

Frontiers in Hydro pedology:  
Interdisciplinary Research  
from Soil Architecture to the  
Critical Zone

# HYBRAS

Hydrophysical Database for Brazilian Soils

## Core Ideas

- We propose a Hydrophysical Database for Brazilian Soils (HYBRAS).
- Data in HYBRAS comprise 445 soil profiles, with 1075 samples of Brazilian soils.
- We compared the accuracy of water retention estimates based on climate-based PTFs.
- In general, the Brazilian PTFs performed better than the temperate models for HYBRAS.
- Model performance differed due to clay content and mineralogical properties.

M.V. Ottoni, Dep. of Hydrology, Geological Survey of Brazil (CPRM), Rio de Janeiro, RJ, Brazil; T.B. Ottoni Filho, Dep. of Water Resources and Environment, Politechnical School, Federal Univ. of Rio de Janeiro, Rio de Janeiro, RJ, Brazil; M.G. Schaap, Dep. of Soil Water and Environmental Science and Dep. of Hydrology and Atmospheric Sciences, Univ. of Arizona, Tucson, AZ 85721; M.L.R.C. Lopes-Assad, Dep. of Natural Resources and Environmental Protection, Federal Univ. of São Carlos, Araras, SP, Brazil; O.C. Rotunno Filho, Civil Engineering Program, Alberto Luiz Coimbra Institute for Postgraduate Studies and Research in Engineering (COPPE), Federal Univ. of Rio de Janeiro, Rio de Janeiro, RJ, Brazil. \*Corresponding author (marta.ottoni@cprm.gov.br).

Received 8 May 2017.  
Accepted 20 Aug. 2017.

Citation: Ottoni, M.V., T.B. Ottoni Filho, M.G. Schaap, M.L.R.C. Lopes-Assad, and O.C. Rotunno Filho. 2018. Hydrophysical database for Brazilian soils (HYBRAS) and pedotransfer functions for water retention. *Vadose Zone J.* 17:170095. doi:10.2136/vzj2017.05.0095

© Soil Science Society of America.  
This is an open access article distributed under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

## Hydrophysical Database for Brazilian Soils (HYBRAS) and Pedotransfer Functions for Water Retention

Marta Vasconcelos Ottoni,\* Theophilo Benedicto Ottoni Filho, Marcel G. Schaap, Maria Leonor R.C. Lopes-Assad, and Otto Corrêa Rotunno Filho

Soil water retention data are fundamental in soil modeling studies. Temperate pedotransfer functions (PTFs) have been commonly used to estimate water retention of Brazilian soils, mainly because of the lack of soil data for Brazil. However, these PTFs may not be suitable for tropical or subtropical conditions such as those found in Brazil. The objective of this study was to establish a dedicated Hydrophysical Database for Brazilian Soils (HYBRAS) suitable for PTF development. Data present in HYBRAS comprise 445 soil profiles with 1075 samples and are representative of a wide range of Brazilian soils. The data are organized in a relational structure of tables that cover general site descriptions, land cover, and hydrophysical and chemical measurement methods. Raw data (e.g., water retention points covering the 0–15,000-cm suction range) and derived data are included in the tables. Another objective of this study was to use the database to compare the accuracy of water retention estimates based on PTFs developed for Brazilian and temperate regions. In general, the Brazilian PTFs performed better than the temperate models, especially for weathered (Ferralsols, Acrisols, and Nitisols) fine-textured (clay, sandy clay, clay loam, silty clay loam, and silty clay) soils. Silt content was not a successful criterion for distinguishing performance of Brazilian and temperate PTFs for Brazilian weathered soils. The water retention of weathered soils was shown to differ from that of temperate soils due to differences in pore structure resulting from their clay content and mineralogical nature, thus confirming results reported in the literature.

Abbreviations: HYBRAS, Hydrophysical Database for Brazilian Soils; HYPRES, Hydraulic Properties of European Soil; ME, mean error; pF,  $\log_{10}$  suction; PTF, pedotransfer function; UNSODA, Unsaturated Soil Hydraulic Database; VG, van Genuchten.

Soil water retention data are fundamental in soil modeling studies. Their direct measurement is costly and demands intense field work, which makes it infeasible for large areas. As a result, pedotransfer functions (PTFs) (Bouma, 1989) are being developed and used increasingly to estimate water retention data from routinely available soil measures.

Brazil plays an important role in the development of tropical water retention PTFs (Botula et al., 2014). Barros and de Jong van Lier (2014) extensively reviewed water retention PTFs for Brazilian soils. These PTFs are commonly developed to estimate the available water content on the basis of field capacity and permanent wilting point, with their use often restricted to certain types of soils or geographic regions (Barros and de Jong van Lier, 2014). To our knowledge and according to Barros and de Jong van Lier (2014), the studies by Tomasella and Hodnett (1998), Tomasella et al. (2000, 2003), Tormena and da Silva (2002), de Mello et al. (2005), Fidalski and Tormena (2007), da Silva et al. (2008), Fiorin (2008), Barros et al. (2013) and Medrado and Lima (2014) are the main publications on PTF development in Brazil for water retention parameters, so-called parametric PTFs, which then can be used directly in mathematical models (Patil and Singh, 2016). The above PTFs were generated using limited soil databases and/or specific geographic regions, whereas some of their predictors are not easily accessible, such as the moisture equivalent

used in Tomasella et al. (2000, 2003). Since these facts limit the use of the parametric Brazilian PTFs in soil modeling studies, temperate PTFs are frequently used for Brazilian soils.

One of the main reasons for slow advances in PTF development in Brazil relative to temperate regions is the lack of an organized hydrophysical soil database (Barros and de Jong Lier, 2014). However, a study by Ottoni et al. (2014) pointed to the viability of setting up an extensive and representative hydrophysical database for Brazilian soils based on a survey of 52 publications containing information available on soil hydrophysical properties. The BDSOLOS (Brazilian Soil Information System Database; BDSOLOS, 2017), a database containing soil profile data and samples from all regions of Brazil, was recently launched. However, this database contains few measurements of hydraulic properties. For example, only 14 of the records contain water content data in a broad suction range (0–15,000 cm). More extensive soil databases with hydrophysical data exist for temperate environments, such as the Unsaturated Soil Hydraulic Database (UNSODA; Nemes et al., 2001), and, more recently, the European Hydropedological Data Inventory (EU-HYDI; Tóth et al., 2015).

The indiscriminate application of temperate PTFs to tropical soils may lead to inconsistent and misleading modeling results and to inappropriate or faulty decision making (Botula et al., 2012). Temperate PTFs may fail to represent the typical hydraulic functioning of tropical soils, such as the hybrid behavior of Oxisols, which have a predominance of kaolinitic and oxidic clays (Tomasella and Hodnett, 2004). Additionally, temperate soil PTFs only minimally cover the clay content ranges usually found for tropical Oxisols (Tomasella and Hodnett, 2004). Hodnett and Tomasella (2002) and Minasny and Hartemink (2011) reported other relevant differences between tropical and temperate soils, such as in the bulk density and cation exchange capacity. Tomasella et al. (2000), Reichert et al. (2009), Botula et al. (2012), and Nguyen et al. (2015) corroborated the better performance of tropical soil PTFs, in relation to the temperate PTFs, for estimating some of the hydraulic properties they investigated. In contrast, Manyame et al. (2007) noted that temperate PTFs can be used to model the hydraulic properties of sandy soils from Nigeria with reasonable reliability. Botula et al. (2012) highlighted that the temperate PTFs from Schaap et al. (2001) predicted water retention at field capacity and wilting point of African tropical soils well. Therefore, expanding our knowledge of the interface between the hydrophysical behavior of tropical and temperate soils is necessary and may contribute to a better understanding of the interactions between pedogenic and hydraulic processes, as well as help clarify the extension of the applicability of PTFs. Brazil still lacks studies comparing the performance of Brazilian and temperate PTFs using an independent and large Brazilian soil database covering different soil types and regions. The work by Tomasella et al. (2000) is one of the pioneering studies with this objective. Reichert et al. (2009) and Medeiros et al. (2014) also contributed to this

approach. However, the independent soil databases used in the two latter studies were related to specific geographic regions of the Brazilian territory (Rio Grande do Sul state and the Amazonian region, respectively). In addition, Tomasella et al. (2000) and Medeiros et al. (2014) used limited numbers of samples in their PTF validation (113 and 67 samples, respectively).

The main objectives of this study were (i) to present a hydrophysical database for Brazilian soils, and (ii) to use the database to compare the accuracy of water retention estimates based on PTFs developed for Brazilian and temperate regions.

## HYBRAS: Hydrophysical Database for Brazilian Soils

The Hydrophysical Database for Brazilian Soils (HYBRAS) is an initiative of the Department of Hydrology of the Geological Survey of Brazil (Companhia de Pesquisa de Recursos Minerais) with the support of the Federal University of Rio de Janeiro. The main objective of the HYBRAS project was to provide consistent and good-quality soil hydrophysical data suitable for PTF development. The project was developed between 2011 and 2015 with collaboration from Brazilian and foreign researchers.

The HYBRAS 1.0 (Version 1) database gathers water retention and saturated hydraulic conductivity ( $K_s$ ) data together with basic soil attributes and soil property measurement methods. The inclusion of unsaturated hydraulic conductivity information is planned for a future version. HYBRAS is available from the corresponding author on request.

### Database Structure

The HYBRAS database was developed using the Microsoft Access 2007 format. The database structure (Fig. 1) was based mainly on HYPRES (Hydraulic Properties of European Soils; Wösten et al., 1999) and partially on UNSODA (Nemes et al., 2001) datasets. The table field descriptions, as well as the table names, are in English, as HYBRAS is meant to have broad public access; however, the records are in Portuguese.

Data are recorded in 14 tables organized in logical groups containing related information. Soil samples are identified in the “code” field, which appears in nearly all database tables, and through which the tables are usually linked. Integer numbers are attributed to this field. The structure of each individual table and the names, data types, and descriptions of each field in the table can be inspected by opening a table in the “Design View.” Missing data are usually indicated with the NULL value, or the sequence 999 for the method tables.

The main HYBRAS table (GENERAL) holds master information about the soils (location, soil group, soil profile description,

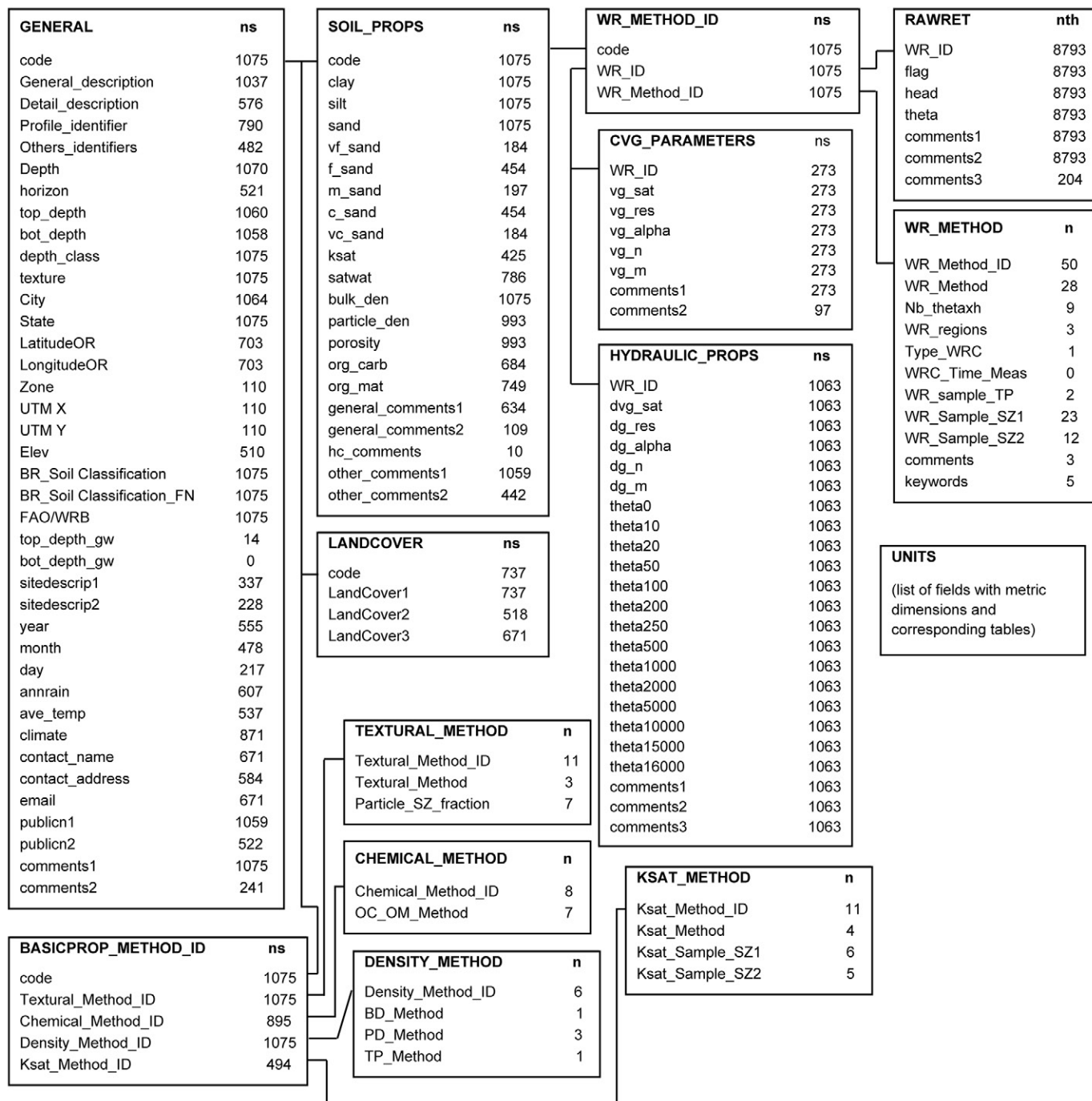


Fig. 1. Relationships between tables in the HYBRAS; ns, number of soil samples; n, number of methods of determination of the indicated soil variable; nth, number of  $\theta-s$  data pairs, where  $\theta$  is the volumetric water content and  $s$  is the suction.

etc.). Soil physical attributes are recorded in the SOIL\_PROPS table, including  $K_s$ . The LAND COVER table describes soil cover classes in a three-level hierarchy. The first level follows the classification criteria of the first category level of the European Land Use and Land Cover Classification System, LUCAS-Land Use/Cover Area Frame Survey (European Commission, 2009). The second and third hierarchical levels record crop types and soil treatment, respectively. The reason for organizing such data is their capacity to possibly improve soil hydraulic estimation by means of PTFs.

The RAWRET table contains all of the contributed data on the  $\theta-s$  pairs, that is, volumetric water content ( $\theta$ ) vs. suction ( $s$ , taken to be positive here). The HYDRAULIC\_PROPS table contains the van Genuchten (VG) parameters (van Genuchten, 1980) fitted to the water retention measurements from RAWRET, as well as calculated  $\theta$  values at predetermined pressure head ( $s$ ) values and the parameter fitting methodology (described below). Contributed VG parameters recorded in the source publication are stored in the CVG\_PARAMETERS table, together with the parameter

fitting procedure. The data from the last three tables are identified by non-numerical codes described in the “WR\_ID” field, which allows linking the other fields of the three tables to the “code” field (Fig. 1). Even though HYBRAS does not contain unsaturated hydraulic conductivity measurements, they can be estimated from the VG water retention parameters and the  $K_s$  data using the traditional Mualem–van Genuchten model (van Genuchten, 1980).

There are two types of tables that contain information on soil properties methods; one contains code fields, and the other method descriptions. The BASICPROP\_METHOD\_ID and WR\_METHOD\_ID tables hold the code fields, the first related to basic soil attributes, and the second to water retention information. The method descriptions are stored in the tables KSAT\_METHOD, TEXTURAL\_METHOD, DENSITY\_METHOD, CHEMICAL\_METHOD, and WR\_METHOD. Each record from the last five tables has a numerical identification stored in a separate field named with the ending “Method\_ID,” through which the BASICPROP\_METHOD\_ID or WR\_METHOD\_ID tables are linked (Fig. 1). Some auxiliary tables are included also in HYBRAS. The table UNITS provides a summary of measurement units of numerical fields present in the database. Two additional hidden tables, Example\_Query1\_general\_information and Example\_Query2\_WRdata, are used in a predefined query. To run a specific query, the user must select one of the two query tables in Design View and then include or exclude the tables and fields of interest. The query result will be displayed in the Layout View.

## Data Collection and Description

The HYBRAS data were taken from publications compiled in the study by Ottoni et al. (2014), and other sources (Table 1). The following soil sample selection criteria were adopted: undisturbed samples with at least five water retention measurements in a broad suction range (0–15,000 cm) performed by methods in which the water pressure and water content were measured directly (such as in the pressure plate method). To ensure that the water retention datasets were well distributed along the suction range, one point was always for saturation conditions (saturated water content or total porosity); another three points were at suction intervals 30 to 80, 250 to 500, and 9000 to 15,000 cm; and a fifth point was outside the suction ranges above. Additionally, information on sand, silt, and clay contents, as well as on bulk density, must be available.

Approximately 9000 samples were gathered from some 60 scientific studies; the majority of the samples were eliminated for not meeting the sample selection criteria. The contributed data were in various forms, either in print or digital. The information was standardized following the structure proposed for HYBRAS, and the data were checked for consistency (data consistency method not presented here). The HYBRAS 1.0 database comprises approximately 16 Mb of data. The database

Table 1. Source references in the Hydrophysical Database for Brazilian Soils (HYBRAS) database.

Reference	States	n†
Aguiar (2008)	Ceará, Minas Gerais	6
Andrade (1987)	Minas Gerais	5
Araujo, Jr., et al. (2011)	Minas Gerais	45
Azevedo (1976)	Minas Gerais	10
Barcelos (1996)	Rio Grande do Sul	9
Bhering (2007)	Rio de Janeiro	9
Carducci et al. (2011)	Goiás	10
Cintra and Libardi (1998)	Sergipe	5
Coelho et al. (2005a, 2005b)	Amazonas	35
Cooper’s soil database‡	São Paulo	76
Costa and Libardi (1999), Costa (1986)	São Paulo	10
da Costa (1993)	Rio Grande do Sul	23
da Silva et al. (2005), da Silva (2003)	Rio Grande do Sul	16
Embrapa and FAO (1991)	Maranhão, Pará	62
Ferreira (2007)	São Paulo	55
Grego et al. (2011)	São Paulo	15
Leal (2011)	Rio de Janeiro	50
Lumbreiras (1996)	Maranhão	20
Macedo (1991)	Rio de Janeiro	45
Marquesi et al. (2010)	Amazonas	25
Moreira and Silva (1987)	Pernambuco	5
Nacif (1994), Nacif et al. (2008)	Bahia	20
Nebel et al. (2010), Parfitt (2009)	Rio Grande do Sul	100
Neuwald (2005)	Santa Catarina	75
Parfitt (2009)	Rio Grande do Sul	99
Rojas (1998)	Rio Grande do Sul	36
Scardua (1972)	São Paulo	12
Souto Filho (2012)	Mato Grosso do Sul	12
Souza and Souza (2001)	Bahia	36
Stone’s soil database§	Goiás	88
Thurler (2000)	Espírito Santo, Rio de Janeiro	13
Toma (2012)	São Paulo	15
Vasconcellos (1993)	Rio Grande do Sul	33
	total	1075

† Number of soil samples with selected water retention data.

‡ Data by Miguel Cooper, from Luiz de Queiroz College of Agriculture (ES-ALQ), University of São Paulo, Brazil.

§ Data by Luis Fernando Stone, from Embrapa, National Center of Rice and Bean Research, Goiás, Brazil.

currently contains 445 sampled locations (or profiles) with 1075 samples, many of which are georeferenced (813 samples), representing 15 of the 26 Brazilian states and 11 different soil groups according to the FAO soil classification system (IUSS Working Group WRB, 2015). Only 588 samples would have been grouped for the HYPRES database (Wösten et al., 1999) if the same sample selection criteria as those for HYBRAS had

been used. This comparison shows the potential of HYBRAS for assembling water retention information across a wide suction range (0–15,000 cm).

Figure 2 shows the geographical locations of the HYBRAS sampling sites and the number of samples in each state of Brazil. The states with the greatest number of data are Rio Grande do Sul, São Paulo, and Rio de Janeiro, three states where major Brazilian pedological research centers are concentrated. The main soil groups are Ferralsols (355 samples), Acrisols (209 samples), and Nitisols (108 samples), which are representative of weathered tropical environments, the first two being predominant in Brazil and corresponding to 60% of the Brazilian territory (Ottoni et al., 2014). Planosols (192 samples), Gleysols (82), Cambisols (69), Phaeozems (28), Podzols (16), Histosols (8), Regosols (6), and Fluvisols (2) are also included. According to Tomasella et al. (2000), Brazilian weathered soils mostly have a low silt content (<20%) (Fig. 3a), as was also pointed out by Oliveira (1968). Despite the low representation of coarse-textured soils (sand and loamy sand) in HYBRAS (Fig. 3b), the presence of Arenosols and other soils with high sand content is common in Brazil. Soils with high silt content (>50%) are underrepresented in HYBRAS because they are not frequent in Brazil (Benedetti et al., 2008; Leão, 2016).

## Soil Hydrophysical Data

The HYBRAS database contains consistent and well-defined measurement methods of the soil properties (Table 2), with ranges in the soil properties (Fig. 4) being larger than those in other studies of Brazilian soils (Assad et al., 2001; Tomasella et al., 2003; Reichert et al., 2009; da Costa et al., 2013; Barros et al., 2013; Medeiros et al., 2014; Medrado and Lima, 2014). The HYBRAS soils are comparable in general with those from Hodnett and Tomasella (2002), who worked with tropical soils worldwide. All of these factors increases the potential of the HYBRAS database to generate accurate water retention PTFs.

Soils with a high organic matter content (>6%) and low bulk density (<0.8 g cm<sup>-3</sup>) are underrepresented in HYBRAS, as are those with a high silt content (>50%) (Fig. 4), as mentioned previously. Average HYBRAS hydrophysical values for the various textural classes and soil groups according to the FAO system (IUSS Working Group WRB, 2015) are shown in Table 3. Although  $K_s$  was available for only 425 samples, the data covered a relatively wide range of values (Fig. 4). The geometric mean of  $K_s$  for the Brazilian clay soils was 65 cm d<sup>-1</sup> (Table 3), highly contrasting with the usual  $K_s$  range of 2 to 5 cm d<sup>-1</sup> reported in the literature for clays of temperate soils (Tietje and Hennings, 1996; Rawls, 2004). The available water content, arbitrarily taken as the difference



Fig. 2. Distribution of HYBRAS sampling locations with water retention data in Brazil (1075 samples).

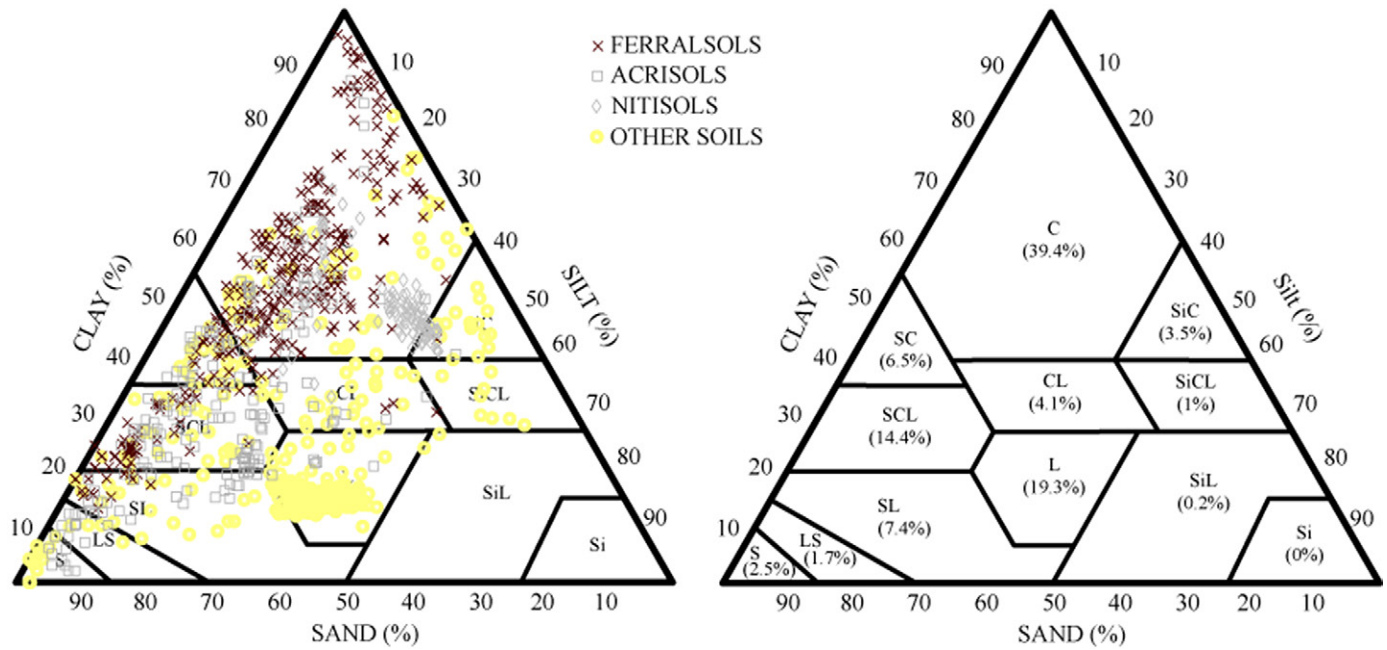


Fig. 3. (a) Distribution of HYBRAS soil samples (1075 samples) in the USDA soil textural triangle, highlighting Ferralsols, Acrisols, and Nitisols, and (b) percentage of samples in each soil texture class: clay (C), sandy clay (SC), clay loam (CL), sandy clay loam (SCL), sandy loam (SL), loamy sand (LS), sand (S), loam (L), silty clay (SiC), silty clay loam (SiCL), silt loam (SiL), silt (Si).

between field capacity and permanent wilting point, was low ( $\sim 0.07 \text{ cm}^3 \text{ cm}^{-3}$ , average for 896 samples). In this study, we arbitrarily adopted the classical water contents at suctions 330 and 15,000 cm for the field capacity and the permanent wilting point, respectively. Our result for available water ( $\sim 0.07 \text{ cm}^3 \text{ cm}^{-3}$ ) was close to that reported by Batjes (1996) for fine-textured Ferralsols ( $0.08 \text{ cm}^3 \text{ cm}^{-3}$ ).

The HYBRAS database contains 8793  $\theta$ - $s$  pairs (RAWRET table), pertaining to 1075 soil samples (Fig. 1). The distribution of recorded water suctions in these samples shows a greater concentration at suctions of 60 (876 samples), 100 (1042), 330 (905), 1000 (1043), and 15,000 cm (1066). The number of  $\theta$ - $s$  pairs per sample in the database is fairly homogeneous. A total of 483 samples are from the soil surface (topsoil), and the others (592) are classified as subsoil samples. The topsoil and subsoil classification followed the methodology described in the supplemental material of Tóth et al.

(2015). Among the subsoil samples, the deepest ones (50) were taken from horizons with their top at depths  $>1 \text{ m}$  (only seven samples were from horizons deeper than 1.50 m).

### Model Parameters and Their Performance in the Estimation of Water Retention Data

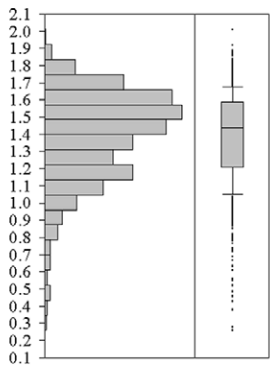
The four parameters of the VG equation ( $\theta_s$ ,  $\theta_r$ ,  $\alpha$ , and  $n$ ) were fitted to the experimental water retention data using the GlobalSearch function from the Global Optimization Toolbox in MATLAB (MathWorks, 2014). Only samples with at least six  $\theta$ - $s$  pairs (1063 samples), including the saturated water content (or total porosity when saturated water content was not available), were considered for the optimization procedure. The van Genuchten equation is given as

$$\theta(s) = \theta_r + (\theta_s - \theta_r) \left[ 1 + (\alpha s)^n \right]^{-(1+1/n)} \quad [1]$$

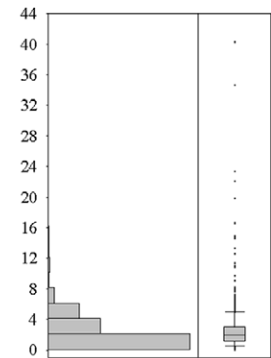
Table 2. Predominant measurement methods of soil properties in HYBRAS. Granulometric fractions follow the USDA system.

Soil property	Soil samples	Predominant measurement methods	Percentage
	no.		%
Saturated hydraulic conductivity	425	constant-head permeameter	80
Granulometric fractions	1075	pipette	67
		densimeter	27
Organic carbon	910	Walkley and Black (1934) by titration	85
Particle density	1075	volumetric flask and pycnometer	91
Bulk density	1075	volumetric ring	100
Water retention curve	1075	tension tables for suctions between saturation and 60 cm, and pressure chambers for higher suctions	60
		pressure chambers for the entire suction range	22

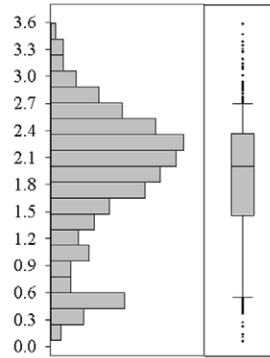
**BULK DENSITY ( $\text{g cm}^{-3}$ )**  
ns=1075 soil samples



**ORGANIC MATTER (%)**  
ns=910 soil samples†

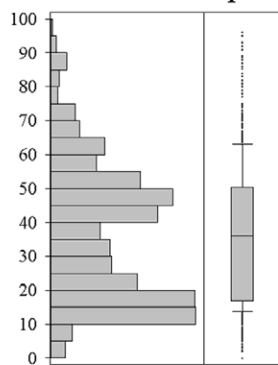


**LOG<sub>10</sub>KSAT ( $\text{cm d}^{-1}$ )**  
ns=419 soil samples‡



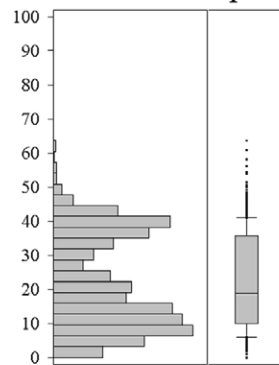
**CLAY (%)**

ns=1075 soil samples



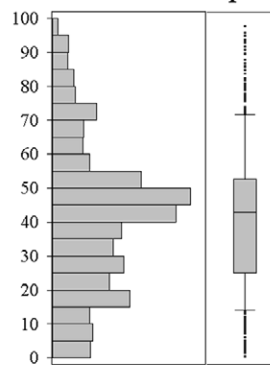
**SILT (%)**

ns=1075 soil samples

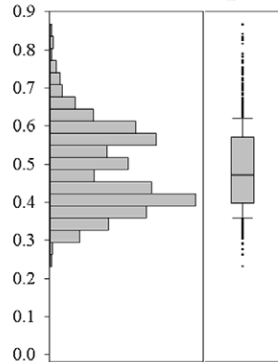


**SAND (%)**

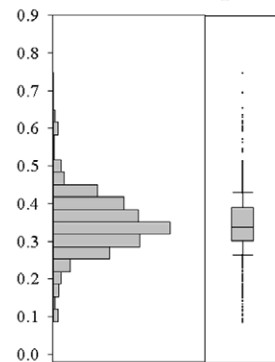
ns=1075 soil samples



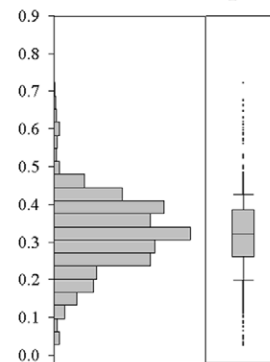
**$\theta$  at s=0 cm ( $\text{cm}^3 \text{cm}^{-3}$ )§**  
ns=1075 soil samples



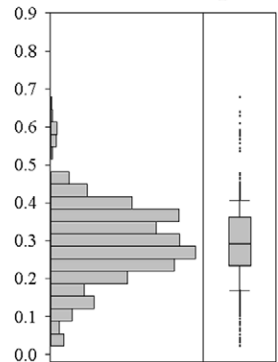
**$\theta$  at s=60 cm ( $\text{cm}^3 \text{cm}^{-3}$ )**  
ns=876 soil samples



**$\theta$  at s=100 cm ( $\text{cm}^3 \text{cm}^{-3}$ )**  
ns=1042 soil samples



**$\theta$  at s=330 cm ( $\text{cm}^3 \text{cm}^{-3}$ )**  
ns=905 soil samples



**$\theta$  at s=15,000 cm ( $\text{cm}^3 \text{cm}^{-3}$ )**  
ns=1066 soil samples

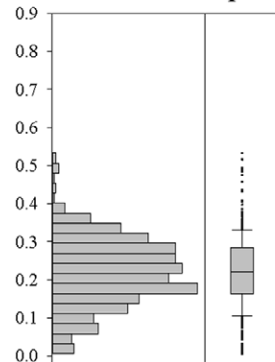


Fig. 4. Distribution of hydrophysical properties in the HYBRAS database. The bar inside the box plot indicates the median value, and the bottom and top of the box are the 25 and 75% quartiles, respectively. The extreme bars indicate the whiskers. The outliers are outside these extreme bars. †The percentages of organic carbon of 161 samples were converted to organic matter values using a multiplying factor of 1.724 (Embrapa, 2011). ‡Six unrepresented samples have saturated hydraulic conductivity expressed as  $0 \text{ cm d}^{-1}$ . §Saturated water content or total porosity when the former was unavailable (289 samples); ns, number of soil samples;  $\log_{10}K_s$ ,  $\log_{10}$  of the saturated hydraulic conductivity;  $\theta$ , volumetric water content; s, water suction.

Table 3. Average values of hydrophysical data in the HYBRAS database, including bulk density (BD), organic matter content (OM), water content at different suctions ( $\theta$ -s), and saturated hydraulic conductivity ( $K_s$ ) calculated as the geometric mean, for various textural classes and soil groups according to the FAO system (IUSS Working Group WRB, 2015).

Soil type	Sand	Silt	Clay	BD	OM	$\theta$ (0 cm)	$\theta$ (60 cm)	$\theta$ (330 cm)	$\theta$ (15,000 cm)	$K_s$
	%			$\text{g cm}^{-3}$	%	$\text{cm}^3 \text{cm}^{-3}$				$\text{cm d}^{-1}$
Sand	92.8 (27)†	2.8	4.4	1.59 (27)	1.76 (27)	0.40 (27)	0.11 (10)	0.08 (27)	0.05 (27)	184 (12)
Loamy sand	85.1 (18)	5.0	9.9	1.52 (18)	2.25 (18)	0.38 (18)	– (4)	0.13 (18)	0.04 (18)	– (8)
Sandy loam	69.8 (80)	14.6	15.6	1.51 (80)	2.17 (65)	0.41 (80)	0.27 (60)	0.21 (58)	0.13 (80)	135 (39)
Loam	45.8 (207)	38.8	15.4	1.60 (207)	2.31 (204)	0.41 (207)	0.33 (207)	0.27 (206)	0.19 (207)	– (6)
Silt loam	– (2)	–	–	– (2)	– (2)	– (2)	– (2)	– (2)	– (2)	– (0)
Sandy clay loam	62.1 (155)	11.6	26.2	1.52 (155)	1.76 (131)	0.42 (155)	0.30 (121)	0.22 (107)	0.16 (155)	66 (74)
Clay loam	34.8 (44)	32.6	32.6	1.23 (44)	4.60 (34)	0.52 (44)	0.39 (43)	0.35 (38)	0.27 (44)	56 (21)
Silty clay loam	12.2 (10)	54.6	33.3	0.97 (10)	6.69 (10)	0.61 (10)	0.44 (10)	0.39 (10)	0.29 (10)	– (4)
Silty clay	12.6 (38)	43.5	44.0	1.17 (38)	4.11 (38)	0.57 (38)	0.41 (38)	0.37 (37)	0.29 (38)	– (7)
Sandy clay	50.0 (70)	9.7	40.3	1.42 (70)	1.74 (54)	0.47 (70)	0.33 (50)	0.28 (52)	0.20 (70)	52 (43)
Clay	24.2 (424)	18.8	57.0	1.24 (424)	2.61 (327)	0.56 (424)	0.39 (331)	0.35 (350)	0.29 (415)	65 (205)
Ferralsol	36.3 (355)	13.5	50.2	1.29 (355)	2.04 (237)	0.537 (355)	0.351 (231)	0.314 (258)	0.243 (346)	70.3 (224)
Acrisol	55.4 (209)	14.6	30.0	1.50 (209)	1.95 (164)	0.422 (209)	0.298 (185)	0.212 (154)	0.175 (209)	103.5 (101)
Nitisol	19.1 (108)	31.5	49.3	1.30 (108)	3.77 (108)	0.542 (108)	0.385 (98)	0.338 (97)	0.268 (108)	– (5)
Cambisol	33.4 (69)	23.4	43.2	1.16 (69)	2.81 (67)	0.561 (69)	0.391 (55)	0.366 (65)	0.245 (69)	50.7 (46)
Gleysol	42.2 (82)	29.8	27.9	1.29 (82)	3.73 (82)	0.502 (82)	0.402 (71)	0.332 (81)	0.241 (82)	66.5 (28)
Planosol	47.0 (192)	36.5	16.6	1.63 (192)	1.80 (192)	0.390 (192)	0.321 (192)	0.260 (192)	0.186 (192)	– (0)
Phaeozem	35.4 (28)	32.3	32.4	1.40 (28)	2.37 (28)	0.453 (28)	0.404 (28)	0.370 (28)	0.303 (28)	– (0)
Fluvisol	– (2)	–	–	– (2)	– (2)	– (2)	– (2)	– (0)	– (2)	– (0)
Histosol	– (8)	–	–	– (8)	– (8)	– (8)	– (8)	– (8)	– (8)	– (6)
Podzol	92.2 (16)	2.1 (16)	5.7	1.42 (16)	3.81 (16)	0.477 (16)	– (0)	0.166 (16)	0.080 (16)	– (9)
Regosol	– (6)	–	–	– (6)	– (6)	– (6)	– (6)	– (6)	– (6)	– (0)
All soils	41.6	21.9	36.5	1.4	2.51	0.484	0.346	0.293	0.221	74.8

† The number of soil samples is given in parentheses; data with fewer than 10 soil samples per group are not represented.

where  $\theta(s)$  is the volumetric water content ( $\text{cm}^3 \text{cm}^{-3}$ ) at suction  $s$  (cm),  $\theta_s$  and  $\theta_r$  are the saturated and residual water contents, respectively ( $\text{cm}^3 \text{cm}^{-3}$ ), and  $\alpha$  ( $\text{cm}^{-1}$ ) and  $n$  (dimensionless) are curve

shape parameters. The parameter optimization was subjected to the following constraints:  $\theta_r$  [0.000; 0.533  $\text{cm}^3 \text{cm}^{-3}$ ],  $\theta_s$  [0.10; 0.96  $\text{cm}^3 \text{cm}^{-3}$ ],  $\alpha$  [0.00001; 0.99999  $\text{cm}^{-1}$ ], and  $n$  [1.01; 15.0].



The limits of  $\alpha$  and  $n$  followed those found in Tóth et al. (2015). The final results are shown in Fig. 5.

The average  $\theta_p$ ,  $\theta_s$ , and  $n$  values were relatively close to the corresponding VG parameter values found by Hodnett and Tomasella (2002) (Fig. 5). The greatest discrepancy was in the magnitude of  $\alpha$  (Fig. 5), which can be partially attributed to the use of different constraints for its fitting interval, as well as its larger variation (many orders of magnitude). A more refined data analysis may be warranted for the development of future PTFs of Brazilian soils, including of the unsaturated hydraulic conductivity.

Root mean square error (RMSE) and mean error (ME) indicators were used to evaluate the performance of the VG model in describing the measured water retention data. Both indicators were defined for each soil sample (subscript “s”) or other  $\theta$ -data grouping (subscript “rs”):

$$RMSE_s = \sqrt{\frac{1}{L-4} \sum_{j=1}^L (\theta_{p_j} - \theta_{m_j})^2} \quad [2]$$

$$ME_s = \frac{1}{L-4} \sum_{j=1}^L (\theta_{p_j} - \theta_{m_j}) \quad [3]$$

$$RMSE_{rs} = \sqrt{\frac{1}{TN} \sum_{j=1}^{TN} (\theta_{p_j} - \theta_{m_j})^2} \quad [4]$$

$$ME_{rs} = \frac{1}{TN} \sum_{j=1}^{TN} (\theta_{p_j} - \theta_{m_j}) \quad [5]$$

where  $L$  is the number of measurements per sample, with four representing the number of parameters,  $TN$  is the total number of measurements per suction interval (or per bulk density, silt interval, or a given soil group, as described in the Results and Discussion), and  $\theta_m$  and  $\theta_p$  are the measured and predicted water content values, respectively. The RMSE informs the global prediction error, while ME expresses the overestimation ( $ME > 0$ ) or underestimation ( $ME < 0$ ) tendency.

The VG model was suitable for fitting HYBRAS water retention data, with a mean  $RMSE_s$  in the order of  $0.0107 \text{ cm}^3 \text{ cm}^{-3}$ , lower than that reported by Tomasella et al. (2003) ( $0.013 \text{ cm}^3 \text{ cm}^{-3}$ ), without bias (mean  $ME_s \sim 0.00 \text{ cm}^3 \text{ cm}^{-3}$ ), with  $\sim 80\%$  of the samples having  $RMSE_s$  values  $< 0.015 \text{ cm}^3 \text{ cm}^{-3}$  and  $96\% < 0.030 \text{ cm}^3 \text{ cm}^{-3}$ . The parametric paired  $t$  test showed that the water retention estimates by the VG model and their corresponding water retention measurements (8732 measurements) were not

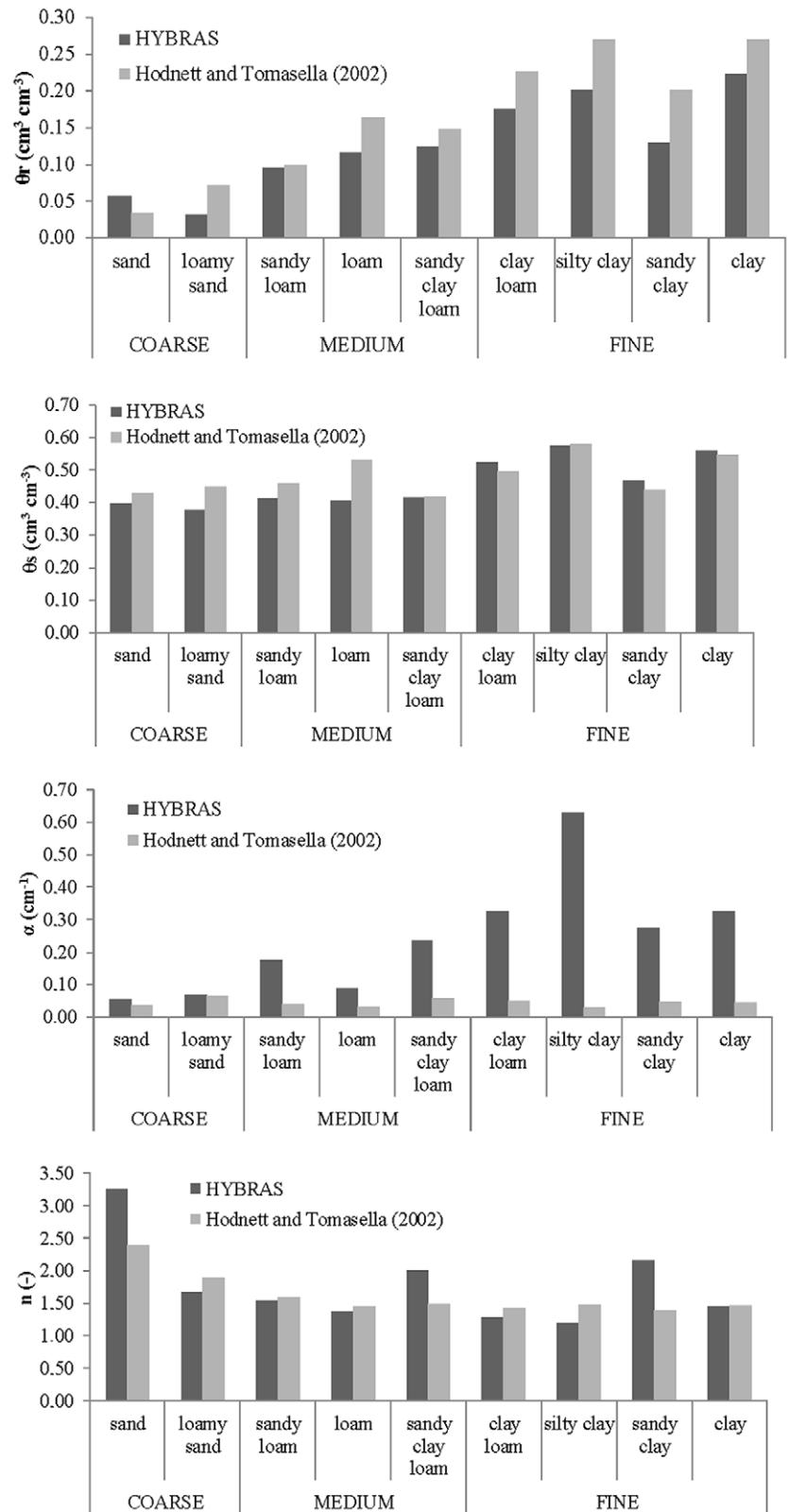


Fig. 5. Mean values of the van Genuchten parameters for soils in the HYBRAS soils (1063 samples) and the tropical soils from Hodnett and Tomasella (2002) in different USDA soil textural classes and in fine-, medium-, and coarse-textured soils, according to Cassel et al. (1983);  $\theta_s$  and  $\theta_r$  are the saturated and residual water contents, respectively, and  $\alpha$  and  $n$  are curve shape parameters.

significantly different ( $p = 0.71$ ;  $p$ -value ranged from 0 to 1; the greater its value, the greater the similarity between measured and estimated  $\theta$  values). The  $RMSE_{rs}$  magnitude was low in all suction intervals from 3 to 15,000 cm, in the order of  $0.01 \text{ cm}^3 \text{ cm}^{-3}$ , and so were the MEs (Table 4). The wet range, very close to saturation, with suction values between 1 and 3 cm, had the worst prediction performance (statistics defined in this suction interval must be treated with care due to the low data resolution, Table 4). Mean  $RMSE_s$  value per textural class did not vary significantly between textural classes, being around  $0.012 \text{ cm}^3 \text{ cm}^{-3}$ .

In general, the water retention measurements of the HYBRAS samples visually adhered well with the fitted VG curves when the  $RMSE_s$  values were less than  $0.03 \text{ cm}^3 \text{ cm}^{-3}$  (96% of the samples) (Fig. 6). For the other samples (with  $RMSE_s > 0.03 \text{ cm}^3 \text{ cm}^{-3}$ ), some soils seemed to tend toward bimodality, in which case the VG model was less effective (Fig. 6c).

## Estimation of Water Retention Data from Pedotransfer Functions

### Methodology

#### Pedotransfer Function Selection

The PTFs from Medrado and Lima (2014) (complete model) and Tomasella and Hodnett (1998), both developed for Brazilian tropical soils, were selected for predicting the water retention data from HYBRAS. The Brazilian PTFs from Tomasella et al. (2000, 2003) were not used for this evaluation since HYBRAS does not contain data for some of their predictors (e.g., moisture equivalent). Additionally, the models from Tóth et al. (2015) (Model 21) and Schaap et al. (2001) (Model H3), derived for temperate soils, were included in the evaluation. All four models were developed using extensive databases representative of large scales, even though the

Table 4. Root mean square error ( $RMSE_{rs}$ ) and mean error ( $ME_{rs}$ ) for water retention data in different suction ( $s$ ) ranges.

$s$	No. of measurements	$RMSE_{rs}$	$ME_{rs}$
cm		$\text{cm}^3 \text{ cm}^{-3}$	$\times 10^{-2} \text{ cm}^3 \text{ cm}^{-3}$
Saturation	1063	0.0106	0.0189
1–3	56	0.0304	-1.7986
3–10	116	0.0125	0.3353
10–30	551	0.0109	-0.0145
30–100	1522	0.0095	0.0741
100–320	1256	0.0084	0.2110
320–1000	1197	0.0100	-0.4004
1000–3200	1328	0.0110	-0.2504
3200–10,000	549	0.0112	0.3054
10,000–15,000	1094	0.0087	0.3216

two former models were calibrated for specific Brazilian territory biomes (Table 5). Therefore, their use is suitable for our soil database. The four PTFs above will be referred to as Savanna, Amazon, Euro, and Rosetta, respectively (Table 5). All of the PTFs are parametric and generally use a common set of predictors: bulk density,

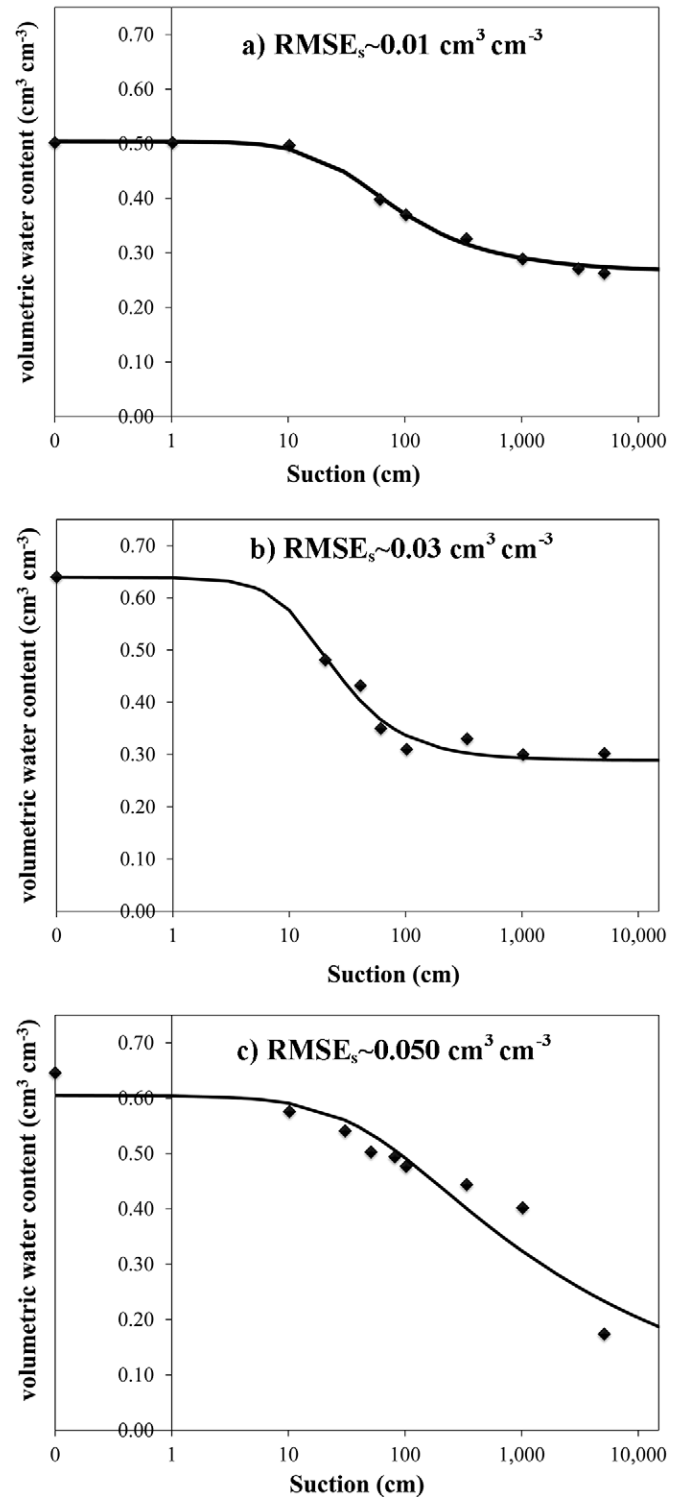


Fig. 6. Water retention curves based on the van Genuchten model and corresponding water retention measurements for some HYBRAS-soils. Root mean square error (RMSE) values are also indicated.

Table 5. Selected pedotransfer functions (PTFs) and their characteristics.

PTF	Geographic domain	$n$ †	Independent variables‡						Output§
			Clay	Silt	Sand	OM/OC	BD	T/S	
Tropical PTFs									
Savanna (complete model from Medrado and Lima, 2014)	Brazilian Savanna (Cerrado)	1092	x	x	x	x	x	–	$\theta_r, \theta_s, \alpha,$ and $n$ from the VG equation
Amazon (Tomasella and Hodnett, 1998)	Brazilian Amazonian region	416	x	x	x	–	–	–	$\theta_r, \theta_s, hb,$ and $B$ from the BC equation
Temperate PTFs									
Rosetta (Model H3 from Schaap et al., 2001)	North America and Europe	2134	x	x	x	–	x	–	$\theta_r, \theta_s, \alpha,$ and $n$ from the VG equation
Euro (Model 21 from Tóth et al., 2015)	Europe	4749	x	x	x	x	x	x	$\theta_r, \theta_s, \alpha,$ and $n$ from the VG equation

† Number of soil samples in the calibration database.

‡ x indicates the existence of data; – indicates the absence of data; OC, organic C content; OM, organic matter content; BD, bulk density; T/S, topsoil and subsoil distinction.

§  $\theta_r$ , residual water content;  $\theta_s$ , saturated water content;  $\alpha$  and  $n$ , curve shape parameters; VG, van Genuchten; hb, suction corresponding to the largest pore size (air-entry pressure);  $B$ , empirical constant; BC, Brooks and Corey.

organic matter (or organic C) content, and percentage of granulometric fractions, all using the same limits (USDA–FAO) of the sand, silt, and clay contents. Exceptions to the predictors are the Rosetta model, which does not take organic matter content into consideration, and the Amazon model, developed only for granulometric fractions (Table 5). The PTFs were generated for the VG parameters, with the exception of the PTF from Tomasella and Hodnett (1998), for which the Brooks and Corey (1964) equation was used.

### Database Selection and Pedotransfer Function Applicability

Since the soils data required by the PTFs may not be available for all of the HYBRAS samples, we first selected a set of soil samples from HYBRAS to which all the chosen PTFs could be applied. Next, we determined whether the sample data fitted the calibration database of the different PTFs. For this procedure, the applicability index proposed by Tomasella and Hodnett (2004), and used also by Nguyen et al. (2015), was used. The applicability index is defined as the ratio between the number of samples for which a given PTF can be applied and the total number of samples in the evaluated database.

### Evaluation Criteria

The performance of the PTFs was evaluated using Eq. [4] and [5] (for ease of notation, the subscript “rs” in  $RMSE_{rs}$  and  $ME_{rs}$  will be omitted from now on). The RMSE and ME values were calculated only for the 10- to 15,000-cm suction interval, since all four models were developed for suctions that contained this interval. To investigate how the RMSE and ME values varied with suction, we also computed these indicators for seven suction classes: 10 (pF 1, pF =  $\log_{10} s$ ), 30 (pF 1.5), 100 (pF 2), 316 (pF 2.5), 1000 (pF 3), 3160 (pF 3.5), 10,000 (pF 4), and 31,600 cm (pF 4.5). The RMSE was also determined for bulk density and silt intervals, as well

as textural class groups, taking into account soils representative of weathered and unweathered environments. Soils classified as Ferralsols, Acrisols, and Nitisols were considered weathered, while the others were characterized as unweathered.

## Results and Discussion

### Pedotransfer Function Applicability

From the total of 1075 HYBRAS samples, 868 had all of the information needed for evaluation of the four retained models. The applicability index was calculated according to this number of samples. The Brazilian and temperate PTFs mostly covered the range of the evaluated database (applicability index  $\geq 95\%$ ) (Table 6). For this reason, we used the 868 soil samples for the evaluation of all four PTFs in this study.

### Evaluation of the Selected Pedotransfer Functions

The lowest global RMSE and ME values were for the Brazilian PTFs (Table 7). Their superior performance in relation to the temperate PTFs was also reported by Tomasella et al. (2000), Reichert et al. (2009), and Medeiros et al. (2014). The Savanna and Amazon models had almost the same performance (RMSE in the order of  $0.065 \text{ cm}^3 \text{ cm}^{-3}$  and ME close to zero) as the two temperate PTFs when they were validated against extensive databases of temperate soils (global RMSEs of  $0.064$  [Tóth et al., 2015] and  $0.068 \text{ cm}^3 \text{ cm}^{-3}$  [Schaap et al., 2001]). This result indicates a consistent performance of the Brazilian PTFs. The global errors of the temperate models were very close to each other (Table 7), as were their errors in the suction intervals (Fig. 7 and 8). These two PTFs had a tendency to overestimate water contents for suction intervals between 10 (pF = 1) and 316 cm (pF = 2.5) and underestimate them for the other suction ranges (Fig. 8). Similar evaluations

Table 6. Applicability index of the selected pedotransfer functions (PTFs) and their validity ranges.

PTF	Applicability index	Clay	Silt	Sand	Organic matter content	Bulk density
Brazilian soils						
HYBRAS (868 samples)	–	0–96	0–63.6	0.40–97.8	0.08–11.0	0.63–2.00
Tropical PTFs						
Savanna	95	4.80–91.5	0.03–55.0	1.20–90.0	0–7.80	0.60–1.92
Amazon	100	~0–99	~0–85	~0–99	–	–
Temperate PTFs						
Rosetta	99	0–89	6–89	0–100	–	0.50 (max. not specified)
Euro	99	0–91.6	0–86.8	0–100	0 (max. not specified)	0.09–2.02

of temperate PTFs in tropical environments gave global RMSE values ranging from 0.06 to 0.20 cm<sup>3</sup> cm<sup>-3</sup>, more frequently from 0.08 to 0.10 cm<sup>3</sup> cm<sup>-3</sup> (Tomasella et al., 2000; Medina et al., 2002; Reichert et al., 2009; Botula et al., 2012; Medeiros et al., 2014; Nguyen et al., 2015), which is consistent with the errors found here. The greatest discrepancies between temperate and Brazilian PTFs were observed at very high suctions (>3160 cm [pF > 3.5], Fig. 7 and 8). The poor performance of the Rosetta model at high suctions was also reported by Cornelis et al. (2001) and Rubio and Llorens (2004); both recorded an underestimation tendency, as observed in this study (Fig. 8). A closer performance of Brazilian and temperate models was found in the suction interval from 316 cm (pF = 2.5) to 1000 cm (pF = 3.0). In fact, the RMSE of models Savanna, Amazon, Euro, and Rosetta were close to each other at a suction of 330 cm, with mean values between 0.061 and 0.070 cm<sup>3</sup> cm<sup>-3</sup>. Only in the suction range from 10 (pF = 1.0) to 31.6 cm (pF = 1.5) did a Brazilian PTF, the Amazon model, perform worse than the temperate models in terms of RMSE (Fig. 7). Among the Brazilian PTFs, the Savanna model, in general, performed the best. This model was less biased than the Amazon PTF in all the suction ranges (Fig. 8), with the exception of the range from 10 (pF = 1.0) to 100 cm (pF = 2.0); however, in this suction

interval, the RMSE of the Amazon model was higher than that of the Savanna model (Fig. 7).

Greater differences in RMSE values were found between the Brazilian and temperate models for weathered soils rather than unweathered soils (Table 7). Also, the Brazilian models performed better for the former than for the latter soils. This reflects the capacity of the two Brazilian PTFs to represent weathered soils better than soils from other pedogenic environments. In fact, the soils predominantly used for calibration of the PTFs were mostly Ferralsols, the most common soil in Brazilian weathered environments. In contrast, the performances of the Brazilian and temperate models were more comparable for unweathered soils. Tomasella et al. (2000) also reported a better performance of Brazilian PTFs relative to temperate PTFs for Brazilian weathered soils. However, their concept of weathered soils only considered the low silt content values, which differs from a weathered soil concept from a pedological classification viewpoint as adopted here.

The performance of the Brazilian and temperate PTFs was also evaluated for groups of textural classes labeled fine (clay, clay loam, sandy clay, silty clay loam, and silty clay), medium (sandy loam, loam, sandy clay loam, silty loam, and silt), and coarse (sand and loamy sand) (according to Cassel et al., 1983) for the same types of soils in Table 7 (weathered and unweathered). The Brazilian models were more accurate than the temperate models for the different textural groups (fine, medium, and coarse) and soil types (weathered and unweathered), with the exception of coarse-textured soils (Fig. 9a and 9b). The worse performance of the Brazilian models in this case may have resulted from the small number of sandy soil samples used for their calibration. In any case, the results for sandy soils (sand and loamy sand) must be considered with care given the small number of samples (43) in these textural classes of the evaluated database (Fig. 9a and 9b). The magnitude of the differences in the RMSE values between the Brazilian and temperate PTFs depended as a whole on the content of fine particles and their pedogenesis. Indeed, the RMSE differences between both climate-based PTFs were much greater for weathered fine-textured

Table 7. Global root mean square error (RMSE) and mean error (ME) for the Brazilian and temperate pedotransfer functions (PTFs) in the suction interval from 10 to 15,000 cm, and RMSE values for weathered and unweathered soils.

Parameter	Brazilian PTFs		Temperate PTFs	
	Savanna	Amazon	Euro	Rosetta
cm <sup>3</sup> cm <sup>-3</sup>				
Complete database: 868 soil samples				
RMSE	0.064	0.065	0.081	0.080
ME	-0.0007	-0.0073	-0.0132	-0.0167
Weathered soils: 484 soil samples				
RMSE	0.057	0.052	0.080	0.073
Unweathered soils: 384 soil samples				
RMSE	0.072	0.081	0.083	0.089

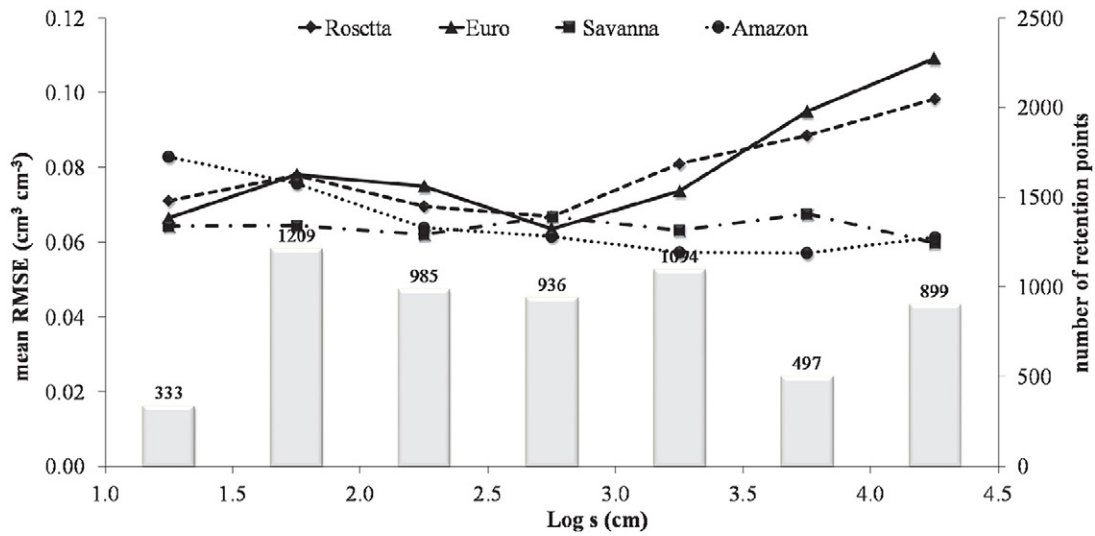


Fig. 7. Root mean square error (RMSE) of the Brazilian and temperate pedotransfer functions. The number of retention points for each suction range is also shown (bars, right axis);  $s$ , suction.

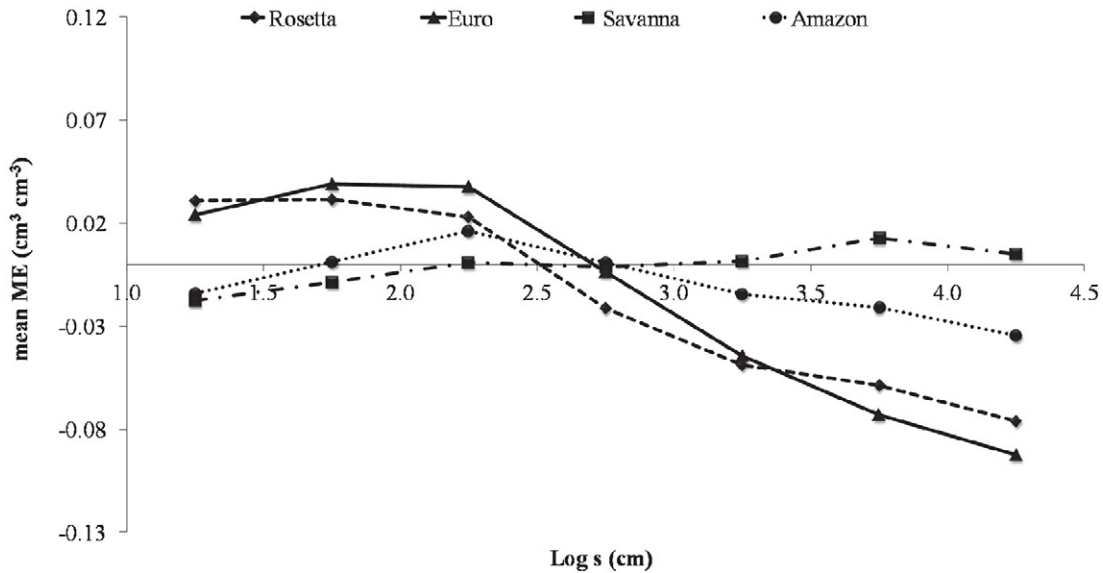


Fig. 8. Mean error (ME) of the Brazilian and temperate pedotransfer functions. A negative value indicates underestimation of water contents;  $s$ , suction.

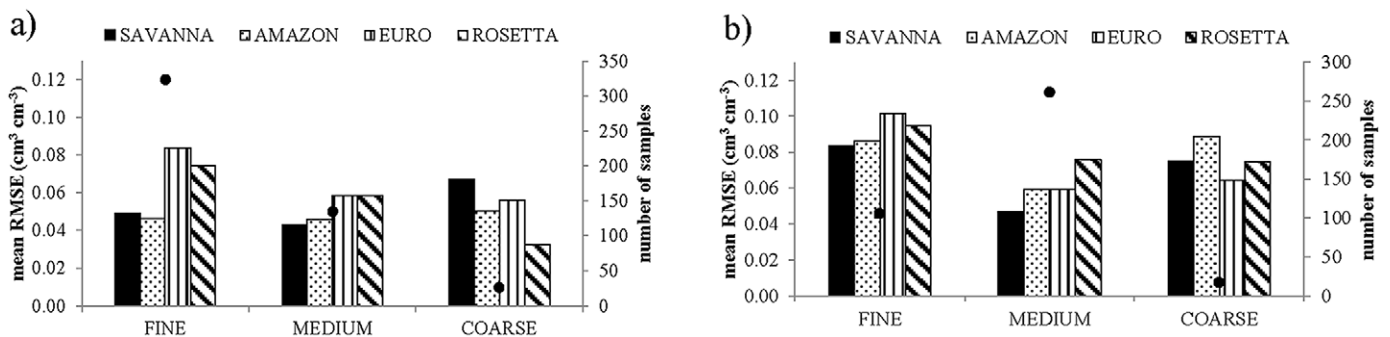


Fig. 9. Performance of the Brazilian and temperate models in groups of textural classes for Brazilian (a) weathered (484 samples) and (b) unweathered (384 samples) soils. The black circles represent the number of samples.

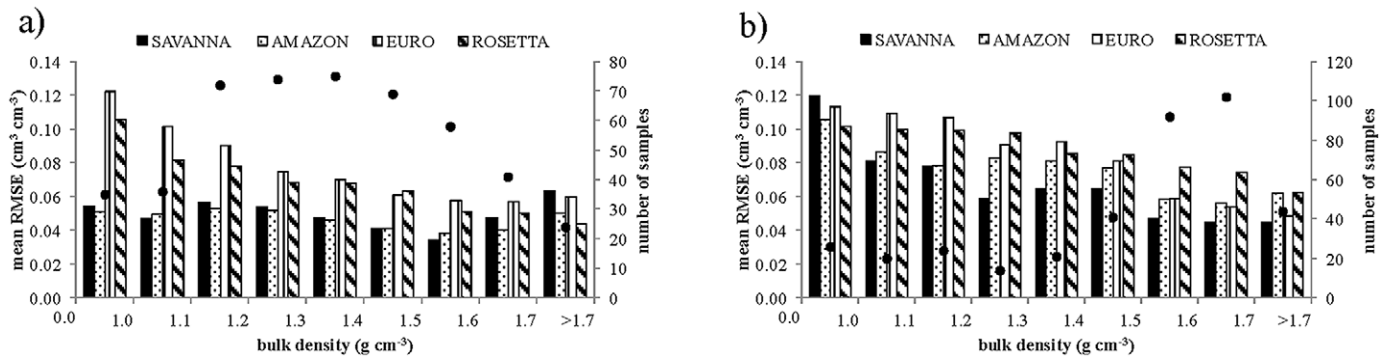


Fig. 10. Performance of the Brazilian and temperate models in bulk density intervals for Brazilian (a) weathered (484 samples) and (b) unweathered (384 samples) soils. The black circles represent the number of samples.

soils (Fig. 9a) than for the medium-textured soils (Fig. 9a and 9b) or the unweathered fine-textured soils (Fig. 9b). Additionally, the mean RMSE values of the two Brazilian PTFs for weathered fine-textured soils ( $\sim 0.048 \text{ cm}^3 \text{ cm}^{-3}$ , Fig. 9a) were even lower than those from the same PTFs for the whole set of weathered soils (Table 7). These results point to the relevance of weathered clays to distinguish the hydraulic behavior of tropical and temperate soils. This difference may have resulted from both the peculiar mineralogy of such clays and their frequent occurrence at high contents in weathered environments, as mentioned above. According to Tomasella et al. (2000), Hodnett and Tomasella (2002), Tomasella and Hodnett (2004), and many others, weathered clays allow the formation of well-developed granular structures with hydraulic conductivities similar to those of sandy soils at low suctions, and a microporosity that holds a high amount of water at high suction, resembling a typical clayey soil. The relevance of weathered clays for characterization of soil pore structure also became apparent when the performance of the models was evaluated for different bulk density ranges (Fig. 10). For the weathered soil group (Fig. 10a), the greatest differences in RMSE between Brazilian and temperate models were found for soils with bulk density values  $\leq 1.2 \text{ g cm}^{-3}$ , which usually have a high clay content. This did not occur for the unweathered soil group (Fig. 10b). The study by Tomasella et al. (2000) suggests that different silt content ranges may be a criterion when distinguishing hydraulic functioning

between weathered and temperate soils, in agreement with the hypothesis that low silt contents ( $<10\%$ ) are indicative of highly weathered soils. This suggestion by Tomasella et al. (2000) was not confirmed for HYBRAS weathered soils since both Brazilian and temperate PTFs tended to perform worse with the increase in silt content (Fig. 11), which did not occur for the temperate PTFs that they used.

## Conclusion

The HYBRAS 1.0 database is representative of a wide range of Brazilian soils. The database is based on consistent and well-defined measurement methods of soil properties and contains a reasonable amount of hydrophysical information on weathered tropical soils, which constitute the most common pedoenvironment in Brazil. The water retention and  $K_s$  data in HYBRAS were mostly obtained in the laboratory using undisturbed samples. Good resolution of water retention data was available across a large suction range (from 3–15,000 cm). The HYBRAS database contains interconnected tables, and its data can be easily accessed through predefined queries. The VG equation was suitable for fitting water retention data of Brazilian soils, especially in the 3- to 15,000-cm suction range, with global RMSE values of  $0.0107 \text{ cm}^3 \text{ cm}^{-3}$  and almost no marked bias across the whole suction range. All of these factors support excellent prospects for

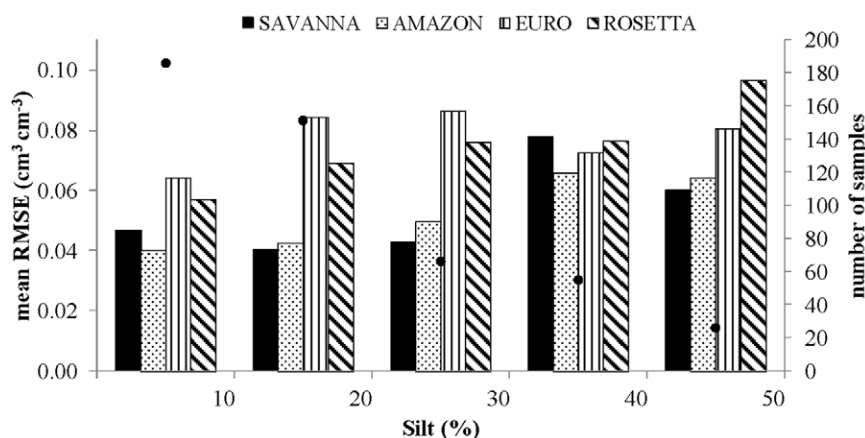


Fig. 11. Performance of the Brazilian and temperate models in silt content intervals for Brazilian weathered soils (484 samples). The black circles represent the number of samples.

the development of accurate water retention PTFs for Brazilian soils. This is an effort to cover hydrophysical data at various scales and for various applications, such as soil modeling. The  $K_s$  data (425 samples) in HYBRAS are less represented than water retention data (1075 samples) but still cover a relatively large range that may be suitable for the development of PTFs.

This study also emphasized the better performance of Brazilian PTFs as compared with temperate soil PTFs in the prediction of water retention data of Brazilian soils, with the possible exception of coarse-textured soils, for which the temperate models proved to be generally adequate. The greater reliability of Brazilian PTFs relative to temperate PTFs, when applied to Brazilian soils, is also confirmed in the literature, but a larger and more pedologically diverse soil database was used in the present work to validate the PTFs. Our study points out that the major differences in hydraulic behavior between weathered Brazilian soils and temperate soils are determined mainly by clay content and its mineralogical nature, as both strongly affect soil structure formation. This reinforces the need for developing water retention PTFs by including information on soil structure. We make the following suggestions regarding the prediction of water retention data of Brazilian soils: (i) the development of Brazilian PTFs for two soil groups, one exclusively for weathered soils (Ferralsols, Acrisols, and Nitisols) and another for other soils; and (ii) in cases where it is not convenient to apply a Brazilian PTF, we propose applying the temperate PTFs used in this study preferentially for soils not belonging to the weathered fine-textured soil group and then paying special attention to suctions between 3000 and 15,000 cm, for which the temperate models gave less satisfactory results.

## Acknowledgments

We thank the Geological Survey of Brazil (CPRM) and the Federal University of Rio de Janeiro for financial and technical support and all the researchers and students who kindly provided the data used in this study, in particular Dr. Allan Lilly for sharing the HYPRES soil database. We also acknowledge financial support from CAPES and the support and encouragement provided by Dr. Yakov Pachepsky and Dr. Martinus Th. van Genuchten. We thank Dr. Dennis Timlin for his comments that have improved the quality of this paper. This research is part of the project Hydrophysical Characterization of Soils from the Department of Hydrology of the Geological Survey of Brazil (CPRM).

## References

- Aguar, M.I. 2008. Qualidade física do solo em sistemas agroflorestais. M.S. thesis. Univ. Fed. Viçosa, Viçosa, MG, Brazil.
- Andrade, C.L.T. 1987. Balanço de água de um Latossolo vermelho-escuro álico, cultivado com milho (*Zea mays* L.), sob irrigação por aspersão. M.S. thesis. Univ. Fed. Viçosa, Viçosa, Minas Gerais, Brazil.
- Araujo, C.F., Jr., M.S. Dias, Jr., P.T.G. Guimarães, and E.N. Alcântara. 2011. Pore system and water retention capacity in a latosol under different weed management systems in a coffee plantation. (In Portuguese with English abstract.) *Planta Daninha* 29:499–513. doi:10.1590/S0100-83582011000300004
- Assad, M.L.L., L.M.A. Sans, and E.D. Assad. 2001. Relationship between soil water retention and amount of sand in Brazilian soils. (In Portuguese with English abstract.) *Rev. Bras. Agrometeorologia* 9:588–596.
- Azevedo, J.A. 1976. Relações físico-hídricas em solos de terraço e de meia encosta de Viçosa (MG). M.S. thesis. Univ. Fed. Viçosa, Viçosa, MG, Brazil.
- Barcelos, A.A. 1996. Infiltração de água em um Latossolo, sob chuva de alta intensidade, em diferentes sistemas de manejo. M.S. thesis. Univ. Fed. Rio Grande do Sul, Porto Alegre, RS, Brazil.
- Barros, A.H.C., and Q. de Jong van Lier. 2014. Pedotransfer functions for Brazilian soils. In: W.G. Teixeira et al., editors, *Application of soil physics in environmental analyses: Measuring, modelling and data integration*. Springer, Cham, Switzerland. p. 131–162. doi:10.1007/978-3-319-06013-2\_6
- Barros, A.H.C., Q. de Jong van Lier, A.H.M. Maia, and F.V. Scarpere. 2013. Pedotransfer functions to estimate water retention parameters of soils in northeastern Brazil. *Rev. Bras. Cienc. Solo* 37:379–391. doi:10.1590/S0100-06832013000200009
- Batjes, N.H. 1996. Development of a world data set of soil water retention properties using pedotransfer rules. *Geoderma* 71:31–52. doi:10.1016/0016-7061(95)00089-5
- BDSOLOS. 2017. Sistema de informação de solos Brasileiros. (In Portuguese.) Embrapa. [https://www.bdsolos.cnptia.embrapa.br/consulta\\_publica.html](https://www.bdsolos.cnptia.embrapa.br/consulta_publica.html) (accessed 27 Nov. 2017).
- Benedetti, M.M., G. Sparovek, M. Cooper, N. Curi, and A. Carvalho Filho. 2008. Coverage and potential use of a soil profile database in Brazil. (In Portuguese.) *Rev. Bras. Cienc. Solo* 32:2591–2600. doi:10.1590/S0100-06832008000600036
- Bhering, S.B. 2007. Influência do manejo do solo e da dinâmica da água no sistema de produção do tomate de mesa: Subsídios a sustentabilidade agrícola do Noroeste Fluminense. Ph.D. diss. Univ. Fed. Rio de Janeiro (UFRJ), Rio de Janeiro, RJ, Brazil.
- Botula, Y.D., W.M. Cornelis, G. Baert, and E. Van Ranst. 2012. Evaluation of pedotransfer functions for predicting water retention of soils in Lower Congo (D.R. Congo). *Agric. Water Manage.* 111:1–10. doi:10.1016/j.agwat.2012.04.006
- Botula, Y.D., E. Van Ranst, and W.M. Cornelis. 2014. Pedotransfer functions to predict water retention for soils of the humid tropics: A review. *Rev. Bras. Cienc. Solo* 38:679–698. doi:10.1590/S0100-06832014000300001
- Bouma, J. 1989. Using soil survey data for quantitative land evaluation. *Adv. Soil Sci.* 9:177–213. doi:10.1007/978-1-4612-3532-3\_4
- Brooks, R.H., and A.T. Corey. 1964. Hydraulic properties of porous media. *Hydrol. Pap.* 3. Colorado State Univ., Fort Collins.
- Carducci, C.E., G.C. Oliveira, E.C. Severiano, and W.M. Zeviani. 2011. Modeling the water retention curve in Oxisols using the double van Genuchten equation. (In Portuguese, with English abstract.) *Rev. Bras. Cienc. Solo* 35:77–86. doi:10.1590/S0100-06832011000100007
- Cassel, D.K., L.F. Ratliff, and J.T. Ritchie. 1983. Models for estimating in-situ potential extractable water using soil physical and chemical properties. *Soil Sci. Soc. Am. J.* 47:764–769. doi:10.2136/sssaj1983.03615995004700040031x
- Cintra, F.L.D., and P.L. Libardi. 1998. Physical characterization of a soil class of the "Tabuleiro Costeiro" ecosystem. *Sci. Agric.* 55:367–378. doi:10.1590/S0103-90161998000300004
- Coelho, M.R., E.C.C. Fidalgo, F.O. Araujo, H.G. dos Santos, M.L.M. Santos, D.V. Pérez, and F.M.S. Moreira. 2005a. Levantamento pedológico de uma área-piloto relacionada ao Projeto BiosBrasil, Benjamin Constant, AM: Janela 6. *Boletim Pesq. Desenvolvimento* 68. (In Portuguese.) Embrapa, Brasília.
- Coelho, M.R., E.C.C. Fidalgo, F.O. Araujo, H.G. dos Santos, M.L.M. Santos, D.V. Pérez, and F.M.S. Moreira. 2005b. Solos das áreas-piloto do Projeto Projeto BiosBrasil, Benjamin Constant, AM. *Boletim Pesq. Desenvolvimento* 67. (In Portuguese.) Embrapa, Brasília.
- Cornelis, W.M., J. Ronsyn, M.V. Meirvenne, and R. Hartmann. 2001. Evaluation of pedotransfer functions for predicting the soil moisture retention curve. *Soil Sci. Soc. Am. J.* 65:638–648. doi:10.2136/sssaj2001.653638x
- Costa, A.C.S. 1986. Balanço hídrico das culturas de feijão (*Phaseolus vulgaris*, L.) e milho (*Zea mays*, L.) em condições de campo. M.S. thesis. Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, SP, Brazil.
- Costa, A.C.S., and P.L. Libardi. 1999. Characterization of the physical and hydraulic properties of the soil "Terra roxa Estruturada Latossólica" by the instantaneous profile method. (In Portuguese with English abstract.) *Rev. Bras. Cienc. Solo* 23:669–677. doi:10.1590/S0100-06831999000300021

- da Costa, A., J.A. Albuquerque, J.A. de Almeida, A. da Costa, and R.V. Luciano. 2013. Pedotransfer functions to estimate retention and availability of water in soils of the state of Santa Catarina, Brazil. *Rev. Bras. Cienc. Solo* 37:889–910. doi:10.1590/S0100-06832013000400007
- da Costa, A.E.M. 1993. Quantificação de atributos físico de solos de várzea, relacionados com a disponibilidade de água, o espaço aéreo e a consistência do solo. M.S. thesis. Univ. Fed. Pelotas, Pelotas, RS, Brazil.
- da Silva, A.P., C.A. Tormena, J. Fidalski, and S. Imhoff. 2008. Pedotransfer functions for the soil water retention and soil resistance to penetration curves. (In Portuguese, with English abstract.) *Rev. Bras. Cienc. Solo* 32:1–10. doi:10.1590/S0100-06832008000100001
- da Silva, M.A.S. 2003. Agregação e atributos físico-hídricos do solo em sistemas conservacionistas de manejo. M.S. thesis. Univ. do Estado de Santa Catarina, Centro de Ciências Agroveterinárias, Lages, SC, Brazil.
- da Silva, M.A.S., A.L. Mafrá, J.A. Albuquerque, C. Bayer, and J. Mielniczuk. 2005. Soil physics properties related to water storage and tillage systems in a Loamy Acrisol. (In Portuguese, with English abstract.) *Cienc. Rural* 35:544–552. doi:10.1590/S0103-84782005000300009
- de Mello, C.R., G.C. de Oliveira, D.F. Ferreira, J.M. de Lima, and D. Lopes. 2005. Models for determination of parameters of van Genuchten equation for a Cambisol. (In Portuguese, with English abstract.) *Rev. Bras. Eng. Agríc. Ambiental* 9:23–29. doi:10.1590/S1415-43662005000100004
- Embrapa. 2011. Manual de métodos de análise de solo. (In Portuguese.) Ctr. Nac. Pesq. Solos, Rio de Janeiro, Brazil.
- Embrapa and FAO. 1991. Caracterização físico hídrica dos principais solos da Amazônia legal: I. Estado do Pará. Relatório técnico. Acordo Embrapa, Natl. Seed Inspect. Cert. Serv., Belém, Brazil.
- European Commission. 2009. LUCAS 2009 (land use/cover area frame survey). Tech. Ref. Doc. C-3: Land use and land cover: Nomenclature (version of 20/03/2009). Eurostat, Luxembourg.
- Ferreira, I.C.M. 2007. Associação entre solos e remanescentes de vegetação nativa em Campinas, SP. M.S. thesis. Inst. Agron. de Campinas (IAC), Campinas, SP, Brazil.
- Fidalski, J., and C.A. Tormena. 2007. Pedotransfer functions for the soil water retention and soil resistance to penetration under groundcover management systems in citrus. (In Portuguese.) *Cienc. Rural* 37:1316–1322. doi:10.1590/S0103-84782007000500015
- Fiorin, T.T. 2008. Estimativa da infiltração de água no solo a partir de pedofunções. Ph.D. diss. Univ. Fed. Santa Maria, Santa Maria, RS, Brazil.
- Grego, C.R., R.M. Coelho, and S.R. Vieira. 2011. Morphological and taxonomic criteria of oxic and nitic horizons validated by measurable physical properties partially analyzed by geostatistics. (In Portuguese, with English abstract.) *Rev. Bras. Cienc. Solo* 35:337–350. doi:10.1590/S0100-06832011000200005
- Hodnett, M.G., and J. Tomasella. 2002. Marked differences between van Genuchten soil water retention parameters for temperate and tropical soils: A new water retention pedotransfer function developed for tropical soils. *Geoderma* 108:155–180. doi:10.1016/S0016-7061(02)00105-2
- IUSS Working Group WRB. 2015. World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resour. Rep. 106. FAO, Rome. Leal, F.G. 2011. Classificação e mapeamento físico-hídricos de solos do assentamento agrícola Sebastião Lan II, Silva Jardim-RJ. M.S. thesis. Univ. Fed. Rio de Janeiro, Rio de Janeiro, RJ, Brazil.
- Leão, T.P. 2016. Particle size distribution of Oxisols in Brazil. *Geoderma Regional* 7:216–222. doi:10.1016/j.geodrs.2016.04.003
- Lumbreiras, J.F. 1996. Regime hídrico do solo sob cobertura de floresta e de eucalipto na pré-amazônia maranhense. M.S. thesis. Univ. Fed. Rural do Rio de Janeiro, Rio de Janeiro, RJ, Brazil.
- Macedo, J.R. 1991. Determinação de retenção hídrica por correlação múltipla e de variabilidade espacial em solos podzólicos de Seropédica/RJ. M.S. thesis. Univ. Fed. Rural do Rio de Janeiro, Rio de Janeiro, RJ, Brazil.
- Manyame, C., C.L. Morgan, J.L. Heilman, D. Fatondji, B. Gerard, and W.A. Payne. 2007. Modeling hydraulic properties of sandy soils of Niger using pedotransfer functions. *Geoderma* 141:407–415. doi:10.1016/j.geoderma.2007.07.006
- Marquesi, J.D.O., W.G. Teixeira, A.M. Reis, O.F. Cruz Junior, S.M. Batista, and M.A.C.B. Afonso. 2010. Chemical, physical and hydric attributes and mineralogy of clay fractions in soils of lower Amazon: Serra de Parintins. (In Portuguese, with English abstract.) *Acta Amazon.* 40:1–12. doi:10.1590/S0044-59672010000100001
- MathWorks. 2014. MATLAB and Statistics Toolbox. Release 2014b. The MathWorks, Natick, MA.
- Medeiros, J.C., M. Cooper, J.D. Rosa, M. Grimaldi, and Y. Coquet. 2014. Assessment of pedotransfer functions for estimating soil water retention curves for the Amazon region. *Rev. Bras. Cienc. Solo* 38:730–743. doi:10.1590/S0100-06832014000300005
- Medina, H., M. Tarawally, A. del Valle, and M.E. Ruiz. 2002. Estimating soil water retention curve in rhodic Ferralsols from basic soil data. *Geoderma* 108:277–285. doi:10.1016/S0016-7061(02)00135-0
- Medrado, E., and J.E.F.W. Lima. 2014. Development of pedotransfer functions for estimating water retention curve for tropical soils of the Brazilian savanna. *Geoderma Regional* 1:59–66. doi:10.1016/j.geodrs.2014.08.003
- Minasny, B., and A.E. Hartemink. 2011. Predicting soil properties in the tropics. *Earth Sci. Rev.* 106:52–62. doi:10.1016/j.earscirev.2011.01.005
- Moreira, J.A.A., and C.J.C.G. da Silva. 1987. Water retention characteristics of a red-yellow podzolic soil at Goiana, Pernambuco State, Brazil. (In Portuguese, with English abstract.) *Pesq. Agropecu. Bras.* 22:411–418.
- Nacif, P.G.S. 1994. Efeitos da Subsolação em propriedades físico-hídricas de um Latossolo amarelo álico coeso, representativo do Recôncavo Baiano. M.S. thesis. Univ. Fed. Viçosa, Viçosa, MG, Brazil.
- Nacif, P.G.S., J.O. Rezende, L.E.F. Fontes, L.M. da Costa, and O.V. Costa. 2008. Efeitos da subsolação em propriedades físico-hídricas de um latossolo amarelo distrocoeso do estado da Bahia. *Magistra, Cruz Almas* 20:186–192.
- Nebel, A.L.C., L.C. Timm, W. Cornelis, D. Gabriels, K. Reichardt, L.S. Aquino, et al. 2010. Pedotransfer functions related to spatial variability of water retention attributes for lowlands soils. *Rev. Bras. Cienc. Solo* 34:669–680. doi:10.1590/S0100-06832010000300008
- Nemes, A., M.G. Schaap, F.J. Leij, and J.H.M. Wösten. 2001. Description of the unsaturated soil hydraulic database UNSODA version 2.0. *J. Hydrol.* 251:151–162. doi:10.1016/S0022-1694(01)00465-6
- Neuwald, O. 2005. Atributos físico e hídricos do solo e produtividade da soja em sistema integrado lavoura-pecuária, em Nitossolo Háplico sob diferentes sistemas de manejo. M.S. thesis. Univ. do Estado de Santa Catarina (UDESC), Lages, SC, Brazil.
- Nguyen, P.M., V.L. Khoa, Y.D. Botula, and W.M. Cornelis. 2015. Evaluation of soil water retention pedotransfer functions for Vietnamese Mekong Delta soils. *Agric. Water Manage.* 158:126–138. doi:10.1016/j.agwat.2015.04.011
- Oliveira, L.B. 1968. Considerações sobre a composição granulométrica de solos do nordeste. *Pesq. Agropecu. Bras.* 3:189–195.
- Ottoni, M.V., M.L.L. Assad, Y. Pachepsky, and O.C. Rotunno Filho. 2014. A hydrophysical database to develop pedotransfer functions for Brazilian soils: Challenges and perspectives. In: W.G. Teixeira et al, editors, Application of soil physics in environmental analyses: Measuring, modelling and data integration. Springer, Cham, Switzerland. p. 467–494. doi:10.1007/978-3-319-06013-2\_20
- Parfitt, J.M. 2009. Impacto da sistematização sobre atributos físicos, químicos e biológicos em solos de várzea. Ph.D. diss. Univ. Fed. Pelotas, Pelotas, Rio Grande do Sul, Brazil.
- Patil, N.G. and S.K. Singh. 2016. Pedotransfer functions for estimating soil hydraulic properties: A review. *Pedosphere* 26:417–430. doi:10.1016/S1002-0160(15)60054-6.
- Rawls, W.J. 2004. Pedotransfer functions for the United States. *Dev. Soil Sci.* 30:437–447. doi:10.1016/S0166-2481(04)30023-1
- Reichert, J.M., J.A. Albuquerque, D.R. Kaiser, D.J. Reinert, F.L. Urach, and R. Carlesso. 2009. Estimation of water retention under availability in soils of Rio Grande do Sul. *Rev. Bras. Cienc. Solo* 33:1547–1560. doi:10.1590/S0100-06832009000600004
- Rojas, C.A.L. 1998. Alterações físico-hídricas de um Podzólico em função do manejo de solo. M.S. thesis. Univ. Fed. Rio Grande do Sul, Porto Alegre, RS, Brazil.
- Rubio, C., and P. Llorens. 2004. Comparing different pedotransfer functions for silty loam soils in a Mediterranean mountain catchment. In: P. Aagaard et al., editors, Saturated and unsaturated zone: Integration process knowledge into effective models. Proceedings of the COST International Workshop, Rome, 5–7 May 2004. La Goliardica Pavese, Pavia, Italy. p. 273–278.
- Scardua, R. 1972. Porosidade livre de água de dois solos do município de Piracicaba, SP. M.S. thesis. Univ. de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", São Paulo, Brazil.
- Schaap, M.G., F.J. Leij, and M.Th. van Genuchten. 2001. ROSETTA: Computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *J. Hydrol.* 251:163–176. doi:10.1016/S0022-1694(01)00466-8



- Souto Filho, S.N. 2012. Variação de armazenamento de água num Latossolos de Cerrado em recuperação. M.S. thesis. Univ. Estadual Paulista (UNESP), Ilha Solteira, SP, Brazil.
- Souza, L.S., and L.D. Souza. 2001. Caracterização físico-hídrica de solos da área do Centro Nacional de Pesquisa de Mandioca e Fruticultura Tropical. *Boletim Pesq. Desenvolvimento* 20. Empresa Bras. Pesq. Agropecu. Ctr. Nacl. Pesq. Mandioca Fruticultura Trop., Cruz das Almas.
- Thurler, A.M. 2000. Determinação da capacidade de campo e retenção de umidade em solos do Terciário da Formação Barreiras, em função de suas características granulométricas e fatores estruturais. Ph.D. diss. Univ. Fed. Rural do Rio de Janeiro, Inst. Agron., Seropédica, RJ, Brazil.
- Tietje, O., and V. Hennings. 1996. Accuracy of the saturated hydraulic conductivity prediction by pedo-transfer functions compared to the variability within FAO textural classes. *Geoderma* 69:71–84. doi:10.1016/0016-7061(95)00050-X
- Toma, R.S. 2012. Evolução do funcionamento físico-hídrico do solo em diferentes sistemas de manejo em áreas de agricultura familiar na região do vale do Ribeira, SP. Ph.D. diss. Univ. de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", São Paulo, Brazil.
- Tomasella, J., and M.G. Hodnett. 1998. Estimating soil water retention characteristics from limited data in Brazilian Amazonia. *Soil Sci.* 163:190–202. doi:10.1097/00010694-199803000-00003
- Tomasella, J., and M.G. Hodnett. 2004. Pedotransfer functions for tropical soils. *Dev. Soil Sci.* 30:415–429. doi:10.1016/S0166-2481(04)30021-8
- Tomasella, J., M.G. Hodnett, and L. Rossato. 2000. Pedotransfer functions for the estimation of soil water retention in Brazilian soils. *Soil Sci. Soc. Am. J.* 64:327–338. doi:10.2136/sssaj2000.641327x
- Tomasella, J., Y. Pachepsky, S. Crestana, and W.J. Rawls. 2003. Comparison of two techniques to develop pedotransfer functions for water retention. *Soil Sci. Soc. Am. J.* 67:1085–1092. doi:10.2136/sssaj2003.1085
- Tormena, C.A., and A.P. da Silva. 2002. Incorporation of the bulk density to two models adjusted to the soil water retention curve. (In Portuguese, with English abstract.) *Rev. Bras. Cienc. Solo* 26:305–314. doi:10.1590/S0100-06832002000200003
- Tóth, B., M. Weynants, A. Nemes, A. Makó, G. Bilas, and G. Tóth. 2015. New generation of hydraulic pedotransfer functions for Europe. *Eur. J. Soil Sci.* 66:226–238. doi:10.1111/ejss.12192
- van Genuchten, M.Th. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 44:892–989. doi:10.2136/sssaj1980.03615995004400050002x
- Vasconcellos, E.B. 1993. Levantamento dos atributos físicos e hídricos de três solos de várzea do Rio Grande do Sul. M.S. thesis. Univ. Fed. Pelotas, Pelotas, RS, Brazil.
- Walkley, A., and I.A. Black. 1934. An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* 37:29–38. doi:10.1097/00010694-193401000-00003
- Wösten, J.H.M., A. Lilly, A. Nemes, and C. Le Bas. 1999. Development and use of a database of hydraulic properties of European soils. *Geoderma* 90:169–185. doi:10.1016/S0016-7061(98)00132-3