]/100
n = [232.17 + (-168.93 Eqm) + (-0.05 CS Sil) + (-0.05 FS Cl) + (-0.009 CS^2) + (0.02 FS^2)]/100
Tomasella et al. (2000) - Level 3 (L_3)
θ_s = {91.62 + (-30 Bd) + (1.59 SOC) + (0.002 CS Sil) + (-0.003 CS Cl) + [-0.002 CS^2 + (-0.001 CS)]}/100
θ_r = [23.387 + (0.11 Cl) + (-4.79 Bd) + (0.005 Sil Cl) + (-0.003 CS^2) + (-0.002 FS^2) + (-0.005 Sil^2)]/100
lnα = [205.65+(-2.56 Sil) + (-0.13 Cl) + (-247.49 Bd) + (-0.02 CS FS) + (0.12 FS Sil) + (0.05 FS Cl) + [0.06 (CS^2)]}/100
n = {168.8 + (-0.03 CS Sil) + (-0.026 FS Cl) + [0.009 FS^2 + (-0.008 Sil^2)]}/100
Tomasella et al. (2000) - Level 4 (L_4)
θ_s = [36.9 + (0.37 Sil) + (3.26 SOC) + (-0.002 CS Cl) + (0.003 FS Cl) + (-0.003 Sil Cl) + (0.003 Cl^2)]/102
θ_r = [15.76 + (0.14 Cl) + (0.005 Sil Cl) + (-0.003 CS^2) + (-0.002 FS^2) + (-0.005 Sil^2)]/100
lnα = [-237.01 + (3.62 CS) + (0.004 CS Sil) + (0.09 FS Cl) + (0.018 (Cl^2)]/100
n = [170.63 + (-0.018 CS Sil) + (-0.031 FS Cl) + [(0.009 FS^2 + (-0.008 Sil^2)]/100
Barros (2010)
θ_s = 1 + (-0.00037 Bd)
θ_r = 0.0858 - (0.1671 S) + 0.3516 Cl + 1.1846 SOC + 0.000029 Bd
α = [0.8118+0.8861 S + (-1.1907 Cl) + (-0.001514 Bd)]
n = [1.1527 + (0.7427 S) + (0.4135 Sil) + (-5.5341 SOC)]
Vereecken et al. (1989)
θ_s = 0.803 - 0.283 Bd + 0.0013 Cl
θ_r = 0.015 + 0.005 Cl + 0.014 SOC
lnα = -2.486 + 0.025 S - 0.351 Cl
lnn = -0.035 - 0.009 S - 0.013 Cl + 0.015 S^2
van den Berg et al. (1997)
θ_s = [84.1- 0.206 Cl - 0.322 (S+Sil)]/100
θ_r = (0.308 Cl)/100
lnα = -0.627
m = 0.503 - 0.0027 (Sil + Cl) - 0.066 SOC + 0.0094 + CEC
Hodnett et al. (2002)
θ_s = [82.072 + (0.089 Cl) - (31.357 Bd) + (0.027 CEC) + (0.517 pH) - (0.0006 S Cl)]/100
θ_r = [23.133 + (-0.172 S) + (0.211 CEC) + (-0.849 pH) + (0.0012 Cl^2 + (0.0029 S Cl)] /100
lnα = [-4.237 - (3.423 Sil) + (4.288 SOC) - (0.801 CEC) - (11.07 pH) + (0.027 Sil^2)]/100
n = [67.093 + (-0.907 Cl) + (-0.574 SOC) + (1.396 pH) + (0.0056 Cl^2]/100

Eqm: equivalent moisture (m^3 m^{-3}); Bd: bulk density (Mg m^{-3}); SOC: soil organic carbon (g kg^{-1}); CS: coarse sand (g kg^{-1}); FS: Fine sand (g kg^{-1}); Cl: clay (g kg^{-1}); S: Sand (g kg^{-1}); Sil: silt (g kg^{-1}); CEC: cation exchange capacity ($cmol_c$ kg^{-1}); pH: pH of the soil; θ_s and θ_r: saturation and residual water content (m^3 m^{-3}), respectively; α and *n*: empirical parameters of the van Genuchten (1980) model.

Table 3. Point PTFs selected for estimating water content at specific matric potentials

Point PTF for volumetric water content estimation
Lal (1979)
θ_{10} = 0.102 + 0.003 Cl
θ_{33} = 0.065 + 0.004 Cl
θ_{1500} = 0.006 + 0.003 Cl
Aina & Periaswamy (1985)
θ_{33} = 0.6788 - 0.0055 S - 0.0013 Bd
θ_{1500} = 0.00213 + 0.0031 Cl
Batjes (1996)
θ_{10} = (0.5266 Cl + 0.3999 Sil + 3.1752 SOC)/100
θ_{33} = (0.46 Cl + 0.3045 Sil + 2.0703 SOC)/100
θ_{1500} = (0.3624 Cl + 0.117 Sil + 1.6054 SOC)/100
van den Berg et al. (1997)
θ_{33} = 0.1088 + 0.00347 Cl + 0.00211 Sil + 0.01756 SOC
θ_{1500} = 0.00383 + 0.00272 Cl + 0.00212 Sil
Point PTFs for gravimetric water content estimation
Pidgeon (1972)
W_{10} = (100 FC - 2.54)/91
W_{33} = (100 FC - 3.77)/95
W_{1500} = -0.0419 + 0.0019 Sil + 0.0039 Cl + 0.009 SOC
Arruda et al. (1987)
W_{33} = [3.07439 + 0.629239 (Sil + Cl) - 0.00343813 (Sil + Cl)^2]/100
W_{1500} = {398.889 (Sil + Cl)/[1308.09 + (Sil + Cl)]}/100
Dijkerman (1988)
W_{33} = 0.3697 - 0.0035 S
W_{1500} = 0.0074 + 0.0039 Cl
Oliveira et al. (2002)
W_{33} = 0.00333 Sil + 0.00387 Cl
W_{1500} = 0.00038 S + 0.00153 Sil + 0.00341 Cl - 0.030861 Bd

Cl: clay (g kg^{-1}); S: Sand (g kg^{-1}); Sil: silt (g kg^{-1}); Bd: bulk density (Mg m^{-3}); CEC: cation exchange capacity (cmol$_c$ kg^{-1}); SOC: soil organic carbon (g kg^{-1}); θ: volumetric water content (m^3 m^{-3}); W: gravimetric water content (kg kg^{-1}); FC: volumetric water content at field capacity (m^3 m^{-3}).

efficiency (Table 4). This is confirmed by the performance of the various PTFs proposed by Tomasella et al. (2000), and by comparing the Barros and Vereecken PTFs.

The *CI* values using the criteria proposed by Camargo & Sentelhas (1997) indicate that the Tomasella PTFs have "very good" performance for the L_1 and "good" performance for the L_2 (Table 4). However, for the L_3 and L_4 levels, performance was rated "poor". The Barros PTFs were classified as "poor" (*CI* = 0.48), while Vereecken PTFs had the lowest *CI* values (0.40) and were classified as "bad" (Table 4). The evaluation of the PTFs for the total data set showed that the Tomasella PTFs had better overall performance than the Barros PTFs and the Vereecken PTFs.

When the estimated data are plotted against the measured data (Figure 3), it is observed that the grouping of the points around the 1:1 line is increasingly better when moving from the Tomasella PTF L_4 to PTF L_1, which confirms the better efficiency of PTF L_1. The Vereecken PTFs showed the highest dispersion around the 1:1 line, producing the worst predictive performance among all the parametric PTFs being tested.

The better predictive capacity of levels 1 and 2 of the Tomasella PTFs is probably related to inclusion of the water content value at the -33 kPa matric potential as an independent variable in the model. This result is consistent with the results of Cresswell & Paydar (2000) and Schaap et al. (2001), who showed that PTF performance was greatly improved when including measurement points of the SWRC as predictive variables. However, the determination of this value using undisturbed samples with volumetric rings is costly and time consuming, which limits its use in a practical and generalized way. Another point that justifies the good performance of the Tomasella PTFs is the fact that these PTFs were developed from soils from various regions of Brazil, including several soils from the Amazon region. The good performance presented by the Tomasella PTFs has also been observed in other studies. Medina et al. (2002) tested several PTFs in soils from Cuba and obtained a better performance of the ME and RMSE values, -0.02 and 0.06 (m^3 m^{-3}), respectively, for the L_4 PTFs. The poor performance shown by the Barros PTFs is justified by the fact that these PTFs were designed to predict the empirical parameters of the van Genuchten model for soils of the Brazilian Cerrado (tropical savanna). According to the author, these soils generally have low SOC and clay content in their compositions, but high r_b values. For the Vereecken PTFs, a tendency to underestimate the moisture values is observed, especially in the central potentials of the SWRC. This fact is related to the low capacity of the function in estimating the shape parameters of the SWRC (α and n), responsible for the accuracy of the water content predictions near the inflection point of the SWRC. This unsatisfactory result is probably related to the fact that these PTFs were developed for temperate soils (soils from Belgium). Tomasella et al. (2003) had already demonstrated the low predictive ability of the PTFs developed for temperate soils when used on soils from tropical regions. The authors asserted that the performance of these PTFs is affected mainly by the difference in silt content between soil types from different regions. Botula et al. (2012) also found that temperate PTFs in hydrological models for studies in the humid tropics can substantially reduce the quality of the results.

Assessment of parametric PTFs for the surface layer (0-5 cm)

As pH and CEC measurements were available only for the 0-5 cm topsoil, van den Berg-1 and Hodnett PTFs could be tested for this particular soil layer only. The statistical indicators of the performance of these PTFs are shown in table 5 together with those of the

Tomasella PTFs. It is worth noting that the four Tomasella PTFs (L_1 to L_4) performed better than the van den Berg-1 and Hodnett PTFs. Furthermore, among the four Tomasella PTFs, an increase in the PTF level reduced its predictive capacity, as was observed for the total data set. An analysis of the Tomasella PTFs tested for the two data sets (total and surface layer) showed that, in general, the PTFs tested for the surface layer had a better performance (Tables 4 and 5, Figures 2 and 4). The function developed by Tomasella (L_1) had a "very good" *CI* when tested for the three depths (Table 4), and an "excellent" *CI* when tested for the surface layer only (Table 5). This same trend was observed for the other Tomasella PTFs.

The performance indicators for the Hodnett PTFs showed low accuracy. On average, considering matric potentials, the Hodnett PTFs was ranked as having a "average" performance (Table 5). The van den Berg-1 PTFs had ME and RMSE values higher than those observed for the Hodnett PTFs, except for the dry part

Table 4. Statistical indicators for the parametric PTFs tested for the three depths. n = 67

Statistic	Soil water matric potential (kPa)									
	0	-1	-3	-6	-10	-33	-100	-300	-1500	Total
					Tomasella et al. (2000) - Level 1					
$\bar{x}$ ($m^3 m^{-3}$)	0.46	0.42	0.36	0.32	0.30	0.25	0.22	0.20	0.19	-
RMSE ($m^3 m^{-3}$)	0.05	0.05	0.05	0.04	0.04	0.05	0.04	0.04	0.06	0.05
ME ($m^3 m^{-3}$)	0.01	0.00	0.00	0.00	0.01	0.02	0.02	0.00	-0.02	0.01
R^2	0.42	0.47	0.63	0.66	0.66	0.70	0.72	0.74	0.62	0.63
CI	0.64	0.68	0.79	0.81	0.81	0.83	0.84	0.85	0.78	0.78
					Tomasella et al. (2000) - Level 2					
$\bar{x}$ ($m^3 m^{-3}$)	0.46	0.42	0.36	0.32	0.30	0.26	0.24	0.22	0.21	-
RMSE ($m^3 m^{-3}$)	0.04	0.05	0.05	0.06	0.06	0.05	0.05	0.04	0.07	0.05
ME ($m^3 m^{-3}$)	0.01	0.01	0.00	0.01	0.01	0.01	0.00	-0.02	-0.04	0.00
R^2	0.42	0.48	0.54	0.58	0.58	0.64	0.68	0.73	0.60	0.58
CI	0.65	0.69	0.73	0.75	0.76	0.80	0.82	0.84	0.77	0.76
					Tomasella et al. (2000) - Level 3					
$\bar{x}$ ($m^3 m^{-3}$)	0.45	0.41	0.34	0.30	0.28	0.23	0.21	0.19	0.18	-
RMSE ($m^3 m^{-3}$)	0.05	0.06	0.07	0.07	0.08	0.08	0.07	0.05	0.06	0.07
ME ($m^3 m^{-3}$)	0.01	0.02	0.02	0.02	0.03	0.04	0.03	0.02	-0.01	0.02
R^2	0.34	0.27	0.32	0.30	0.27	0.31	0.40	0.62	0.44	0.36
CI	0.58	0.51	0.56	0.55	0.52	0.55	0.63	0.78	0.66	0.59
					Tomasella et al. (2000) - Level 4					
$\bar{x}$ ($m^3 m^{-3}$)	0.46	0.42	0.35	0.30	0.27	0.23	0.21	0.19	0.18	-
RMSE ($m^3 m^{-3}$)	0.06	0.06	0.07	0.08	0.08	0.08	0.07	0.05	0.06	0.07
ME ($m^3 m^{-3}$)	0.01	0.01	0.01	0.03	0.03	0.04	0.03	0.02	-0.01	0.02
R^2	0.08	0.16	0.23	0.24	0.22	0.26	0.35	0.57	0.41	0.28
CI	0.28	0.40	0.47	0.48	0.47	0.51	0.59	0.74	0.64	0.51
					Vereecken et al. (1989)					
$\bar{x}$ ($m^3 m^{-3}$)	0.47	0.34	0.25	0.21	0.20	0.18	0.18	0.18	0.18	-
RMSE ($m^3 m^{-3}$)	0.07	0.13	0.14	0.14	0.14	0.12	0.10	0.07	0.08	0.12
ME ($m^3 m^{-3}$)	-0.01	0.08	0.11	0.12	0.11	0.10	0.07	0.04	0.00	0.07
R^2	0.17	0.00	0.05	0.11	0.11	0.31	0.28	0.78	0.18	0.22
CI	0.35	0.29	0.40	0.42	0.41	0.50	0.38	0.47	0.35	0.40
					Barros (2010)					
$\bar{x}$ ($m^3 m^{-3}$)	0.50	0.43	0.39	0.36	0.34	0.29	0.25	0.22	0.20	-
RMSE ($m^3 m^{-3}$)	0.08	0.06	0.08	0.08	0.08	0.08	0.09	0.07	0.09	0.08
ME ($m^3 m^{-3}$)	-0.04	-0.01	-0.03	-0.03	-0.03	0.00	-0.01	0.03	-0.02	-0.02
R^2	0.21	0.25	0.26	0.28	0.26	0.37	0.31	0.51	0.26	0.30
CI	0.35	0.38	0.43	0.46	0.45	0.54	0.53	0.63	0.53	0.48

$\bar{x}$: mean of the estimated values ($m^3 m^{-3}$); RMSE: root mean square error; ME: mean error; R^2: coefficient determination; *CI*: Confidence Index proposed by Camargo & Sentelhas (1987).

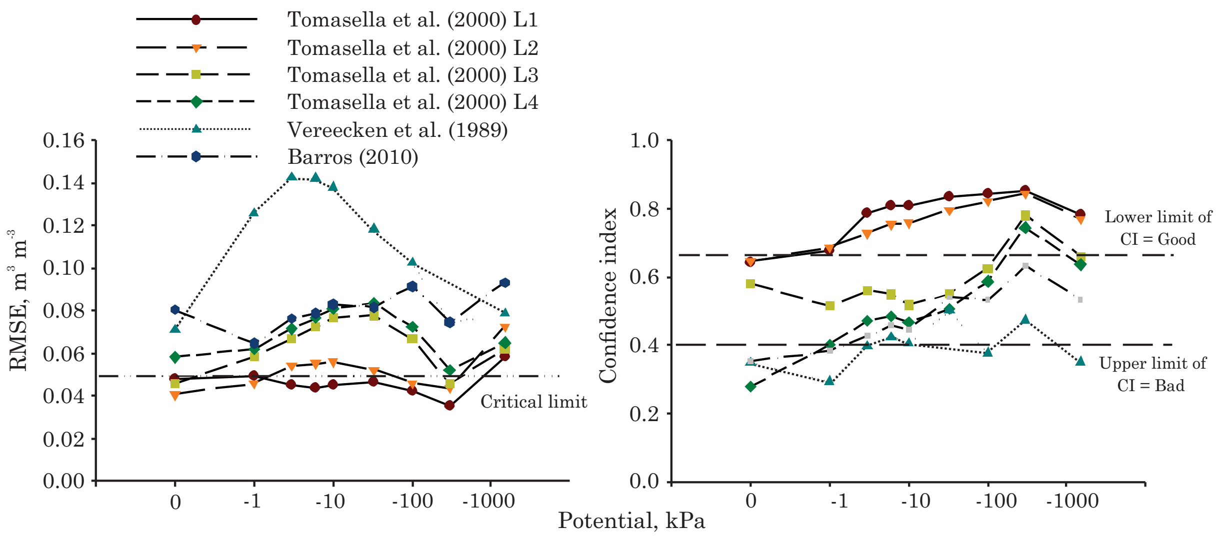

Figure 2. Values of RMSE and confidence index (CI) for the parametric PTFs tested for all soil depths; CI > 0.85 = optimum; CI from 0.85 to 0.76 = very good; CI from 0.75 to 0.66 = good; CI from 0.65 to 0.61 = average; CI from 0.60 to 0.51 = tolerable; CI from 0.50 to 0.41 = bad; CI ≤ 0.40 = very bad.

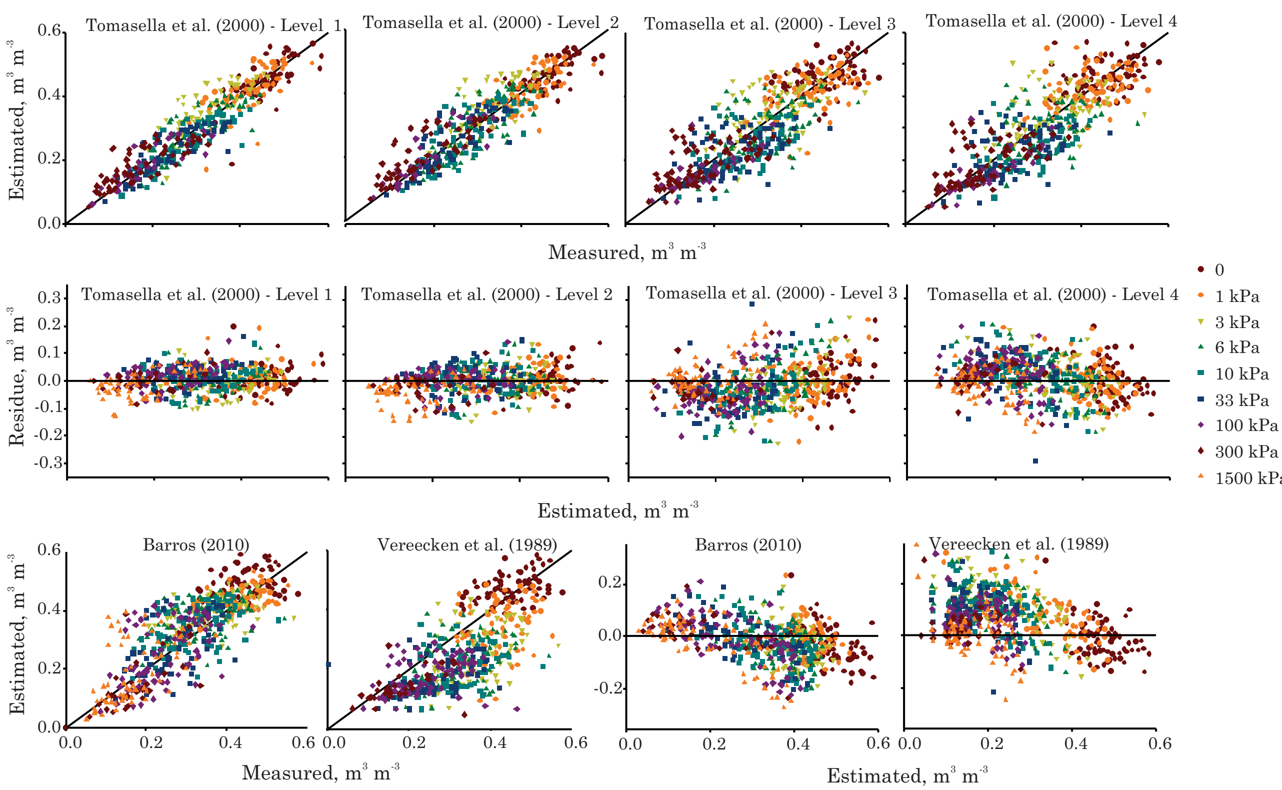

Figure 3. Estimated *vs* measured volumetric water content, and estimation residues for the parametric PTFs tested for all depths (n = 67).

of the SWRC, and significantly below the ideal values for the current study. The *CI* indicated low predictive ability of the van den Berg-1 PTFs, rated as "bad" (Table 5). The low efficiency of the van den Berg-1 PTFs may be attributed to the fact that it was developed for Oxisols (horizons A, AB, and B). Our data set has several soil types, providing large variability to the properties used in the model, which reflects the high RMSE values of the van den Berg-1 PTFs. Oliveira et al. (2002) reported that PTFs have greater predictive ability when the soil properties that comprise the database are homogeneous.

The estimated and measured data were plotted on a scatter chart (Figure 5). It is observed that the best fit was obtained for Tomasella PTF L_1. The Hodnett PTFs have a tendency to overestimate water content values in the points near saturation, while the van den Berg-1 PTFs underestimate water content in the dry part of the SWRC (Figure 5). Both the van den Berg-1 and Hodnett PTFs are characterized by a dispersion of the regression points (Figure 5), which confirms the previous statements about these PTFs. Moreover, it was found that the Hodnett and van den Berg-1 PTFs, despite the addition of CEC and pH to the set of predictive variables, did not have good predictive abilities.

Assessment of point PTFs

Performance analysis of the point PTFs tested indicates that most of them have low predictive capacity (Table 6). For estimations of the water content at the -10 kPa potential, all the PTFs tested showed RMSE values above 0.07 $m^3\ m^{-3}$ (Table 6), which is considered high for this kind of study. In addition,

Table 5. Statistical indicators for the parametric PTFs tested for the topsoil layer (0-5 cm). n = 27

Statistic	Soil water matric potential (kPa)									
	0	-1	-3	-6	-10	-33	-100	-300	-1500	Total
	Tomasella et al. (2000) - Level 1									
$\bar{x}$ ($m^3\ m^{-3}$)	0.46	0.41	0.34	0.30	0.28	0.23	0.20	0.18	0.17	-
RMSE ($m^3\ m^{-3}$)	0.06	0.06	0.04	0.04	0.04	0.04	0.03	0.02	0.04	0.04
ME ($m^3\ m^{-3}$)	0.02	0.02	0.01	0.02	0.02	0.03	0.02	0.00	-0.03	0.01
R^2	0.41	0.55	0.81	0.87	0.87	0.91	0.91	0.91	0.95	0.80
CI	0.62	0.72	0.89	0.92	0.92	0.94	0.93	0.94	0.88	0.86
	Tomasella et al. (2000) - Level 2									
$\bar{x}$ ($m^3\ m^{-3}$)	0.46	0.41	0.34	0.30	0.28	0.24	0.22	0.21	0.19	-
RMSE ($m^3\ m^{-3}$)	0.06	0.06	0.05	0.05	0.06	0.05	0.04	0.04	0.06	0.05
ME ($m^3\ m^{-3}$)	0.02	0.02	0.01	0.01	0.02	0.02	0.00	-0.02	-0.05	0.00
R^2	0.31	0.44	0.62	0.68	0.69	0.78	0.82	0.86	0.76	0.66
CI	0.55	0.65	0.77	0.81	0.82	0.87	0.89	0.91	0.85	0.79
	Tomasella et al. (2000) - Level 3									
$\bar{x}$ ($m^3\ m^{-3}$)	0.46	0.39	0.31	0.26	0.24	0.20	0.17	0.16	0.15	-
RMSE ($m^3\ m^{-3}$)	0.06	0.07	0.07	0.08	0.08	0.08	0.06	0.04	0.03	0.07
ME ($m^3\ m^{-3}$)	0.02	0.04	0.05	0.06	0.07	0.07	0.05	0.02	-0.01	0.04
R^2	0.22	0.27	0.48	0.53	0.53	0.59	0.69	0.81	0.73	0.54
CI	0.47	0.51	0.68	0.71	0.71	0.75	0.81	0.89	0.85	0.71
	Tomasella et al. (2000) - Level 4									
$\bar{x}$ ($m^3\ m^{-3}$)	0.44	0.39	0.31	0.26	0.23	0.19	0.17	0.15	0.14	-
RMSE ($m^3\ m^{-3}$)	0.07	0.06	0.06	0.07	0.08	0.08	0.07	0.04	0.03	0.07
ME ($m^3\ m^{-3}$)	0.04	0.03	0.04	0.06	0.07	0.07	0.05	0.03	0.00	0.04
R^2	0.14	0.29	0.50	0.54	0.53	0.58	0.69	0.82	0.75	0.54
CI	0.37	0.52	0.69	0.72	0.71	0.74	0.81	0.89	0.86	0.70
	Hodnett et al. (2002)									
$\bar{x}$ ($m^3\ m^{-3}$)	0.38	0.29	0.23	0.20	0.19	0.17	0.16	0.15	0.14	-
RMSE ($m^3\ m^{-3}$)	0.11	0.15	0.14	0.13	0.12	0.10	0.07	0.04	0.03	0.11
ME ($m^3\ m^{-3}$)	0.09	0.13	0.12	0.11	0.11	0.09	0.06	0.03	-0.01	0.08
R^2	0.25	0.23	0.28	0.36	0.39	0.54	0.70	0.76	0.83	0.48
CI	0.48	0.44	0.48	0.55	0.58	0.70	0.81	0.86	0.90	0.64
	van den Berg et al. (1997)									
$\bar{x}$ ($m^3\ m^{-3}$)	0.47	0.36	0.30	0.26	0.24	0.20	0.17	0.15	0.13	-
RMSE ($m^3\ m^{-3}$)	0.08	0.09	0.09	0.10	0.11	0.11	0.09	0.08	0.06	0.09
ME ($m^3\ m^{-3}$)	0.00	0.06	0.05	0.05	0.05	0.06	0.04	0.03	0.01	0.04
R^2	0.04	0.08	0.02	0.02	0.05	0.00	0.04	0.11	0.20	0.05
CI	0.17	0.24	0.10	0.08	0.09	0.06	0.20	0.32	0.43	0.17

$\bar{x}$: mean of the estimated values ($m^3\ m^{-3}$); RMSE: root mean square error; ME: mean error; R^2: coefficient determination; *CI*: Confidence Index proposed by Camargo & Sentelhas (1987).

the *CI* of the PTFs tested ranged from "bad" to "very poor" (Table 6). Among the point PTFs tested that estimate water content at the -10 kPa potential, the van den Berg-2 PTF had the best predictive ability. It had the lowest RMSE and ME values, and the highest R^2 and *CI* (Table 6). However, according to Camargo & Sentelhas (1997), this PTF was classified as "tolerable", which confirms its low performance in estimating water content at the -10 kPa potential. The worst performance in estimating water content at the -10 kPa potential was observed for the Pidgeon PTF, which showed the highest RMSE and ME, and a CI rated as "poor".

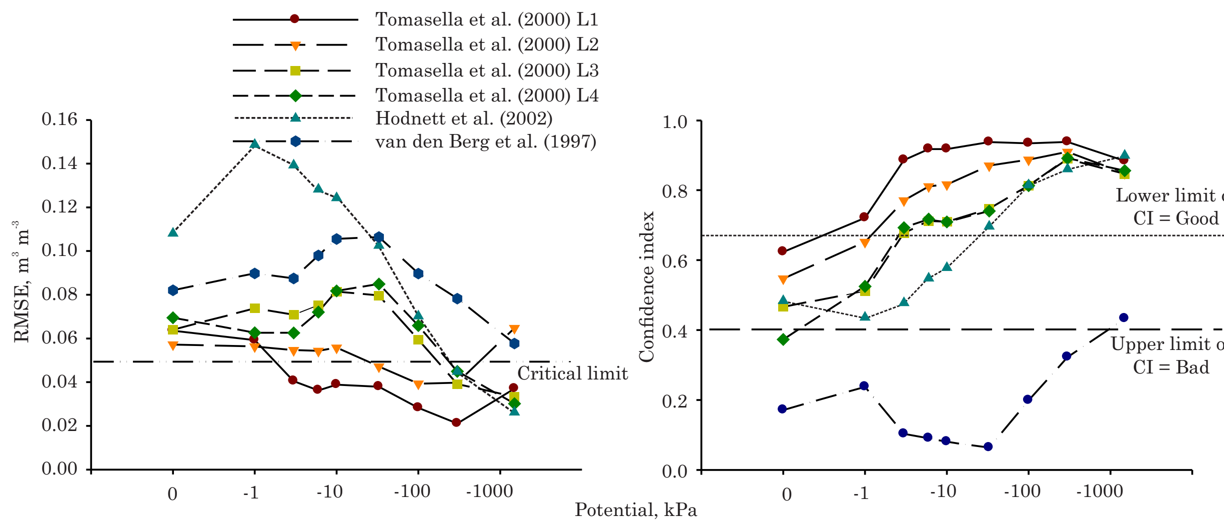

Figure 4. Values of RMSE and confidence index (CI) for the parametric PTFs tested for the surface soil layer (0-5 cm). CI > 0.85 = optimum; CI from 0.85 to 0.76 = very good; CI from 0.75 to 0.66 = good; CI from 0.65 to 0.61 = average; CI from 0.60 to 0.51 = tolerable; CI from 0.50 to 0.41 = bad; CI ≤ 0.40 = very bad.

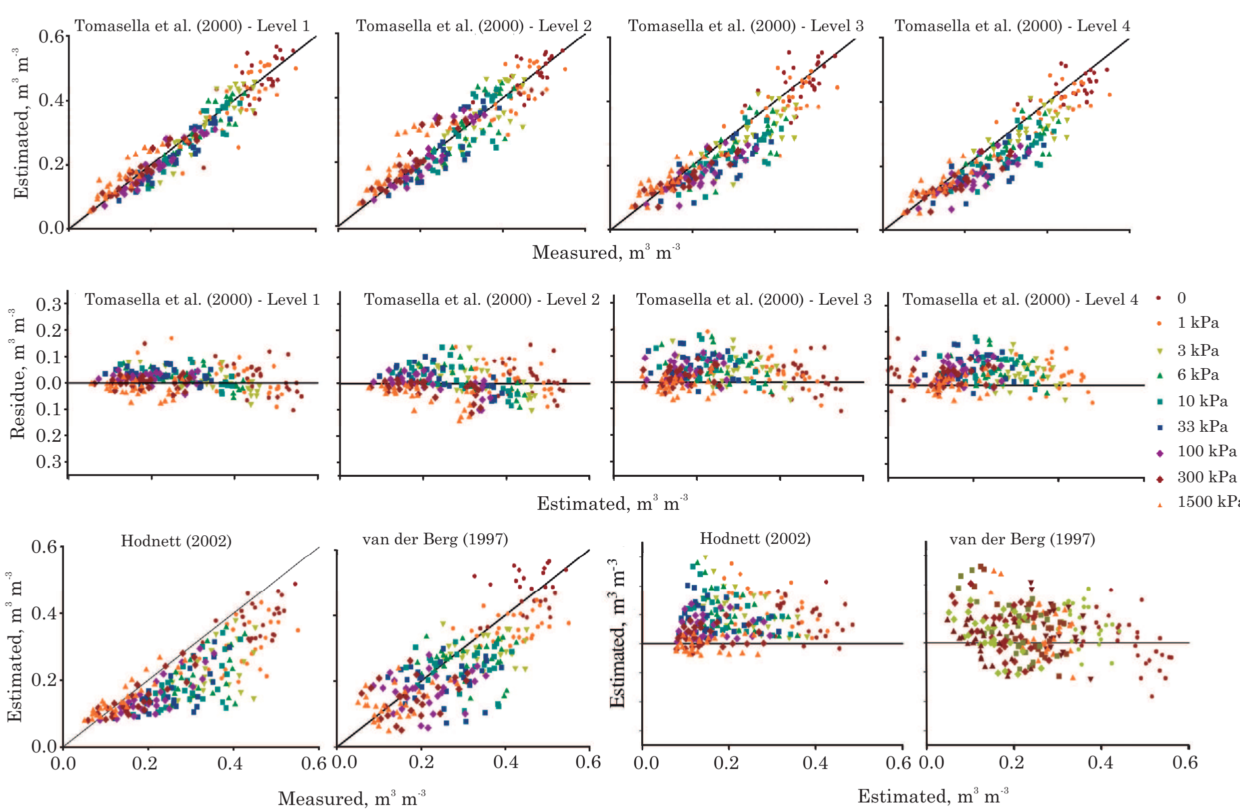

Figure 5. Measured *vs* estimated volumetric water content, and estimation residue for the parametric PTFs tested in the surface soil layer (0-5 cm) (n = 27).

For the -33 kPa potential, the PTF that had the best performance was the Batjes PTF (Table 6). The worst performance was observed for the Aina PTF, with a *CI* performance rated as "bad". A similar behavior was observed for the water content estimations at -1500 kPa. The PTF with the best performance was the Batjes PTF. However, at this potential, the van den Berg and Oliveira PTFs had similar performance results (Table 6). The worst performance was observed for the Arruda PTFs, followed by the Lal, Aina, and Dijkerman PTFs ($CI \leq 0.37$).

Some PTFs overestimate water content at a given potential and underestimate it at another, as observed for the Oliveira and Aina PTFs (Figures 6 and 7). The Lal PTFs underestimate water content at all three potentials. The Pidgeon PTF overestimates water content at both potentials (Figure 7).

The PTFs that estimate volumetric water content showed better results than those that estimate gravimetric water content, except for the Lal PTFs. There are many reasons that lead to low efficiency of a PTF. Finke et al. (1996) showed that a major source of inaccuracy of a PTF is the spatial variability of soil properties that are transferred to the PTF. The performance of several point PTFs was evaluated by Tomasella & Hodnett (2004) using a database of tropical soils composed of 771 horizons. The authors found that some PTFs had great difficulty in estimating water content at specific potentials, and they attributed this difficulty to their simplicity, i.e.,

Table 6. Statistical indicators for the point PTFs for predicting volumetric or gravimetric water content. n = 67

PTF	-10 kPa					-33 kPa					-1500 kPa				
	$\bar{x}$	RMSE	ME	R^2	*IC*	$\bar{x}$	RMSE	ME	R^2	*IC*	$\bar{x}$	RMSE	ME	R^2	*IC*
	PTF for volumetric water content ($m^3\ m^{-3}$)														
Lal (1979)	0.22	0.12	0.09	0.05	0.21	0.16	0.14	0.11	0.15	0.38	0.12	0.09	0.05	0.12	0.34
Batjes (1996)	0.28	0.10	0.04	0.19	0.44	0.23	0.09	0.05	0.25	0.50	0.17	0.07	0.01	0.28	0.52
van den Berg et al. (1997)	0.28	0.08	0.03	0.20	0.44	no	no	no	no	no	0.16	0.07	0.01	0.28	0.53
Oliveira et al. (2002)	no	no	no	no	no	0.18	0.13	0.11	0.26	0.46	0.17	0.07	0.01	0.30	0.53
	PTF for gravimetric water content ($kg\ kg^{-1}$)														
Pidgeon (1972)	0.57	0.37	-0.34	0.25	0.37	0.53	0.39	-0.35	0.27	0.41	0.14	0.08	0.04	0.21	0.42
Aina & Periaswamy (1985)	no	no	no	no	no	0.39	0.19	-0.16	0.09	0.27	0.12	0.19	0.09	0.17	0.37
Arruda et al. (1987)	no	no	no	no	no	0.24	0.07	-0.01	0.13	0.35	0.14	0.07	0.08	0.15	0.31
Dijkerman (1988)	no	no	no	no	no	0.19	0.09	0.05	0.11	0.28	0.16	0.08	0.06	0.21	0.37

$\bar{x}$: mean of the estimated values ($m^3\ m^{-3}$); RMSE: root mean square error; ME: mean error; R^2: coefficient determination; *CI*: Confidence Index proposed by Camargo & Sentelhas (1987); no: no PTF for that potential.

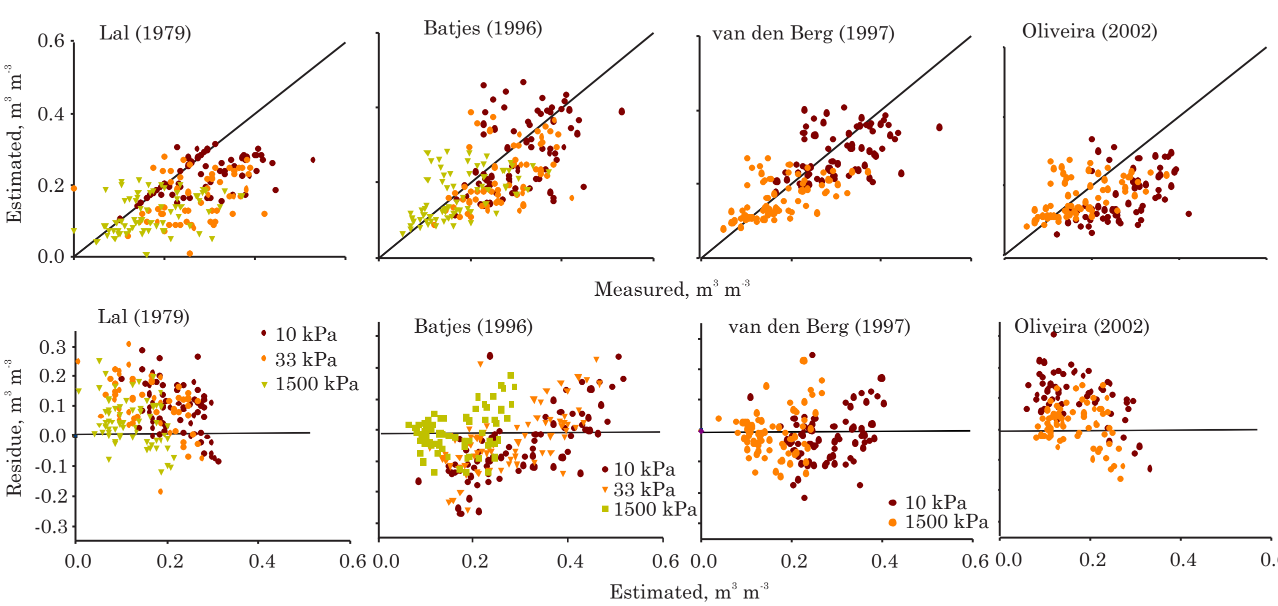

Figure 6. Estimated *vs* measured volumetric water content, and estimation residues of the point PTFs tested for all depths (n = 67).

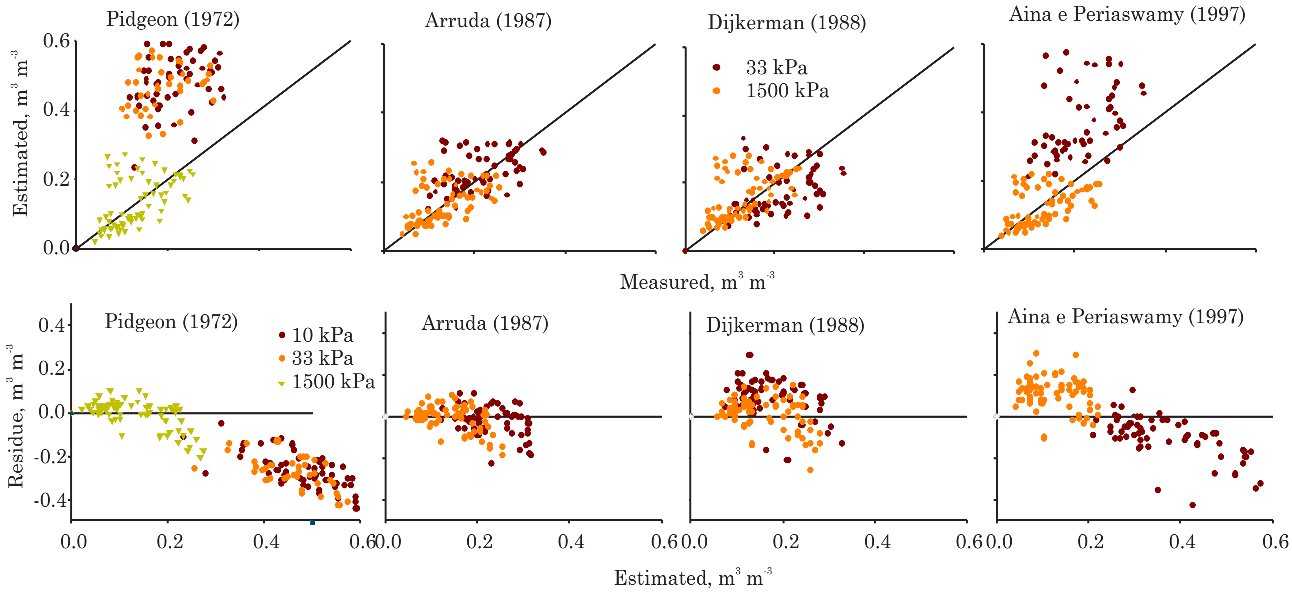

Figure 7. Estimated *vs* measured gravimetric water content, and estimation residues for the point PTFs tested for all depths (n = 67).

the limited number of predictive variables, which may cause a reduction in the robustness of the PTFs. Another effect to consider is the type of clay found in soils, given that the mineralogy of the clay fraction determines the amount of water a soil can retain. Furthermore, soil mineralogy is one of the factors responsible for the formation of different types of microstructure, which also affects the SWRC (Gaiser et al., 2000).

CONCLUSIONS

1. Parametric PTFs were more efficient than point PTFs in estimating water content at specific potentials (-10, -33, -1500 kPa).

2. Among the PTFs tested, those elaborated with homogeneous sets of soils do not show good efficiency for the set of soils that were tested.

3. All parametric PTFs assessed in this study, except for those proposed by Tomasella et al. (2000), levels 1 and 2, showed limited capacity for predicting the SWRC.

4. The Tomasella PTFs showed higher efficiency when tested in the topsoil layer (0-5 cm) than when tested for the three depths combined (0-5, 10-15, and 40-45 cm).

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