ISSN 1808-8546 (ONLINE) 1808-3765 (CD-ROM)

FUNÇÕES DE PEDOTRANSFERÊNCIA PARA PREDIÇÃO DE ATRIBUTOS FÍSICO-HÍDRICOS DE SOLOS DO PIAUÍ, BRASIL*

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** Trabalho proveniente de parte da tese de doutorado do primeiro autor, apresentada ao Programa de Pós-graduação em Agronomia (PPGA), da Universidade Federal do Piauí, UFPI, Teresina, Piauí, Brasil*

1 RESUMO

A determinação de atributos físico-hídricos do solo é trabalhosa e demorada, o que inviabiliza a análise de numerosos conjuntos de amostras. Este estudo foi conduzido com o objetivo de desenvolver uma função de pedotransferência (FPT) para a predição da capacidade de campo (CC), ponto de murcha permanente (PMP) e água disponível (AD) em solos do estado do Piauí. Amostras de solo foram coletadas em quarenta e dois perfis nas profundidades: 0 a 0,20 m; 0,20 a 0,40 m; e 0,40 a 0,60 m. Foram determinados os seguintes atributos: análise granulométrica, teores de carbono orgânico total, fósforo disponível, cátions trocáveis (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), alumínio, acidez potencial, nitrogênio, soma de bases, capacidade de troca de cátions (CTC) efetiva, CTC a pH 7,0, CTC da argila, saturação por bases, CC, PMP e AD. As classes de solos selecionadas foram: Latossolo, Argissolo, Neossolo Quartzarênico e Plintossolo. Para obter as FPTs, utilizou-se análise de regressão linear múltipla. Foram gerados dois modelos de FPT um incluindo todos os dados dos atributos determinados e outro incluindo apenas a análise granulométrica e o carbono orgânico total. A CC, o PMP e a AD podem ser estimados com razoável precisão a partir das funções físico-hídricas de pedotransferência.

Palavras-chave: pedometria, regressão linear múltipla, água no solo.

RAMOS, H. M. M.; VALLADARES, G. S.; MOUSINHO, F. E. P.; ANDRADE JUNIOR, A. S. E SOUSA, R. S. DE
PEDOTRANSFERFUNCTIONS FOR PREDICTING PHYSICO-HYDRIC ATTRIBUTES OF SOILS IN PIAUÍ, BRAZIL

Recebido em 06/05/2023 e aprovado para publicação em 17/06/2023
DOI: http://dx.doi.org/10.15809/irriga.2023v28n2p400-416

2 ABSTRACT

Determining hydrophysical soil attributes is laborious and time-consuming, making the analysis of numerous sample sets unfeasible. This study aimed to develop a pedotransfer function (PTF) for predicting the field capacity (FC), permanent wilting point (PWP), and available water (AW) in soils in the state of Piauí, Brazil. Soil samples were collected from forty-two profiles at depths of 0 to 0.20 m, 0.20 to 0.40 m, and 0.40 to 0.60 m. The following attributes were determined: particle size, total organic carbon content, available phosphorus, exchangeable cations (Ca^{2+}, Mg^{2+}, $^{Na+}$, $^{K+}$), aluminum, potential acidity, nitrogen, base sum, effective cation exchange capacity (CEC_E), cation exchange capacity at pH 7.0 (CEC_7), clay cation exchange capacity (CEC_{clay}), base saturation, FC, PWP, and AW. The selected soil classes were Oxisols, Ultisols, Quartzarenic Neosols, and Plinthosols. Multiple linear regression analysis was used to obtain the PTFs. Two PTF models were generated, one including all the attribute data determined and another including only particle size analysis and total organic carbon. The FC, PWP, and AW can be estimated with reasonable accuracy via hydrophysical pedotransfer functions.

Keywords: pedometry, multiple linear regression, soil water.

3 INTRODUCTION

The study of the physical–hydric attributes of the soil is important and necessary since it allows knowledge of the soil–water–plant–atmosphere relationships. In planning the rational use of soil and water, field capacity, wilting point permanent and available water are highly relevant physical–hydric attributes.

Available water refers to the ability of soil to make water available to plants. This value is determined by the difference between the field capacity, which represents the moisture retained at matric potentials (Ψ m) of -6, -10 or -33 kPa, and the permanent wilting point, which represents the moisture retained at the matric potential of -1,500 kPa. The permanent wilting point is the moisture content at which the plant can no longer extract water from the soil, whereas the field capacity is the maximum capacity of the soil to retain water, above which losses occur due to water percolation in the soil profile or surface runoff (BERNARDO *et al.*, 2019).

Determining these physical–hydric attributes in soils is laborious and time-consuming, which makes it impossible to analyze numerous sets of samples. In this sense, methods for estimating water availability on the basis of parameters that are easy to determine and/or available in soil surveys have recently aroused interest in the scientific community (BARROS; FEARNSIDE, 2015).

According to Haddad *et al.* (2018), pedotransfer functions (PTFs) allow basic soil information to be transformed into other information that is more difficult to obtain and generally expensive. In general, PTFs estimate soil attributes that are difficult to determine via other attributes that are routinely determined.

The FTP approach, according to Padarian *et al.* (2018), assists in several simulation models applied to the transport of water, air, thermal energy and solutes; structural stability; compaction and resistance to penetration of the root system; chemical and soil management; and, finally, precision agriculture.

In recent research, FPTs have been used mainly to estimate water availability and soil density through regression models that correlate soil physical and chemical variables, especially texture, soil density and organic matter (BORTOLINI *et al.*, 2018; BARROS; FEARNSIDE, 2015; BEUTLER *et al.*, 2017; CAVIGLIONE, 2018; PÁDUA; GUERRA; ZINN, 2015; REICHERT *et al.*, 2020; SILVA *et al.*, 2015; SOUZA *et al.*, 2016; TAVANTI *et al.*, 2019).

However, as reported by Padarian *et al.* (2018), the published FTPs show large differences in performance when applied in environments other than those in which they were adjusted. Therefore, the safest option is to use a pedotransfer function developed for data from the application area or for an area with soils of similar genesis.

In the state of Piauí, there is a great lack of information regarding the availability of water in soils, an attribute of fundamental importance for irrigated agriculture and the determination of agricultural zoning. In this sense, this work was conducted with the objective of developing, through pedotransfer functions, the prediction of field capacity, permanent wilting point and available water in soils of the state of Piauí.

4 MATERIAL AND METHODS

Soil samples were collected from 42 profiles in the state of Piauí in native forest areas. The areas were selected on the basis of annual precipitation between 1,000 and 1,600 mm according to the isohyet map of average annual precipitation in Brazil. The climate classification of the study area, according to Köppen, is Aw (warm subhumid tropical) (Almeida *et al*., 2019). To characterize the soil, mini-trenches were opened, from which samples with deformed and undisturbed structures were collected at depths of 0 to 0.2, 0.2 to 0.4 and 0.4 to 0.6 m.

The soil classes selected for this work were Yellow Latosol (LA), Red–Yellow Latosol (LVA), Red–Yellow Argisol (PVA), Yellow Argisol (PA), Gray Argisol (PAC), Plinthosol Argiluvic (FT), Plinthosol Haplic (FX), Cambisol Haplic (CX), Chernosol Argiluvic (MT), Chernosol Hapico (MX), Planosols Haplic (SX), Planossolo Natric (SN) and Neosol Quartzsand (RQ). These classes represent the soils most commonly used in dryland agriculture in the state of Piauí (JACOMINE, 1986).

The determined attributes were granulometric analysis (clay, silt, fine sand, coarse sand and total sand content), soil density (Ds), total organic carbon content (TOC), hydrogen potential (pH), phosphorus (P), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium ($^{Na+}$), potassium ($^{K+}$), aluminum (Al^{3+}), potential acidity ($H^{+}+Al^{3+}$), total nitrogen (N), sum of bases (SB), effective cation exchange capacity (effective CEC), cation exchange capacity at pH 7.0 (CEC at pH 7.0), cation exchange capacity of the clay fraction (CEC of the clay), base saturation (V%), field capacity (CC), permanent wilting point (PMP) and available water (AD), resulting from the difference in volumetric soil moisture between the CC and the PMP.

The analyses of the physical-hydric and chemical parameters were carried out according to the soil analysis methods manual (TEIXEIRA *et al.*, 2017). The soil classification was performed by consulting the pedological map of the state of Piauí (JACOMINE, 1986). After the consultation, field checks were carried out, and the final classification was defined according to the Brazilian Soil Classification System (SANTOS *et al.*, 2018) through the results obtained for the granulometry and the chemical and physical analyses of the samples.

The stress table method at specific matric potentials was used to determine the CC and the PMP. The -6 kPa matric potential was adopted for the CC, and the -1,500 kPa matric potential in the Richards pressure chamber was adopted to calculate the PMP (TEIXEIRA *et al.*, 2017).

The data were subjected to descriptive statistical analysis, with observations of the mean, minimum and maximum values, standard deviation and coefficient of variation (SILVA; ARMINDO, 2016). To assess the relationships among the variables, Pearson correlation analyses were performed.

The pedotransfer functions were developed according to the following steps:

1st) Development of generalized pedotransfer functions (general) considering data from all the determined soil classes.

2) Development of specific pedotransfer functions for soil classes Latosols, Argisols, Quartzarenic Neosols and Plinthosols. For the other classes (Chernossolo, Planossolo and Cambisol), the number of data points was greatly reduced for the elaboration of the pedotransfer functions.

To obtain the pedotransfer functions, multiple linear regression analysis was used. In the selection of predictor variables, the *"forward" stepwise procedure* was used, relating CC, PMP and AD to the physical and chemical attributes of the soil. This option selects the main variables from a set of independent variables at a preestablished significance level (P value > 0.10), generating a coefficient for each of the selected independent variables.

Two models of pedotransfer functions for predicting physical–hydric attributes (CC, PMP and AD) were developed. In Model I, all the data on the determined soil attributes (granulometric analysis; total organic carbon, pH, phosphorus, calcium, magnesium, sodium, potassium, and aluminum contents; potential acidity; and cation exchange capacity at pH=7.0) were used as independent variables in the selection of predictor variables, whereas in Model II, only the data on the clay, silt, fine sand, coarse sand, total sand and total organic carbon contents were used as independent variables in the selection of predictor variables.

The performance of the regression models was evaluated by comparing the estimated values with the measured values and calculating the coefficient of determination (R2), the mean error (ME) and the root mean square error (RMSE), which were obtained via Equations 1, 2 and 3, respectively (SILVA; ARMINDO, 2016). The confidence index (CI) was also considered, and its calculation was performed according to Equation (6), which is the result of multiplying the Willmott index, Equation (4), by the Pearson correlation coefficient, Equation (5). The CI values were classified according to Camargo and Sentelhas (1997) (Table 1).

Table 1. Confidence Index (CI) classification

"IC" values	**Performance**
> 0.90	Excellent
0.81 to 0.90	Very good
0.71 to 0.80	Good
0.51 to 0.70	Median
0.41 to 0.50	bearable

0.31 to 0.40	Bad
< 0.30	Terrible

Source: Camargo and Sentelhas (1997)

$$R^2 = \frac{\sum_{i=1}^{n} (Ei - \overline{Ei}) (Mi - \overline{Mi})}{\sum_{i=1}^{n} (Ei - \overline{E})^2 \sum_{i=1}^{n} (Mi - \overline{M})^{0,5}} \quad (1)$$

$$EM = \frac{1}{n} \sum_{i=1}^{n} (Mi - Ei) \quad (2)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (Mi - Ei)^2} \quad (3)$$

$$d = 1 - \frac{\sum_{i=1}^{n} (Ei - \overline{Mi})^2}{[\sum_{i=1}^{n} (|Ei - \overline{Ei}|) + \sum_{i=1}^{n} (|Mi - \overline{Mi}|)]^2} \quad (4)$$

$$r = \frac{\sum_{i=1}^{n} (Ei - \overline{Ei}) (Mi - \overline{Mi})}{[\sum_{i=1}^{n} (Ei - \overline{Ei})^2 \sum_{i=1}^{n} (Mi - \overline{Mi})^{0,5}]} \quad (5)$$

$$IC = r.d \quad (6)$$

where:

Ei = estimated value; Mi = measured value; $\overline{Ei}$ e $\overline{Mi}$ = are the averages of the estimated and measured values, respectively; n = total number of data and CI = confidence index that jointly integrates precision (r) and accuracy (d).

5 RESULTS AND DISCUSSION

The descriptive statistics of the variables used in generating the FPTs are presented in Table 2, which shows the means, minimum values, maximum values, standard deviations and coefficients of variation of the results obtained for the soil attributes considering all the soil classes.

Table 2. Descriptive statistics of the variables used to develop the pedotransfer functions considering all the soil classes.

Variable	Average	Min.	Max.	DP	CV
COT (dag kg $^{-1}$)	1.1	0.0	4.0	4.0	62
pH	5.3	4.0	8.4	0.9	17
Phosphorus (mg kg $^{-1}$)	9.3	5.9	41.4	5.2	57
Calcium (cmol $_c$ dm $^{-3}$)	1.7	0.0	17.1	3.9	233
Magnesium (cmol $_c$ dm $^{-3}$)	1.5	0.0	18.3	3.2	208
Sodium (cmol $_c$ dm $^{-3}$)	0.3	0.0	2.7	0.5	155
Potassium (cmol $_c$ dm $^{-3}$)	0.2	0.0	0.7	0.2	84
Aluminum (cmol $_c$ dm $^{-3}$)	0.6	0.0	2.0	0.5	77
Potential acidity (cmol $_c$ dm $^{-3}$)	3.3	0.0	11.7	2.2	68
Total nitrogen (dag kg $^{-1}$)	0.3	0.1	1.4	0.2	72
Sum of bases (cmol $_c$ dm $^{-3}$)	3.7	0.1	35.3	7.1	192
Effective CEC (cmol $_c$ dm $^{-3}$)	4.3	0.5	35.4	6.9	162
CTC at pH 7.0 (cmol $_c$ dm $^{-3}$)	7.0	1,2	35.3	7.1	102
CTC of clay (cmol $_c$ dm $^{-3}$)	36.3	6.9	141.9	28.1	77
Base saturation (%)	35.9	1.9	100.0	27.8	77
Clay (g kg $^{-1}$)	224	44	610	145	65
Silt (g kg $^{-1}$)	137	8.0	433	90	65
Coarse sand (g kg $^{-1}$)	240	44	715	165	69
Fine sand (g kg $^{-1}$)	399	100	761	153	38
Total sand (g kg $^{-1}$)	639	200	927	184	29
Ds (Mg m $^{-3}$)	1.4	1.1	1.9	0.2	13
CC (cm ^{3} cm $^{-3}$)	0.34	0.18	0.58	0.08	25
PMP (cm ^{3} cm $^{-3}$)	0.15	0.06	0.42	0.07	50
AD (cm ^{3} cm $^{-3}$)	0.19	0.05	0.29	0.05	25

Source: Own authorship (2022). Min = minimum; Max. = maximum; SD = standard deviation; CV = coefficient of variation (%); CC = field capacity; PMP = permanent wilting point; AD = available water; TOC = total organic carbon content; pH = hydrogen potential; CEC = cation exchange capacity

The WC varied between 0.18 and 0.58 cm ^{3} cm $^{-3}$, with a mean of 0.34 cm ^{3} cm $^{-3}$, a coefficient of variation of 25%, and a standard deviation of 0.08. The PMP varied between 0.06 and 0.42 cm ^{3} cm $^{-3}$, with a mean of 0.15 cm ^{3} cm $^{-3}$, a coefficient of variation of 50%, and a standard deviation of 0.07. The AD varied between 0.05 and 0.29 cm ^{3} cm $^{-3}$, with a mean of 0.19 cm ^{3} cm $^{-3}$, a coefficient of variation of 25%, and a standard deviation of 0.05 (Table 2).

The variation observed for CC and PMP was probably due to the heterogeneity of the structural and granulometric characteristics of the collected samples. At high matric potentials, capillary forces are more active, and at these potentials, water retention is influenced by the soil structure (MICHELON *et al.*, 2010). On the other hand, for low matric potentials in the soil, retention depends on adsorption phenomena, which are more influenced by the texture and specific surface of the particles.

The coefficients of variation for most variables are high (>30%), with the exceptions of pH, CC, AD, total sand and Ds. According to Pádua, Guerra and Zinn (2015), such behavior is in accordance with the complexity, diversity and interactivity of the factors, processes that control the physical–hydric attributes of soils and the cause of the difficulty and inaccuracy commonly reported for their modeling.

Table 3 presents the Pearson correlation data between the variables (soil attributes) and CC, PMP and AD. The highest correlations for CC are observed with total sand (r = - 0.73), clay content (r = 0.70), coarse sand content (r = -0.61), CEC at pH 7.0 (r = -0.63), effective CEC (r = - 0.53) and the sum of bases (r = -0.51). For the PMP, the total sand (r = -0.71) and clay contents (r = 0.66) presented the highest correlations. AD did not present a strong correlation with any of the variables analyzed, with a moderate or weak correlation being observed with Ds (r = - 0.41), coarse sand content (r = -0.34), aluminum content (r = 0.28), clay CTC (r = -0.28), sodium content (r = -0.28) and magnesium content (r = -0.28).

Table 3. Correlation matrix between soil attributes and field capacity, permanent wilting point and available water

Attributes	Correlation coefficient		
	CC	PMP	AD
Ds (Mg m $^{-3}$)	-0.52*	-0.33*	-0.41*
Coarse sand (g kg $^{-1}$)	-0.61*	-0.48*	-0.34*
Fine sand (g kg $^{-1}$)	-0.22*	-0.33*	0.13 ^{us}
Total sand (g kg $^{-1}$)	-0.73*	-0.71*	-0.20*
Clay (g kg $^{-1}$)	0.70*	0.66*	0.28*
Silt (g kg $^{-1}$)	0.35*	0.39*	0.02 ^{us}
pH	0.03 ^{us}	0.22*	-0.28*
Phosphorus (mg kg $^{-1}$)	0.26*	0.36*	-0.09 ^{us}
Calcium (cmolc dm $^{-3}$)	0.45*	0.58*	-0.11 ^{us}
Magnesium (cmolc dm $^{-3}$)	0.53*	0.66*	-0.06 ^{us}
Sodium (cmolc dm $^{-3}$)	0.24*	0.46*	-0.28*
Potassium (cmolc dm $^{-3}$)	0.26*	0.47*	-0.28*
Aluminum (cmolc dm $^{-3}$)	0.20*	0.08 ^{us}	0.28*
Potential acidity (cmolc dm $^{-3}$)	0.39*	0.32*	0.22*
Total nitrogen (dag kg $^{-1}$)	0.49*	0.52*	0.05 ^{us}
Organic carbon content (dag kg $^{-1}$)	0.41*	0.38*	-0.01 ^{us}
Sum of bases (cmolc dm $^{-3}$)	0.51*	0.66*	0.11 ^{us}
Effective CTC (cmolc dm $^{-3}$)	0.53*	0.68*	-0.10 ^{us}
CEC at pH 7.0 (cmolc dm $^{-3}$)	0.63*	0.76*	-0.15 ^{us}
Clay CTC (cmolc dm $^{-3}$)	0.07 ^{us}	0.27*	-0.28*
Base saturation (%)	0.17 ^{us}	0.33*	-0.21*

Source: Own authorship (2022). *Significant correlations at 5% probability and ns = nonsignificant correlations; Ds = soil bulk density; pH = hydrogen potential; CC = field capacity (cm ^{3} cm $^{-3}$); PMP = permanent wilting point (cm ^{3} cm $^{-3}$); CEC = cation exchange capacity; AD = available water (cm ^{3} cm $^{-3}$).

In general, granulometry is the characteristic that best describes the availability of water in the soil. Clay presents a positive correlation, and total sand presents a negative correlation, which is an expected result because of the effect of the specific surface area of the particles.

Similar results were obtained by Michelon *et al.* (2010) when pedotransfer functions were developed to estimate water retention in some soils in Rio Grande do Sul. The negative effect of fine sand content is explained by the fact that soils with finer textures have greater microporosity than those richer in coarse sand. According to Andrade and Stone (2011), microporosity is responsible for most of the water retained at the highest matric potentials (up to -100 kPa) and presents the highest correlation coefficient with retained water.

Regarding the correlations between the chemical attributes and the physical–hydric attributes, a possible explanation for these correlations is that the concentrations of H+ and $^{Al3+}$ are related to the formation of aggregates, where the flocculant cations bring the particles closer together, allowing good aggregation and, consequently, greater total porosity, which implies greater water retention. Similar results were reported by Bortolini *et al*. (2018), who estimated water retention and availability in soils in Santa Catarina and reported a significant correlation between soil water availability and the following variables: aluminum saturation, aluminum saturation, base saturation, clay activity, effective CEC and CEC at pH 7. According to the authors, these variables may be correlated because of the strong relationship between acidity and the presence of organic material in the soil.

The exploratory analysis procedure (*forward stepwise*) of the data revealed the predictor variables that significantly influenced ($p<0.010$) the CC, PMP and AD, thus allowing us to obtain a pedotransfer function capable of satisfactorily describing these physical–hydric attributes of the soil (Table 4).

With respect to the PMP, the clay content influenced almost all the models, with the exception of Model II for Neossolos and Plintossolos. For AD, fine sand was identified in five models. These results are corroborated by the findings of Bortolini *et al.* (2018), who, when estimating water retention and availability in soils in Santa Catarina, reported that the granulometric fraction as a predictor variable included in the function was the one that best estimated the CC and the PMP.

Importantly, total organic carbon influences several soil characteristics, mainly those related to the formation of aggregates and the conferral of negative charges, increasing the cation exchange capacity in the soil. In relation to the formation of aggregates, the decomposition of organic matter acts as a cementing agent, uniting and stabilizing both unitary and secondary soil particles (BATISTA *et al.*, 2013).

The equations of models I and II with the predictors and respective regressors for the grouping of all the soil classes (general) are presented in Table 4, and those for each class are presented in Tables 5 and 6.

ISSN 1808-8546 (ONLINE) 1808-3765 (CD-ROM)

Table 4. Pedotransfer functions and their respective regression indices pooled all data (general) for models I (all soil attributes) and II (granulometric analysis and total organic carbon content).

Model	Equations
	General
CC I	0.607 – 0.00027*TA + 0.0096*Mg $^{2+}$ – 0.0002*AG – 0.00037*S
CC II	0.645 – 0.00033*TA – 0.0002*AG – 0.0003*S
PMP I	0.066 + 0.008*CTC + 0.00024*AR - 0.00008*AG + 0.0662*K $^{+}$ – 0.00889*Ca $^{2+}$ – 0.02275*Al $^{3+}$ + 000394*CTC of AR
PMP II	0.375 – 0.3452*TA
AD I	0.338–0.00014*AG–0.0478*Na $^{+}$ –0.112*K $^{+}$ +0.003*Mg $^{2+}$ –0197*pH+0.0006*V
AD II	0.249 – -0.000147*AG – 0.000157*S

Source: Own authorship (2022). CC = field capacity (cm3 cm-3); PMP = permanent wilting point (cm3 cm-3); AD = available water (cm3 cm-3); pH = hydrogen potential; Mg2+ = magnesium; Al3+ = aluminum; Na+ = sodium; AR= clay; Ca2+ = calcium; S = sum of bases, AG = coarse sand; TA= total sand; Al3+ = aluminum; V= base saturation; CEC= cation exchange capacity and CEC of clay

Table 5. Pedotransfer functions and their respective regression indices for the soil classes Latosols and Argisols for models I (all soil attributes) and II (granulometric analysis and total organic carbon content).

Model	Equations
	Latosols
CC I	0.122 + 0.0004*AR + 0.0138*P + 0.0049*T
CC II	0.224 + 0.0004*AR + 0.0303*COT
PMP I	0.0303 + 0.00027*AR + 0.0378*COT – 0.0632*S
PMP II	0.074 + 0.00033*AR + 0.0382*COT – 0.0001*AG
AD I	-0.27+0.02*P + 0.058*pH + 0.087*Al $^{3+}$ - 0.02*AR CTC + 0.002*V – 0.024*S
AD II	0.2368 – 0.00004*TA
	Argisols
CC I	0.3062 + 0.0003*AF + 0.0123*H $^{+}$ +Al $^{3+}$ – 0.0674*COT – 0.00012*TA
CC II	0.1821 + 0.00034*AF + 0.00022*AR – 0.0347*COT
PMP I	-0.0301+0.0441*Al $^{3+}$ +0.0266*pH–0.0082*Ca $^{2+}$ +0.0003*AR–0.0002*Silt
PMP II	0.0858 + 0.00021*AR – 0.0002*Silt + 00001*AF
AD I	0.1963 + 0.0002*AF – 0.1486*K $^{+}$ – 0.0539*COT
AD II	0.1105 + 0.0002*AF

Source: Own authorship (2022). CC = field capacity (cm ^{3} cm $^{-3}$); PMP = permanent wilting point (cm ^{3} cm $^{-3}$); AD = available water (cm ^{3} cm $^{-3}$); pH = hydrogen potential; COT = total organic carbon; T = cation exchange capacity at pH 7.0; AR = clay; P = phosphorus; Ca $^{2+}$ = calcium; H $^{+}$ +Al $^{3+}$ = potential acidity; S = sum of bases; AG = coarse sand; TA = total sand; Al $^{3+}$ = aluminum; V = base saturation; AF = fine sand and CTC of clay

Recebido em 06/05/2023 e aprovado para publicação em 17/06/2023
DOI: http://dx.doi.org/10.15809/irriga.2023v28n2p400-416

Table 6. Pedotransfer functions and their respective regression indices for the soil classes Neossolos and Plintossos for models I (all soil attributes) and II (granulometric analysis and total organic carbon content).

Model	Equations
	Neossolos
CC I	0.254+0.0006*AF+0.0154*T+0.3970*N – 0.0014*Silt+0.0903*Na^{+} – 0.0505*pH + 0.1332*Ca^{2+} - 0.0154*AR CTC + 0.0511*TOC – 0.0819*t + 0.0006*V
CC II	0.0507 + 0.0004*AF + 0.1039*COT – 0.0007*Silt
PMP I	0.127 – 0.0783*Al^{3+} – 0.0151*T + 0.00004*AF
PMP II	0.1174 – 0.00034*AR
AD I	-1.7516 + 0.0006*AF - 0.0205*T + 0.0026*AR + 0.5965*N + 0.0016*TA + 0.2269*Na^{+} + 0.0630*Mg^{2+}
AD II	-0.0303 + 0.0004*AF+ 0.1086*COT– 0.0006*Silt
	Plinthosols
CC I	0.5358 - 0.0002*AG + 0.0140*Ca^{2+} – 0.0379*pH – 0.0340*COT + 0.00005*AF
CC II	0.4098 - 0.0002*AG - 0.0001*Silt - – 0.0397*COT
PMP I	0.4082 + 0.2541*K^{+} – 0.0133*T – 0.0591*pH + 0.0015*V - 0.00007*AG
PMP II	0.2682 – 0.0002*TA
AD I	0.1604 - 0.2541*K^{+} – 0.0002*AG – 0.0193*T + 0.0001*TA + 0.0427*Mg^{2+} + 0.0221*H+Al^{3+}
AD II	0.0888 + 0.0002*AF

Source: Authors (2022). CC = field capacity (cm^{3} cm^{-3}); PMP = permanent wilting point (cm^{3} cm^{-3}); AD = available water (cm^{3} cm^{-3}); Mg^{2+} = magnesium; Al^{3+} = aluminum; Na^{+} = sodium; TOC = total organic carbon, T = cation exchange capacity at pH 7.0; AR = clay; Ca^{2+} = calcium; H^{+}+Al^{3+} = potential acidity; S = sum of bases, AG = coarse sand; TA = total sand; K^{+} = potassium; Al^{3+} = aluminum; V = base saturation; pH = hydrogen potential; AF = fine sand; N = total nitrogen and CTC of clay

Table 7 presents the evaluation of the model's performance (general), Table 8 presents the statistical indicators and confidence indices for the soil classes of Latosols and Argisols, and Table 9 presents the regression classes of the soil classes of Neossolos and Plintossolos. Most variables had a high prediction capacity. The closer the EM and RMSE values are to zero and the closer the IC and R^2 values are to 1, the more appropriate the FPT is (CAMPELO JUNIOR *et al.*, 2014).

Table 7. Evaluation of the regression model performance (general), statistical indicators and confidence indices for models I (all soil attributes) and II (granulometric analysis and total organic carbon content)

Model	R^2	IN	RMSE	d	r	IC	Performance
			General				
CC I	0.73	-0.00001	0.0449	0.99	0.85	0.85	Very good
CC II	0.62	-0.00002	0.0530	0.99	0.79	0.79	Very good
PMP I	0.77	0.00001	0.0367	0.99	0.88	0.88	Very good
PMP II	0.51	-0.00002	0.0538	0.99	0.71	0.71	Good
AD I	0.38	0.00002	0.0396	0.99	0.62	0.61	Median
AD II	0.14	0.0002	0.0463	0.99	0.42	0.41	bearable

Source: Authors (2022). R^2 = coefficient of determination; EM = mean error; RMSE = root mean square error; d = Willmott index; CI = confidence index

Table 8. Evaluation of the regression model performance for the soil classes of Latosols and Argisols, the statistical indicators and the confidence indices for models I (all soil attributes) and II (granulometric analysis and total organic carbon content)

Model	R^2	IN	RMSE	d	r	IC	Performance
			Latosols				
CC I	0.80	-0.00002	0.0348	0.99	0.89	0.89	Very good
CC II	0.78	-0.00005	0.0367	0.99	0.88	0.87	Very good
PMP I	0.89	-0.00007	0.0221	0.99	0.94	0.94	Excellent
PMP II	0.88	-0.00010	0.0234	0.99	0.94	0.93	Excellent
AD I	0.43	0.00010	0.0281	0.99	0.65	0.65	Median
AD II	0.10	-0.00310	0.0193	0.98	0.31	0.30	Terrible
			Argisols				
CC I	0.60	-0.00296	0.0235	0.98	0.77	0.76	Good
CC II	0.39	-0.00178	0.0288	0.98	0.62	0.61	Good
PMP I	0.61	0.00056	0.0225	0.98	0.78	0.76	Good
PMP II	0.23	0.00270	0.0280	0.97	0.48	0.47	bearable
AD I	0.20	-0.00041	0.0317	0.98	0.46	0.45	bearable
AD II	0.16	-0.00304	0.0330	0.98	0.41	0.40	bearable

Source: Own authorship (2022). R^2 = coefficient of determination; EM = mean error; RMSE = root mean square error; d = Willmott index; CI = confidence index

Table 8. Evaluation of the regression model performance for the soil classes of Neossolos and Plintossolos, the statistical indicators and the confidence indices for models I (all soil attributes) and II (granulometric analysis and total organic carbon content)

Model	R^2	IN	RMSE	d	r	IC	Performance
			Neossolos				
CC I	0.99	0.00020	0.0009	0.99	1.00	0.99	Excellent
CC II	0.86	0.00000	0.0188	0.99	0.93	0.91	Excellent
PMP I	0.51	0.00007	0.0115	0.97	0.71	0.69	Median
PMP II	0.33	-0.00060	0.0135	0.95	0.58	0.55	Median
AD I	0.98	0.00020	0.0072	0.99	0.99	0.98	Excellent
AD II	0.80	0.00020	0.0214	0.99	0.90	0.89	Very good
			Plinthosols				
CC I	0.91	-0.00012500	0.0172	0.99	0.95	0.94	Excellent
CC II	0.61	-0.00004167	0.0357	0.99	0.78	0.77	Good
PMP I	0.90	0.00004167	0.0218	0.99	0.95	0.93	Excellent
PMP II	0.20	0.00758333	0.0483	0.98	0.45	0.44	bearable
AD I	0.87	-0.00008333	0.0178	0.99	0.93	0.92	Excellent
AD II	0.25	-0.00008333	0.0427	0.97	0.50	0.48	bearable

Source: Own authorship (2022). R^2 = coefficient of determination; EM = mean error; RMSE = root mean square error; d = Willmott index; CI = confidence index

The confidence indices showed excellent and very good performance for CC and PMP in the soil classes Latisol, Argisol, Neosol and Plinthosol. AD showed excellent and very good performance only for the Neosol class, presenting confidence indices that indicate average or poor performance for the other soil classes.

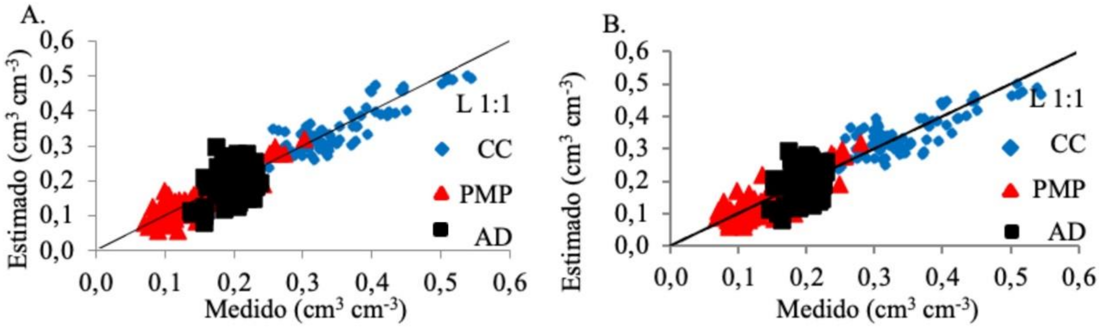
The average errors of the generated models indicate that most tend to underestimate, presenting negative values. Similar results were obtained by Oliveira *et al*. (2002), who, when developing pedotransfer functions to estimate water content in the state of Pernambuco, reported very good performance for CC and PMP and poor performance for AD, with negative values being observed for the error of most variables.

The root mean square error for most models was low, indicating a good fit. The exceptions were the models for available water, which showed high dispersion for most models and low dispersion in the models generated for the Quartzarenic Neosol class and the Plinthosol I model.

Figures 1, 2, 3, 4 and 5 show the results of the evaluation graphically through the relationship between the values estimated and measured by the FPT models generated for CC, PMP and AD for models I (A) all the soil attributes and II (B) granulometric analysis and total organic carbon content, considering all the soil classes (General) or just one soil class (Latosol, Argisol, Quartzarenic Neosol and Plinthosol).

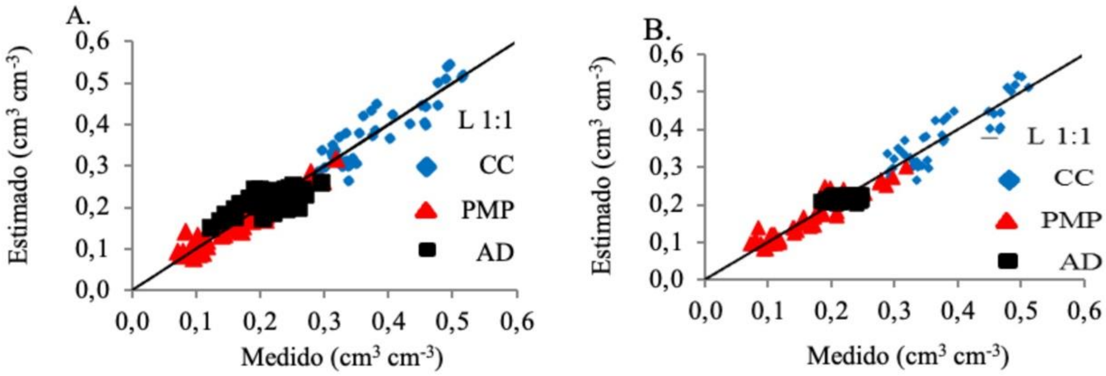
ISSN 1808-8546 (ONLINE) 1808-3765 (CD-ROM)

Figure 1. Relationships between the measured and estimated values of CC, PMP and AD via models I (A) and II (B) for all the soil classes (general).



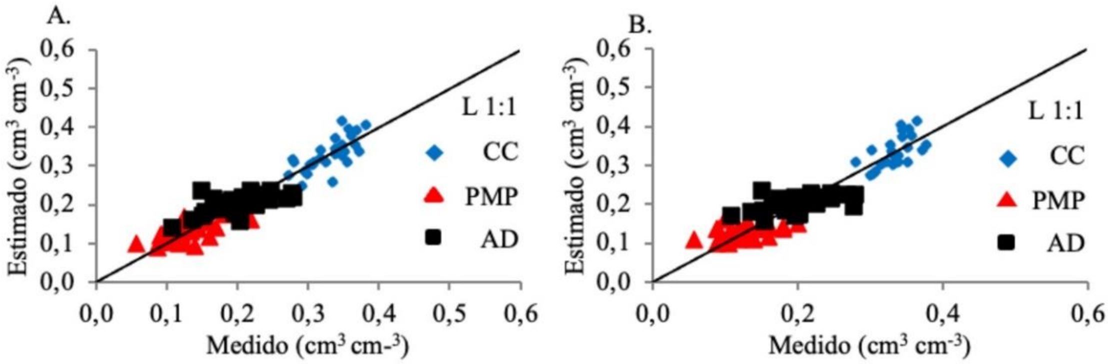
Source: Own authorship (2022)

Figure 2. Relationships between the measured and estimated values of CC, PMP and AD by models I (A) and II (B) for the Latosol classes.



Source: Own authorship (2022)

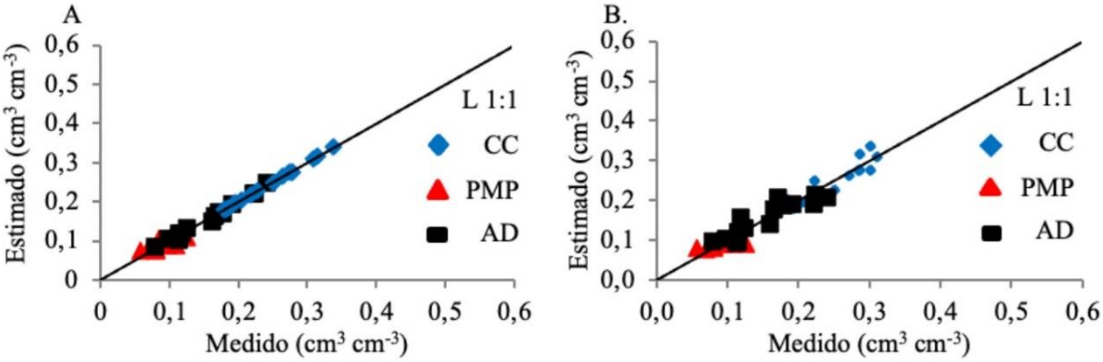
Figure 3. Relationships between the measured and estimated values of CC, PMP and AD via models I (A) and II (B) for the Argisol classes.



Source: Own authorship (2022)

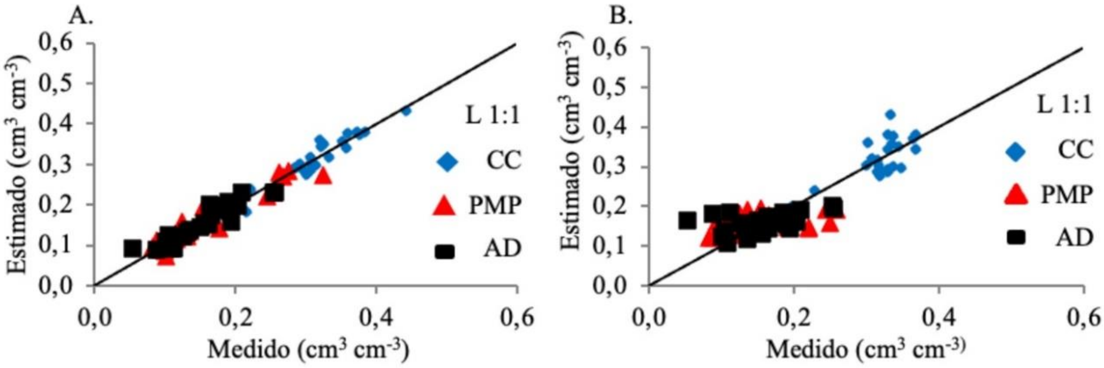
Recebido em 06/05/2023 e aprovado para publicação em 17/06/2023
DOI: http://dx.doi.org/10.15809/irriga.2023v28n2p400-416

Figure 4. Relationships between the measured and estimated values of CC, PMP and AD via models I (A) and II (B) for the classes of quartzarenic Neosols.



Source: Own authorship (2022)

Figure 5. Relationships between the measured and estimated values of CC, PMP and AD via models I (A) and II (B) for the Plinthosol classes.



Source: Own authorship (2022)

For the CC and PMP, the distributions of the points basically occurred around the line, which is in good agreement with the predictions. For AD, a greater dispersion of the points is noted because of the presence of anomalous values (points distant from the main 1:1 line).

Similar results were obtained by Bortolini *et al*. (2018), who also obtained equations for soil water content that were quite accurate for matric potentials of -6, -10 and -1500 kPa when estimating water retention and availability in soils in Santa Catarina.

6 CONCLUSIONS

Field capacity, permanent wilting point and available water can be estimated with reasonable accuracy from pedotransfer functions developed for all soil classes, which use the clay content, potential acidity, sodium content, magnesium content, coarse sand, phosphorus content, clay CEC, fine sand content and total organic carbon of soils in the state of Piauí as predictor variables.

The model developed for Latosols, which included the clay content, magnesium content, clay CTC, base saturation, total sand content and sodium content as predictor variables, performed better in predicting physical–hydric attributes.

The developed pedotransfer functions can support agricultural planning and irrigation management and can be used in soil physics laboratories to obtain, more quickly and easily, field capacity, permanent wilting points and available water in soils in the state of Piauí.

7 REFERENCES

ALMEIDA, KNS; SILVA, JBL; NÓBREGA, JCA; RATKE, RF; SOUZA, KB Agricultural suitability of soils in the state of Piauí. **Native** , Sinop, v. 7, n. 3, p. 233-238, 2019. DOI: http://dx.doi.org/10.31413/nativa.v7i3.7119 . Available at: https://periodicoscientificos.ufmt.br/ojs/index.php/nativa/article/view/7119. Accessed on: Jan. 14, 2023.

ANDRADE, RDS; STONE, LF Estimation of moisture content at field capacity in soils under Cerrado. **Brazilian Journal of Agricultural and Environmental Engineering** , Campina Grande, v. 15, n. 2 , p. 111-116, 2011. DOI: https://doi.org/10.1590/S1415-43662011000200001. Available at: https://www.scielo.br/j/rbeaa/a/3m63gPBHPhGb9HFxG6C7rYz/?lang=en. Access on : Jan 11 , 2023.

BARROS, H.S.; FEARNSIDE, P.M. Pedo-transfer functions for estimating soil bulk density in central Amazonia. **Brazilian Journal of Soil Science** , Viçosa, v. 39, n. 2, p. 397-407, 2015. DOI: https://doi.org/10.1590/01000683rbcs20140358. Available at: https://www.scielo.br/j/rbcs/a/7Czc4Ty4RP8mzGddcPgTr6x/?lang=en. Accessed on: March 20, 2023.

BATISTA, I.; CORREIA, MEF; PEREIRA, MG; BIELUCZYK, W.; SCHIAVO, JA; MELLO, NA Characterization of aggregates in soils under cultivation in Cerrado, MS. **Semina** : Agricultural Sciences, Londrina, v. 34, n. 4, p. 1535-1548, 2013. DOI: https://doi.org/10.5433/1679-0359.2013v34n4p1535 . Available at: https://ojs.uel.br/revistas/uel/index.php/semagrarias/article/view/10613. Accessed on: March 20, 2023.

BERNARDO, S.; MANTOVANI E, C.; SILVA DD; SOARES, AA **Irrigation manual** . 9th ed. Viçosa: UFV, 2019. 545 p.

BEUTLER, S.J.; PEREIRA, MG; TASSINARI, WDS; MENEZES, MD D; VALLADARES, GS; ANGELS, LHCD Bulk density prediction for Histosols and soil horizons with high organic matter content. **Revista Brasileira de Ciência do Solo** , Viçosa, v. 41, p. 1-13, 2017. DOI: https://doi.org/10.1590/18069657rbcs20160158 . Available at: https://www.scielo.br/j/rbcs/a/r5SD47sjzjwnpYWHTmpr7nP/?lang=en. Accessed on: January 11, 2023.

BORTOLINI, D.; ALBUQUERQUE, J. A. Estimation of the Retention and Availability of Water in Soils of the State of Santa Catarina. **Brazilian Journal of Soil Science** , Viçosa, v. 42, p. 1-13, 2018. DOI: https://doi.org/10.1590/18069657rbcs20170250 . Available at: https://www.scielo.br/j/rbcs/a/WXnDnNCvnQYrzcJkdCsjWyp/?lang=en. Accessed on: January 11, 2023.

CAMARGO, A.D.; SENTELHAS, P.C. Performance evaluation of different methods for estimating potential evapotranspiration in the State of São Paulo, Brazil. **Brazilian Journal of Agrometeorology** , Santa Maria, v. 5, n. 1, p. 89-97, 1997. Available at: http://www.sbagro.org/files/biblioteca/124.pdf. Accessed on: January 11, 2023.

CAMPELO JUNIOR, JH; DE AZEVEDO, EC; DE CARVALHO ALVES, M.; DE

MELLO, D.; DE ALMEIDA LOBO, F.; AMORIM, RS S . Estimation of water retention in Oxisols of the Cerrado of Mato Grosso cultivated with cotton **. Agro@mbiente On-line Magazine** , Boa Vista, v. 8, n. 3, p. 318-326, 2014. DOI: https://doi.org/10.18227/1982-8470ragro.v8i3.1902. Available at: https://revista.ufrr.br/agroambiente/article/view/1902. Access on : 12 Dec . 2022.

CAVIGLIONE, J.H. Pedotransfer functions of soil water properties to estimate the S-index. **Brazilian Journal of Agricultural and Environmental Engineering** , Campina Grande , v. 22, n.7, p. 465-470, 2018. DOI: https://doi.org/10.1590/1807-1929/agriambi.v22n7p465-470. Available at: https://www.scielo.br/j/rbeaa/a/fs8jZwMTYmQwYywRP8PqQDs/abstract/?lang=en. Accessed on: December 12, 2022.

HADDAD, DB; ASSIS, LS; TARRATACA, L.; GOMES, ADS; CEDDIA, MB; OLIVEIRA, RF; BRANDAO, DN Brazilian soil bulk density prediction based on a committee of neural regressors . *In* : INTERNATIONAL JOINT CONFERENCE ON NEURAL NETWORKS, 2018, Rio de Janeiro. **Procedure** […]. Rio de Janeiro : IEEE, 2018. p. 1-8. DOI: https://doi.org/10.1109/IJCNN.2018.8489177 . Available at: https://ieeexplore.ieee.org/document/8489177 . Accessed on: December 12, 2022.

JACOMINE, PKT **Exploratory survey-reconnaissance of soils in the State of Piauí** . Rio de Janeiro: EMBRAPA: SNLCS-SUDENE-DRN, 1986. Available at: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/336097. Accessed on: December 12, 2022.

MICHELON, CJ; CARLESSO, R.; OLIVEIRA, ZBD; KNIES, AE; PETRY, MT; MARTINS, JD Pedotransfer functions for estimating water retention in some soils of Rio Grande do Sul. **Ciência Rural** , Santa Maria , v. 40, n. 4 , p. 848-853, 2010. DOI: https://doi.org/10.1590/S0103-84782010005000055. Available at: https://www.scielo.br/j/cr/a/B3bjVtTGFFM4VfYCS7cRQYL/?lang=pt. Accessed on: December 10, 2022.

OLIVEIRA, LB; RIBEIRO, MR; JACOMINE, PKT; RODRIGUES, JJV; MARQUES, F.A. Pedotransfer functions for predicting retained moisture at specific potentials in soils of Pernambuco state. **Revista Brasileira de Ciência do Solo** , Viçosa, v. 26, n. 2, p. 315-323, 2002. DOI: https://doi.org/10.1590/S0100-06832002000200004. Available at: https://www.scielo.br/j/rbcs/a/KfQ7HJzG4RyKkJTW7RGrbry/?lang=pt. Accessed on: December 10, 2022.

PADARIAN, J.; MORRIS, J.; MINASNY, B.; MCBRATNEY, AB Pedotransfer functions and soil inference systems. *In* : MCBRATNEY, A.; MINASNY, B.; STOCKMANN, U. (ed.). **Pedometrics .** Cham : Springer, 2018. p. 195-220. DOI: https://doi.org/10.1007/978-3-319-63439-5_7. Available at: https://www.researchgate.net/publication/324743230_Pedotransfer_Functions_and_Soil_Inference_Systems . Accessed on: December 2, 2022.

PÁDUA, EJD; GUERRA, AR; ZINN, Y. L Modeling of soil density in depth under native vegetation in Minas Gerais. **Brazilian Journal of Soil Science** , Viçosa, v. 39, n. 3, p. 725-736, 2015. DOI: https://doi.org/10.1590/01000683rbcs20140028. Available at: https://www.scielo.br/j/rbcs/a/qGdNQ56LPxprHN5CwrX4gHQ/abstract/?lang=pt. Access on : Mar 10, 2023.

REICHERT, JM; ALBUQUERQUE, JA; PERAZA, JES; COSTA, A. Estimating water retention and availability in cultivated soils of southern Brazil. **Geoderma Regional** , Amsterdam v. 21, p. e00277, 2020. DOI: https://doi.org/10.1016/j.geodrs.2020.e00277. Available at: https://www.scielo.br/j/rbcs/a/qGdNQ56LPxprHN5CwrX4gHQ/abstract/?lang=pt. Accessed on: March 10, 2023.

SANTOS, HD; JACOMINE, P.; ANJOS, L.; OLIVEIRA, V.; LUMBRERAS, J.; COELHO, M.; OLIVEIRA, J. **Brazilian soil classification system** . Brasília, DF: Embrapa, 2018. Available at: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1094003. Accessed on: March 10, 2023.

SILVA, A.C.; ARMINDO, R.A. Importance of pedotransfer functions in the study of hydraulic properties and functions of Brazilian soils. **Multi-Science Journal** , Urutaí, v. 1, n. 5, p. 31-37, 2016. DOI: https://doi.org/10.33837/msj.v1i5.200 . Available at: https://periodicos.ifgoiano.edu.br/multiscience/article/view/200. Access on : Mar 10 , 2023.

SILVA, ED; CURI, N.; FERREIRA, MM; VOLPATO, MML; SANTOS, WJRD; SILVA, SHG Pedotransfer functions for water retention in the main soils from the brazilian coastal plains. **Ciência e Agrotecnologia** , Lavras, v. 39, n. 4, p. 331-338, 2015. DOI: https://doi.org/10.1590/S1413-70542015000400003. Available at: https://www.scielo.br/j/cagro/a/YjsNJJ6MLdgHLjLN6bTBg3J/abstract/?lang=en. Accessed on: March 10, 2023.

SOUZA, ED; FERNANDES FILHO, EI; SCHAEFER, CEGR; BATJES, NH; SANTOS, GRD; PONTES, LM Pedotransfer functions to estimate bulk density from soil properties and environmental covariates : Rio Doce basin . **Scientia Agricola** , Piracicaba, v. 73, n. 6, p. 525-534, 2016. DOI: https://doi.org/10.1590/0103-9016-2015-0485 . Available at: https://www.scielo.br/j/sa/a/vgjCtFKcvpd6GHNZZttq9zQ/?lang=en. Access on : Mar 10 , 2023.

TAVANTI, RF; FREDDI, ODS; TAVANTI, TR; RIGOTTI, A.; MAGALHÃES, WDA Pedofunctions applied to the least limiting water range to estimate soil water content at specific potentials. **Agricultural Engineering** , Jaboticabal, v. 39, n. 4, p. 444-456, 2019. DOI: https://doi.org/10.1590/1809-4430-eng.agric.v39n4p444-456/2019 . Available at: https://www.scielo.br/j/eagri/a/mYjVqfd6mcpQ6bTsp9MkrXG/?lang=en. Accessed on: March 10, 2023.

TEIXEIRA, PC; DONAGEMMA, GK; FONTANA, A.; TEIXEIRA, WG **Manual of soil analysis methods.** 3rd ed. rev. and ampl . Brasília, DF: Embrapa, 2017. Available at: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1085209 . Accessed on: March 10, 2023.