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Pedotransfer functions for water contents at specific pressure heads of silty soils from Amazon rainforest

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ABSTRACT

There is a lack of information and studies investigating physical and chemical properties of silty soils that occur in the western part of the Amazon region, especially in the State of Acre, Brazil. Due to their exceptional high silt contents, these soils show different physical properties than common tropical soils. No pedotransfer functions (PTFs) for prediction of water contents for these unusual soils have been developed and regional PTFs developed by data from common Brazilian soils fail to give good predictions for the silty soils from Acre. To address this shortcoming, in this study we developed PTFs for water contents at specific pressure heads based on soil samples from silty soils of Acre. Samples were collected in soils under three land uses: native forest, integrated crop livestock systems and grazing pastures. Particle size fractions, bulk density, organic matter, cation exchange capacity, aggregate stability and water contents were measured with replicates. PTFs were developed per land use and for all data together using a stepwise linear regression (SL-PTF) and a random forest algorithm (RF-PTF), which performed much better than the regional PTFs. Determining some water contents in the pressure head range between 0 and –100 cm, together with θ_{15000} was enough to yield an accurate water retention curve for the entire range. PTFs developed using data from all land uses together resulted in a better prediction of water contents. The best PTFs for the prediction of water contents at specific pressure heads were developed by the random forest method. The developed PTFs using only sand, clay and organic matter contents and bulk density led to an acceptable prediction of water contents in the dry range. For the wet range, a robust performance was obtained when clay content, CEC and saturated water content were used as predictors. The predicted available water capacity in silty soils from Acre State was in the range between 5 and 10%, far below the amount required for optimum crop growth. The SL- PTF was a robust model as well but required more predictors.

1. Introduction

Predicting the flow of water in the soil-crop system and the vadose zone requires the knowledge of soil water retention (SWR) properties. SWR databases frequently contain missing values, especially in remote areas, due to the difficulty, cost and time problems of measurement methods which include undisturbed sampling and specific laboratory equipment such as pressure plates (Klute, 1986; Madi et al., 2018). Therefore, pedotransfer functions (PTFs) explaining statistical relationships between available soil data (predictors) and water contents at specific pressure heads can be developed and used for different soil types (Vereecken et al., 2010; Van Looy et al., 2017). The soil properties used as predictors in PTFs depending on data availability or facility in measurements may vary, but most common predictors are particle size fractions (sand, clay and silt contents), bulk density (BD) and organic matter content (OM) (Pachepsky and Rawls, 2004; Lilly et al., 2008; Cichota et al., 2013). A variety of other soil properties might be involved in developing PTFs such as more detailed information on texture (Vereecken et al., 1989; Børgesen et al., 2008), on soil structure (Pachepsky and Rawls, 2003), a climatic and land use factor (Jarvis et al., 2013), chemical soil properties like pH and cation exchange capacity (CEC) (Hodnett and Tomasella, 2002; Costa et al., 2013), as well as water contents at some pressure heads (Twarakavi et al., 2009; da Silva et al., 2017). Among studies that applied aggregate-based parameters such as penetration rate (PR), mean weight diameter (MWD) and geometric mean diameter (GMD) for the development of pedotransfer functions for soil water retention, Dashtaki et al. (2010) showed that GMD and its deviation were better predictors for the drier part of the water retention curve. These parameters were also used successfully in the prediction of fitting parameters of the van Genuchten

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(1980) model by Scheinost et al. (1997).

An extensive diversity exists in theoretical frameworks behind the development of PTFs. PTFs may be developed based on (i) simple look-up tables firstly introduced by Cosby et al. (1984) and Bouma (1989) and still used in more recent models such as Rosetta H1 (Schaap et al., 2001), (ii) widely used linear or nonlinear regression techniques with the general form of $\theta(h) = a\,\mathrm{OM} + b\,\mathrm{Sand} + c\,\mathrm{Clay} + d\,\mathrm{BD} + \ldots e\,\mathrm{X}$ (θ is the volume-based water content at pressure head h and a, b, c, d and e are regression coefficients; X may be any measurable soil property) and finally (iii) advanced methods such as artificial neural networks (Merdun et al., 2006; Baker and Ellison, 2008; D'Emillio et al., 2018), support vector machines (Lamorski et al., 2008; Twarakavi et al., 2009), k-Nearest Neighbor Methods or Gaussian process approach (Nemes et al., 2006; Kotlar et al., 2019) and ensemble methods such as random forest (RF) or decision trees (Cichota et al., 2013; Tóth et al., 2015; Shiri et al., 2017) or an ensemble of published PTFs for parameterizing a Richards equation-based soil water flow model (Guber et al., 2006).

PTFs for the prediction of SWR properties for Brazilian soils were developed based on soils with a wide variety of properties and from different locations, e.g. for soils from the Amazon region (Tomasella and Hodnett, 1998; Tomasella et al., 2000), from the northeast of Brazil (Oliveira et al., 2002; Barros et al., 2013), from the Caatinga or Brazilian savanna (Medrado and Lima, 2014) and from the subtropical southeast (Arruda et al., 1987; Reichert et al., 2009). The wide variety of Brazilian soil classes which cover many climate types, parent materials and hydrological and anthropogenic factors causes the currently used PTFs to be unable of properly predicting SWR properties for soils outside of the pool used for PTF training.

The State of Acre is located in the south-western part of the Brazil's North, bordering the north of Bolivia and the east of Peru. Acre state is part of the Amazon biome, and access to many areas in this region is very limited, resulting in a lack of information on soil properties. A major part of the state is covered by soils with a very high silt content (Oliveira and Alvarenga, 1985; Bernini et al., 2013). Customary Brazilian PTFs are mainly developed on typical tropical soils with a low silt content and therefore their extrapolation to the silty soils of Acre might not be possible.

The objective of this study was to compile a dataset of silty soils from Acre State, Brazil, and to develop PTFs for SWR prediction, comparing two common techniques for PTF development, random forest and stepwise linear regression. Moreover, the combination of typical predictors such as particle size distribution, BD and OM with less common ones including CEC and properties of aggregate stability as potential predictors was addressed. The performance of developed PTFs was compared to the more general PTFs for Brazilian soils.

2. Material and methods

2.1. Site study and soil properties measurements

The study area is located about 50 km from Rio Branco, capital of Acre state, Brazil (latitude 9°56′40″S, longitude 68°14′10″W, Fig. 1). The average elevation of the study site is 194 m with annual rainfall varying between 1877 and 1982 mm and average temperature of 25° C. Sampling locations were subdivided into the following land use systems:

(i) Tropical native forest (NF): mainly under palm species (Arecaceae) and bamboo (Bambusoideae).
(ii) Integrated crop livestock system (ICLS): after the removal of the native forest and burning of the surface litter layer in 1966, pasture was cultivated in the area. From 2011, the ICLS system integrating pasture and maize crop was used. In this year, tillage was performed, including acidity correction.
(iii) Pasture (P): the conventional pasture with Brachiaria grass (*Brachiaria brizantha*) was initially sown in combination with the tropical kudzu (*Pueraria phaseoloides*) in 1994, without acidity correction or fertilizers, remaining with the same land use for 20 years. During this period, the area was burned twice, in 1994 right after deforestation and again in 1999.

The soil was morphologically classified based on the evaluation of two pits, one in the ICLS and one in NF. For the pasture, only texture was determined in disturbed samples. According to the Brazilian soil classification system (dos Santos et al., 2018), the soil from ICLS and P are "Argissolo Vermelho-Amarelo distrófico plintossólico" (which translates to a Plinthic Paleudult in USDA Soil Taxonomy) and "Argissolo Vermelho-Amarelo eutrófico plintossólico" (corresponding to a Plinthic Paleudult in Soil Taxonomy) for NF. The solum layer is mostly shallow, poorly drained, with high activity of clay and fertility varying between eutrophic, epieutrophic and dystrophic (Acre, 2010). The vegetation cover within the area is tropical forest with predominance of bamboo (Bambusoideae) under flat-undulating or undulating regional relief (Acre, 2010). According to previous studies at this same site, Araújo et al. (2010) reported the presence of minerals of 2:1 type in the clay fraction and the presence of hydroxides between layers of vermiculite and traces of smectites.

The distance between the locations of the land use systems NF, ICLS and P was about 500 m. In each system, four trenches 1.40 m deep and 40 m away from each other were opened. 192 undisturbed (100 cm^3 rings) samples and the same number of disturbed (auger) samples were taken at depths of 0–5, 5–10, 10–20, 20–30, 30–40, 40–60, 60–80 and 80–100 cm to determine particle size distribution, penetration resistance (PR), aggregate stability and chemical properties like OM and CEC.

2.2. Experimental measurements and water retention curve fitting

The disturbed soil samples were air-dried and ground to pass a 2-mm sieve. OM content was determined by the Walkley–Black method with dichromate extraction and titrimetric quantization (Nelson and Sommers, 1996). CEC was obtained by summation of exchangeable cation contents. Exchangeable cations Ca^{2+}, Mg^{2+} and Al^{3+} were extracted with 1 M KCl, and potential soil acidity (H + Al) was determined using a solution of 0.5 M calcium acetate, at pH 7.0. P, Na^+ and K^+ were extracted with 0.0125 M H_2SO_4 solution + 0.05 M HCl. Ca^{2+} and Mg^{2+} contents were determined by titration with 0.0125 M EDTA solution, Na^+ and K^+ by flame photometry, P by colorimetry, and Al^{3+} and H^+ by titration with 0.025 M NaOH.

To measure the laboratory soil penetration resistance (PR), undisturbed soil samples (100 cm^3 ring) were equilibrated at a −100 cm pressure head using a sandbox device and then subjected to penetration by a bench top electronic penetrometer with a 4 mm cone, penetrating at the speed of 30 mm s^{-1}.

The aggregate stability was represented by the mean weight diameter (MWD) and the geometric mean diameter (GMD). Undisturbed samples (100 cm^3 rings) were passed through an 8 and 4 mm sieve. Soil aggregates remaining on the 4 mm sieve were separated by wet sieving according to Kemper and Chepil (1965) and Claessen (1997). 25 g of pre-wetted aggregates were passed through a nest of sieves with opening screens of 2.0, 1.0, 0.25 mm. The soil retained on each sieve was removed and dried at 105 °C for 24 h and then weighed to calculate MWD by

$$MWD = \sum_{i=1}^{n} w_i \bar{X}_i / \sum_{i=1}^{n} w_i \quad (1)$$

where w_i is the weight of aggregates in each size class and $\bar{X}_i$ is the mean diameter in that size class (mm).

Similarly, the geometric mean diameter (GMD) was calculated as

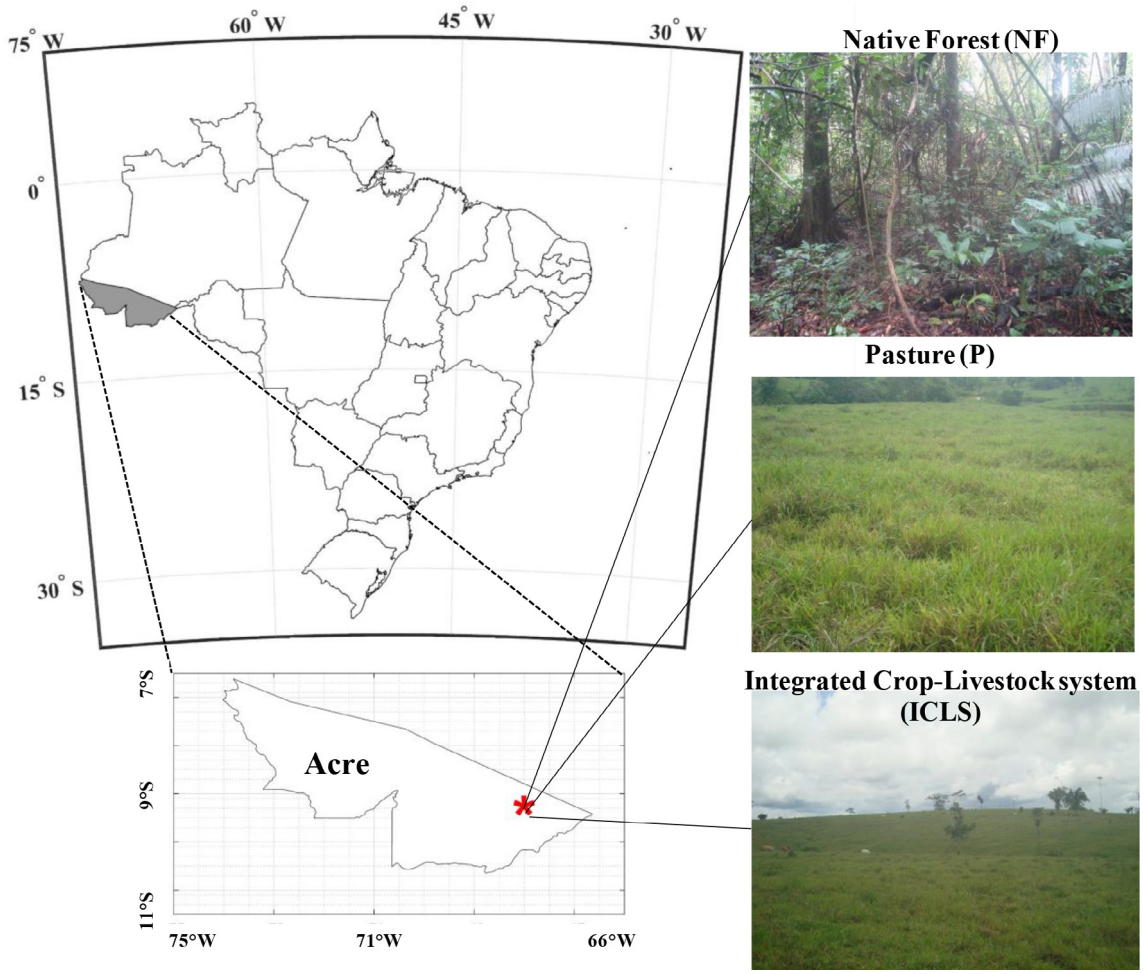

Fig. 1. Geographical location of the study site in the State of Acre, Brazil. Photographs refer to the three studied land uses: native forest, pasture, and integrated crop-livestock system.

$$GMD = \exp\left\{ \left(\sum_{i=1}^{n} w_i \ln \bar{X}_i \right) / \left(\sum_{i=1}^{n} w_i \right) \right\} \tag{2}$$

Water content at saturation was considered to be equal to total porosity calculated with known bulk and particle densities for each sample. Water contents at −10, −60 and −100 cm pressure heads were determined by equilibration of samples (100 cm^3 rings) on a sandbox apparatus. For the drier water contents (at − 330, –1000, −3000, −5000 and − 15000 cm pressure heads), equilibrium was established in the same samples on a pressure plate apparatus (Klute, 1986). All water contents were measured in the undisturbed ring samples, except the − 15000 cm water content for which disturbed material was placed directly on the porous plate.

Measured water contents were fitted to the van Genuchten (1980) equation:

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = (1 + |\alpha h|^n)^{-m} \tag{3}$$

$$K(h) = K_s S_e^{\lambda} [1 - (1 - S_e^{1/m})^m]^2 \tag{4}$$

using the RETC software (van Genuchten et al., 1991). In this equation, S_e is the effective saturation, θ_s and θ_r are saturated and residual volume-based water contents, $K(h)$ and K_s are unsaturated and saturated hydraulic conductivities (cm d^{-1}), and the three parameters including α (cm^{-1}), $m = 1–1/n$, and λ are fitting parameters. A nonlinear least square optimization approach is used by RETC to fit van Genuchten (1980) parameters from observed water retention data (van Genuchten et al., 1991). The RETC program was run with different initial parameter estimates from the library of the program, selected based on sample texture. Convergence to a global minimum and parameter uniqueness was assumed for the run with the lowest minimum objective function. To reduce the number of fitting parameters parameter λ was considered equal to 0.5.

Since the measurements of water retention values (θ-h data pairs), especially at high suctions using pressure plates, are time consuming and cumbersome, we investigated the loss of the predicting capacity of the van Genuchten (1980) equation for the Acrean soils when using less θ-h data pairs. Water contents at eight pressure heads were available, and we investigated to what extent the fitted van Genuchten parameters depend on the number of θ-h data pairs used, down to at least the number of fitting parameters. Three scenarios were tested: (I) exclusion of θ_{5000} and θ_{3000}, (II) exclusion of θ_{5000} and θ_{3000} and θ_{1000} and (III) exclusion of θ_{5000} and θ_{3000} and θ_{1000} and θ_{330}.

2.3. Description of PTFs from literature

To predict water contents by PTF, those developed in the same region or at least in similar soils in terms of texture and structure are always recommended. Silty soils like the ones used in this study from Acre state, Brazil, were never used in developing PTFs. The Brazilian soil hydraulic database HYBRAS (Ottoni et al., 2014) contains only 48 soil samples (corresponding to 2% of the total amount of samples available) with a high silt content. In order to show the importance of a specific PTF for the Acre soils, four PTFs developed for Brazilian soils

Table 1
Selected PTFs from literature for the prediction of mass-based water content at –330 cm (w_{330}) and –15000 cm (w_{15000}) (conversion to volume based water contents by multiplying by bulk density for each sample was performed).

Literature source	State in Brazil	PTF
Arruda et al. (1987)	São Paulo	$w_{330} = 3.074 + 0.629 \times (C + Si) - 0.003438 \times (C + Si)^2$ $w_{15000} = 1.074 + 0.2712 \times (C + Si)$
Tomasella and Hodnett (1998)	Amazon	$w_{330} = 4.046 + 0.426 \times Si + 0.404 \times C$ $w_{15000} = 0.91 + 0.15 \times Si + 0.396 \times C$
Oliveira et al. (2002)	Pernambuco	$w_{330} = 0.0333 \times Si + 0.0387 \times C$ $w_{15000} = -0.0038 \times S + 0.0153 \times Si + 0.0341 \times C - 0.309BD$
Reichert et al. (2009)	Rio Grande do Sul	$w_{330} = 0.0333 \times Si + 0.0387 \times C$ $w_{15000} = 0.236 + 0.045 \times C - 0.21 \times S$

C:clay mass fraction; Si: silt mass fraction; S: sand mass fraction; BD: bulk density (g cm^{-3}); w_{330}: mass-based water content at –330 cm pressure head, w_{15000}: mass-based water content at –15000 cm pressure head.

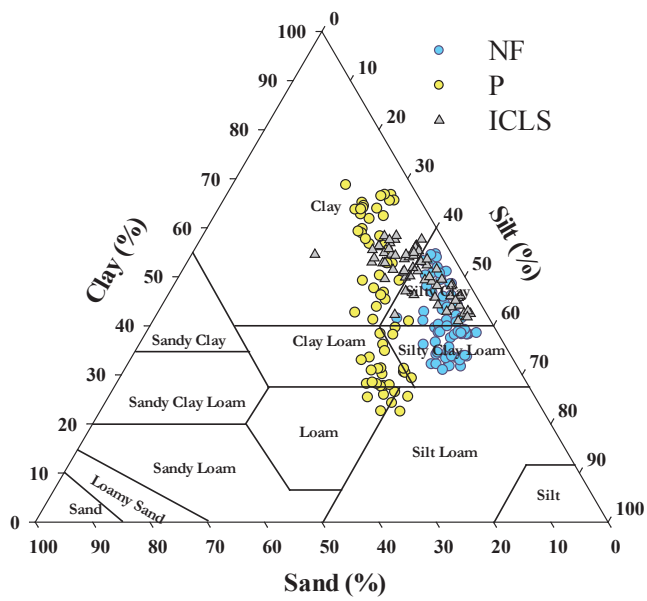

Fig. 2. Studied soils from Acre under native forest (NF), pasture (P) and integrated crop livestock system (ICLS) on a USDA textural diagram (mass-based percentages).

were used to evaluate how accurate they can predict soil water contents at pressure heads of −330 cm and −15000 cm for the soils from Acre. The four selected PTFs are (1) Arruda et al. (1987), pioneers in developing PTFs for water content prediction by particle size distribution and widely cited in PTF based studies for Brazilian soils; (2) Tomasella and Hodnett (1998), PTFs developed from data from Amazonia; (3) Oliveira et al. (2002) and (4) Reichert et al. (2009), both well-known PTFs developed based on soils from the southeast and south of Brazil. This variety of PTFs could allow us to evaluate the efficacy of available PTFs for prediction of water contents for Acrean soils. These PTFs, summarized in Table 1, were tested and root mean square error (RMSE) and correlation coefficient R^2 for water contents at pressure heads of −330 cm and −15000 cm were reported.

2.4. Development of PTFs

PTFs were developed to predict volume-based water contents at pressure heads of −10, −60, –100, −330, − 1000, −3000, −5000 and −15000 cm (referred to as θ_{10}, θ_{60}, θ_{100}, θ_{330}, θ_{1000}, θ_{3000}, θ_{5000} and θ_{15000} respectively) and available water capacity (AWC), defined as AWC = $\theta_{330} - \theta_{15000}$.

Firstly, PTFs were generated using stepwise linear regression (SL-PTF). The stepwise linear regression is a variable selection method which removes the least significant predictor, the one with the largest p-value. This elimination process continues until all remaining features have individual p-values smaller than 0.05 (Friedman et al., 2001).

Secondly, PTFs were developed using the random forest technique (RF-PTF). To do so, a hundred decision tree learners were bagged to ensemble one high quality ensemble predictor. Every node in the decision trees is a condition on a single feature, designed to split the dataset into two in such a way that similar response values end up in the same set. Predictor importance in random forest is obtained by summing the changes in the errors due to each split in the predictor and dividing the sum by the number of branch nodes. We used normalized predictor importance where division of each predictor importance by the sum of predictors' importance is used. Once important predictors were detected, a summarized model with only these predictors was trained to predict the targets and obtain the corresponding RMSE and R^2. The RF-PTF using all predictors to estimate water contents at specific pressure heads will be referred to as the AP- model.

Prediction of targets for each land use (NF, ICLS and P) was performed to explore the performance of the developed PTFs for each specific land use. Subsequently, PTFs were developed for the scenario comprising all data together, not considering the effect of land use.

3. Results and discussion

3.1. Data description

Textural classification of soil samples for the three different land uses is shown in Fig. 2. In the native forest (NF), soils pertain to two soil texture classes: silty clay and silty clay loam. On average, the sand fraction of the soils from NF is lower, i.e., less than half of the sand content of the soils from ICLS and P (Table 2). Soils from ICLS are mostly clayey or silty clay. For the soils under pasture, a wider textural distribution was observed. About half of them has a clayey texture, 25% is clay loam and the remaining soils are loam, silty loam or silty clay.

The land use system may affect the physical soil attributes, where machine traffic and cattle trampling increase the bulk density and resistance to soil penetration, as may have occurred in ICLS and P (Fernández et al., 2011) and also explained in Table 2 when compared to NF. The higher bulk density of integrated systems was also reported by Araújo et al. (2010) for the same region. The reducing trend of bulk density of soils under ICLS, P and NF is accompanied by an increasing organic matter content. The largest maximum values of GMD under P and ICLS, 6.4 and 6 mm respectively, mostly occurred in samples from the surface layer, however, the GMD of surface soil samples under NF were all below 4 mm. The low value of average GMD in ICLS (2.5 mm) compared to NF (2.9 mm) is due to the smaller GMD in samples taken from depths below 30 cm. Generally, the large difference in aggregate stability parameters were observed only for samples down to 50 cm depth; for deeper samples no significant difference occurred among land use systems. This depth dependency also occurred for values of bulk density, with an average of 1.45 g cm^{-3} below 40 cm and

Table 2
Soil attributes for 64 samples taken from each land use including NF (native forest), ICLS (integrated crop livestock system) and P (pasture).

Land use	NF				ICLS				P			
Target	min	Mean	Max	SD	min	Mean	Max	SD	min	Mean	Max	SD
C (%)	31.1	41.5	54.7	7.1	16.7	35.4	64.2	16.3	22.6	45.1	68.8	15.2
S (%)	2.7	7.7	16.1	3.5	4.0	17.2	47.7	7.7	4.5	17.4	29.2	6.9
BD (g cm^{-3})	1.1	1.35	1.5	0.1	1.3	1.5	1.8	0.1	1.2	1.45	1.7	0.1
PR (mm)	0.7	1.3	2.2	0.3	1.1	3.0	7.9	1.2	1.0	2.1	3.0	0.4
GMD (mm)	1.3	2.9	4.6	0.9	0.7	2.5	6	1.5	1.0	3.7	6.4	1.6
MWD (mm)	2.3	4.4	6.2	1.2	1.4	3.7	6.2	1.4	1.1	4.1	6.5	1.7
OM (g 100 g^{-1})	0.1	1.7	6.1	1.7	0.2	1.1	4.2	1.0	0.3	1.4	5.7	1.5
CEC(cmol kg^{-1})	12.0	15.5	20.7	2.7	5.2	10.2	19.1	3.9	5.6	12.2	24.0	4.9
θ_{sat}	0.43	0.52	0.59	0.04	0.40	0.49	0.59	0.05	0.44	0.50	0.57	0.04

1.15 g cm^{-3} for samples from the surface layer.

Volume-based saturated water content, equivalent to total porosity, in samples from the top layer (0–5 scm) of NF, P and ICLS were on average 0.53, 0.50 and 0.42 respectively. Mean saturated water content for all depths (Table 2) was the highest under NF (0.52) followed by P and ICLS with 0.50 and 0.49 respectively.

3.2. Retention curve fitting and the number of water contents used

Soil water retention curves of all collected samples from different land uses obtained using all measured water contents (θ_{10}, θ_{60}, θ_{100}, θ_{330}, θ_{1000}, θ_{3000}, θ_{5000} and θ_{15000}) are plotted in Fig. 3a. Fig. 3b also provides the distributions of fitted θ_r, θ_s, α, n and AWC obtained from measured water contents at –330 and –15000 cm pressure head. High silt and low clay contents resulted in small values of AWC, which are lower than the critical values (15%) reported by Cockroft and Olsson (1997) for optimum root growth and function. The standard variation of water retention parameters obtained for soils under NF are larger than under ICLS and P (Table 3). There is a large difference between the average of residual water content of ICLS when compared to NF and P, probably because soils under NF show lower sand contents generally resulting in higher residual water contents. Values of α show a high

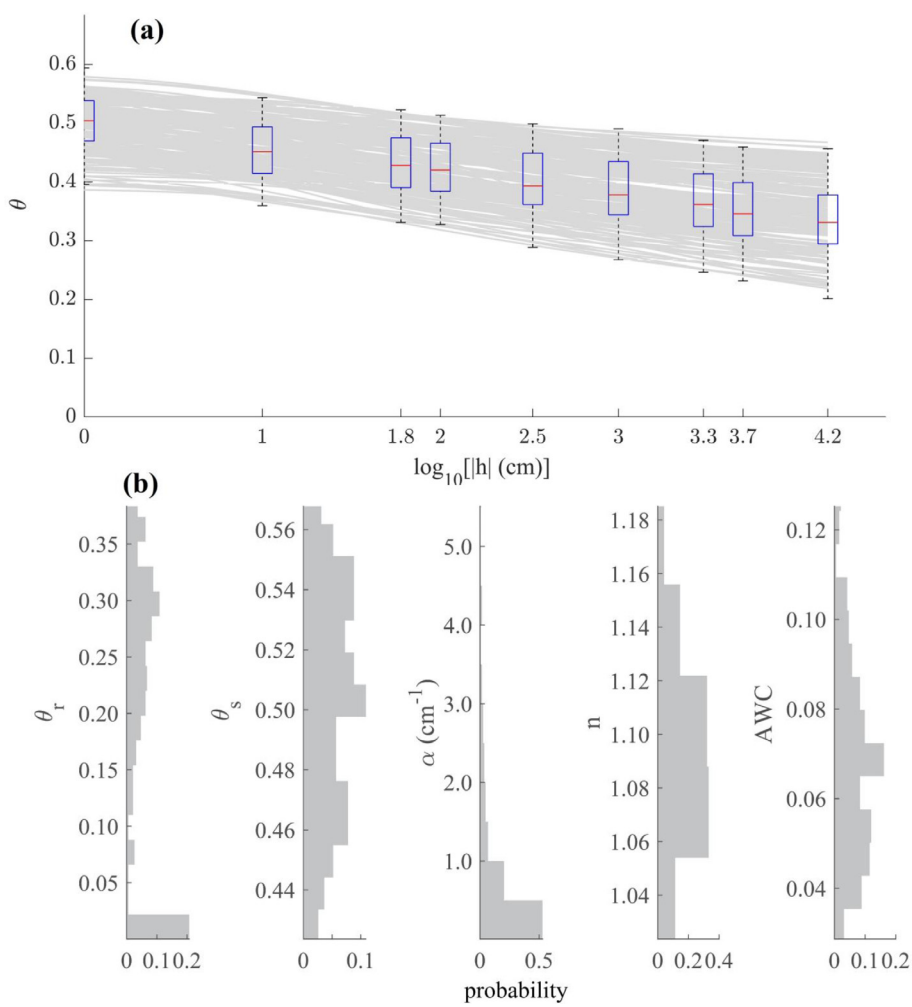

Fig. 3. Soil water retention curves of soil samples from the three land uses in Acre (a) and the distribution of their corresponding van Genuchten parameters besides available water capacity (AWC) (b).

Table 3
Soil water retention parameters for the van Genuchten (1980) equation, with minimum and maximum values obtained from fitting to observed water contents for all 64 samples of each land use NF, ICLS and P.

Land use	NF				ICLS				P			
parameter	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
θ_r	0.23	0.00	0.43	0.13	0.14	0.00	0.35	0.12	0.26	0.00	0.41	0.11
θ_s	0.51	0.43	0.59	0.04	0.49	0.39	0.59	0.05	0.50	0.44	0.57	0.04
$\alpha(cm^{-1})$	1.59	0.01	9.93	2.43	0.47	0.01	2.48	0.49	1.23	0.05	9.22	1.69
N	1.12	1.03	1.69	0.09	1.10	1.03	1.41	0.05	1.10	1.02	1.26	0.04
AWC	0.07	0.03	0.10	0.02	0.09	0.04	0.18	0.03	0.06	0.03	0.09	0.01

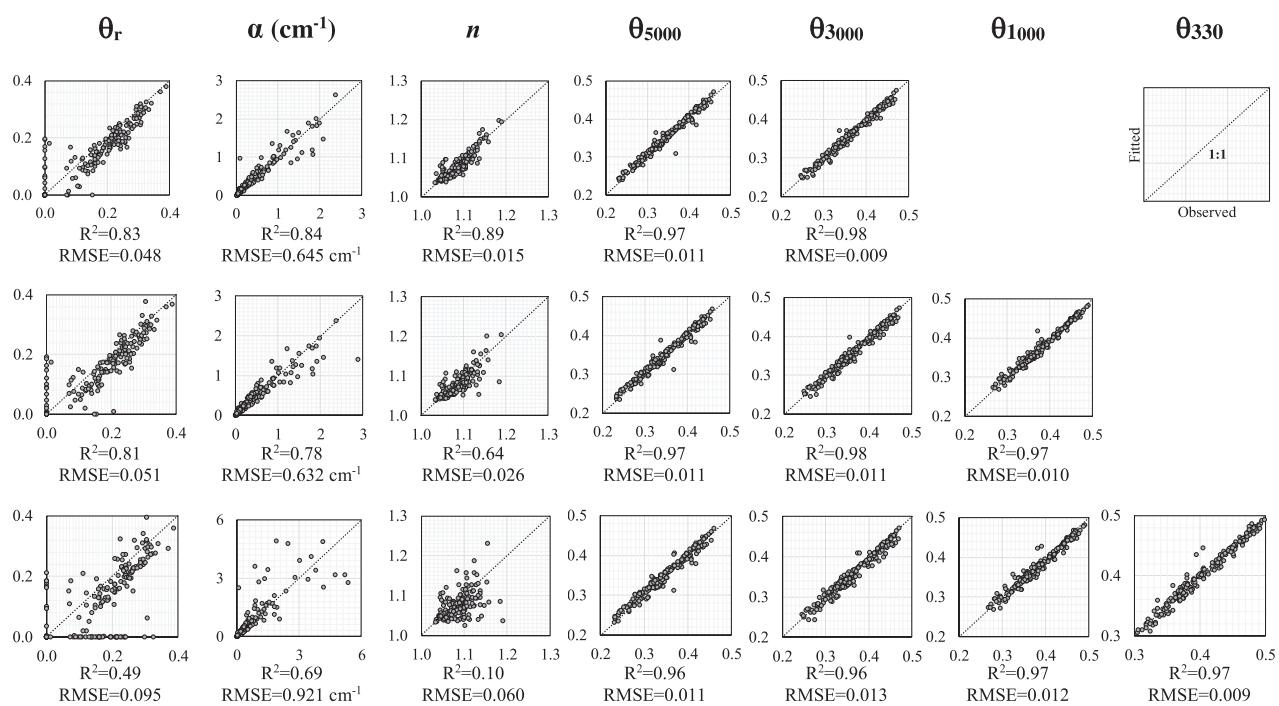

Fig. 4. Scatter plots of fitted van Genuchten parameters (α, θ_r and n) as well as estimated water contents (θ_{330}, θ_{1000}, θ_{3000} and θ_{5000}) from scenario I (exclusion of θ_{3000} and θ_{5000}), II (exclusion of θ_{1000}, θ_{3000} and θ_{5000}) and III (exclusion of θ_{330}, θ_{1000}, θ_{3000} and θ_{5000}) versus their corresponding values obtained from fitting to all 9 water contents.

standard deviation for all land uses, which is probably related to the log-normal distribution which is normally found for this parameter (Barros et al., 2013).

The effect of the elimination of a progressive number of θ-*h* data pairs was evaluated in three scenarios: Scenario (I) exclusion of θ_{5000} and θ_{3000}, (II) exclusion of θ_{5000}, θ_{3000} and θ_{1000} and (III) exclusion of θ_{5000}, θ_{3000}, θ_{1000} and θ_{330}. In scenario I, the excluded values θ_{5000} and θ_{3000} could be accurately predicted by the resulting PTFs with an RMSE of 0.011 and 0.009 respectively (Fig. 4). On the other hand, the fitted van Genuchten parameters differed from those obtained using all water contents (especially θ_r and α with RMSE values of 0.65 cm^{-1} and 0.05 respectively, Fig. 4). Scenario II, excluding also θ_{1000} caused inaccuracy in fitted *n* values and the R^2 reduced by 0.25 compared to scenario I. α and θ_r in scenario II became more scattered around the 1:1 line and their R^2 dropped by 0.06 and 0.02, respectively compared to scenario I. In scenario II, the excluded water contents θ_{1000}, θ_{3000} and θ_{5000} were estimated precisely from the resulting PTFs with an average RMSE of 0.01 and R^2 of 0.97. Excluding four θ-*h* data pairs (scenario III) caused a slight decrease in estimation accuracy θ_{1000}, θ_{3000}, but the R^2 for the estimation of all four excluded water contents remained high (Fig. 4). θ_r, α and *n* were in poor agreement with the values obtained from fits to all nine water contents, with R^2 of 0.49, 0.69 and 0.10 respectively.

The high uncertainty in the *n* value is important in vadose zone hydrological modeling, as it does not affect only the water retention curve, but it also propagates in the unsaturated hydraulic conductivity function. To illustrate this, assuming a K_s of 100 cm d^{-1} and $\lambda = 0.5$ for all available soils under three land uses, their unsaturated hydraulic conductivities in the pressure head range between 0 and –15000 cm pressure heads were calculated using the *n* value obtained from curve fitting to all nine water contents. Then, hydraulic conductivities under the same assumptions were obtained using *n* from scenario I, II and III. The RMSE values for $\log_{10}[K(h)]$ were higher using the *n* values from scenario III for soils under all land uses (Fig. 5). Average RMSE values for $\log_{10}[K(h)]$ for soils from P, ICLS and NF were 0.17, 0.26 and 0.29, respectively.

In most soil samples, fitted *n* values were similar in scenarios I and II, with R^2 of 0.84 and 0.78 (Fig. 4). Consequently, the *K(h)* values were predicted with less bias, and the differences between the average RMSE of scenario I and II under NF, ICLS and P were 0.03, 0.08 and −0.05, respectively.

Due to the high sensitivity of van Genuchten parameters to the water contents used in curve fitting, as well as the sensitivity of the hydraulic conductivity function to *n* values, the prediction of these parameters by a parametric PTF may be considered unreliable. Consequently, development of any PTF for estimation of van Genuchten (1980) parameters are highly sensitive to θ-*h* data pairs thus parametric PTF is not recommended, while point PTFs can be reliably developed and used for fitting of these parameters with high accuracy. The better

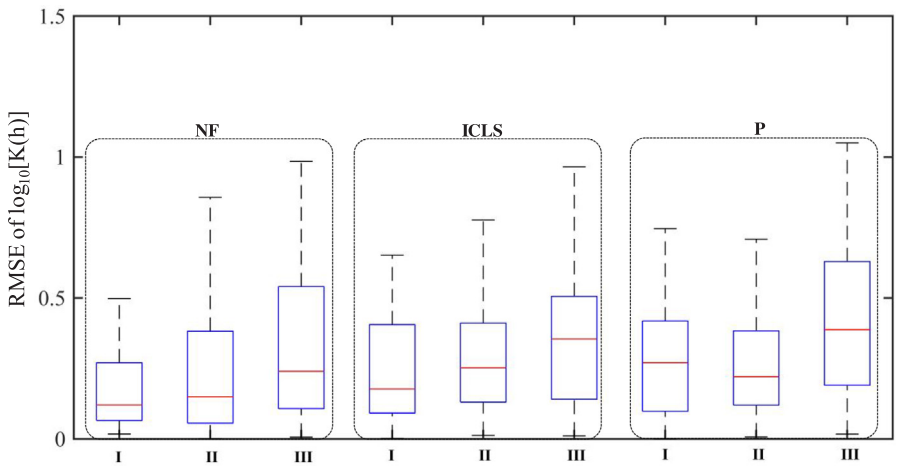

Fig. 5. RMSE values obtained for log-transformed unsaturated hydraulic conductivities using *n* parameter values from three different scenarios compared to the hydraulic conductivities using *n* parameter values obtained fitting to all nine water contents (NF, soils under native forest; ICLS, soils under integrated livestock system and P, soils under pasture).

estimates of water content by point PTFs rather than by parametric PTFs were also discussed by Pachepsky et al. (1996), Tomasella et al. (2003) and Vereecken et al. (2010). However, we here confirmed that the water contents at the median pressure heads may be estimated without significant error using only θ_s, θ_{10}, θ_{60}, θ_{100}, θ_{15000}. These values can be obtained on a sand box or tension table (θ_s, θ_{10}, θ_{60}, θ_{100}) or using a dewpoint device like WP4 (θ_{15000}), and measurement time and costs may thus be reduced.

3.3. Assessment of existing PTFs

RMSE and R^2 values of predicted θ_{330} and θ_{15000} using PTFs mentioned in Table 1 are shown in Table 4. The PTF by Tomasella and Hodnett (1998), developed based on data from the Amazon biome, predicted both water contents with an R^2 of 0.32 and 0.65, respectively, and performed better than the other evaluated PTFs. The soils used to develop their PTF had an average clay content of about 40% and included some intermediate silt content soils from the south of the central sedimentary basin of the Amazon.

The PTF developed by Oliveira et al. (2002) was based soils with average sand, silt and clay contents of 55, 14 and 31%, respectively, very different from the soils used in this study. Consequently, their PTF was able to explain only 0.11 and 0.49 of the variation in θ_{330} and θ_{15000}. Note that the average values of θ_{330} and θ_{15000} used in this study were 0.15 and 0.10 larger than the corresponding values reported by Oliveira et al. (2002). Although the soils used in development of PTFs for θ_{330} and θ_{15000} by Reichert et al. (2009) were similar to the soils used by Oliveira et al. (2002), the performance of the former was weaker, with an R^2 of 0.05 for θ_{330} and 0.38 for θ_{15000}.

Finally, the PTF proposed by Arruda et al. (1987) gave the worst estimation among the compared PTFs, with a very low R^2. In conclusion, we may say that the currently available PTFs for Brazil are unable to give a good estimation of water contents for soils from Acre, regardless of land use, and that the development of specific PTFs for the silty soils from Acre is required.

Table 4
Performance of the regional PTFs by Arruda, et al. (1987), Tomasella and Hodnett (1998), Oliveira et al. (2002) and Reichert et al. (2009) in terms of R^2 and RMSE for prediction of θ_{330} and θ_{15000} from soils of Acre (192 samples).

Water content	Criteria	Arruda, et al. (1987)	Tomasella and Hodnett (1998)	Oliveira et al. (2002)	Reichert et al. (2009)
θ_{330}	RMSE	0.093	0.043	0.079	0.060
	R^2	0.04	0.32	0.11	0.05
θ_{15000}	RMSE	0.067	0.102	0.099	0.049
	R^2	0.06	0.65	0.49	0.38

3.4. PTF development

Once the low performance of the commonly used PTFs (Table 1) for Brazilian soils to estimate water contents for silty soils from Acre was demonstrated, stepwise linear regression (SL) and random forest (RF) based PTFs were developed to predict water contents at various pressure heads using data from each specific land use and also all data together. The goal was to evaluate whether it is possible to present land use specific PTFs for NF, ICLS and P, as well as choosing the best model among SL and RF. Fig. 6 shows the variation of R^2 for the SL and RF-PTF developed for each single water content. Considering land use, the weakest prediction was implemented for NF data using either SL or RF, average values for all eight water contents, with an R^2 of SL-PTF of 0.69 and of RF-PTF of 0.67 (Fig. 6a and b). On average for all eight water contents (θ_{10} to θ_{15000}) from the pasture soil samples (P), R^2 for SL-PTF was 0.78 ± 0.04 and for RF-PTF it was 0.72 ± 0.03.

The weaker prediction of RF was mainly due to poor prediction of θ_{10} with an R^2 of 0.67, though SL explained 0.85 of θ_{10}. Both algorithms had better predictive performance for data from ICLS, as the average R^2 were 0.89 ± 0.05 for SL and 0.93 ± 0.03 for RF. Using soil data from all three land use systems together, RF predicted slightly better than SL with R^2 of 0.88, 3% higher than SL. The slightly lower performance of SL-PTF was mainly due to the weaker prediction of θ_{330} (Fig. 6). The average RMSE obtained by both SL and RF PTFs for all water contents was approximately similar and equal to 0.020, which is lower than obtained from regional PTFs (Table 4) and also values reported by Medeiros et al. (2014) when using PTFs by Tomasella et al. (2000) (Level 1 and 2) and Vereecken et al. (1989) for Amazonian soils. Both RMSE and R^2 values shown in Fig. 6 confirm that predicted water contents for soils under NF and P are less accurate however when only ICLS or all data were used, developed PTFs resulted in better predictions.

3.5. Feature selection of the developed PTFs

Using the RF-PTF, a minimal feature subset was identified among all included predictors resulting in a high predictive accuracy for water contents (Table 5). The normalized importance of each predictor to predict targets (θ_{10} to θ_{15000}) is shown. Saturated water content (θ_{sat}), CEC, and clay content allowed to estimate water contents at various pressure heads with high accuracy. The loss of quality of prediction using only these three parameters compared to the use of all parameters is slightly higher for lower water contents. For example, R^2 values decreased by 6% for θ_{50} and θ_{150}, but drops of 4 and 5% for R^2 were observed for the other water contents. Reducing the normalized

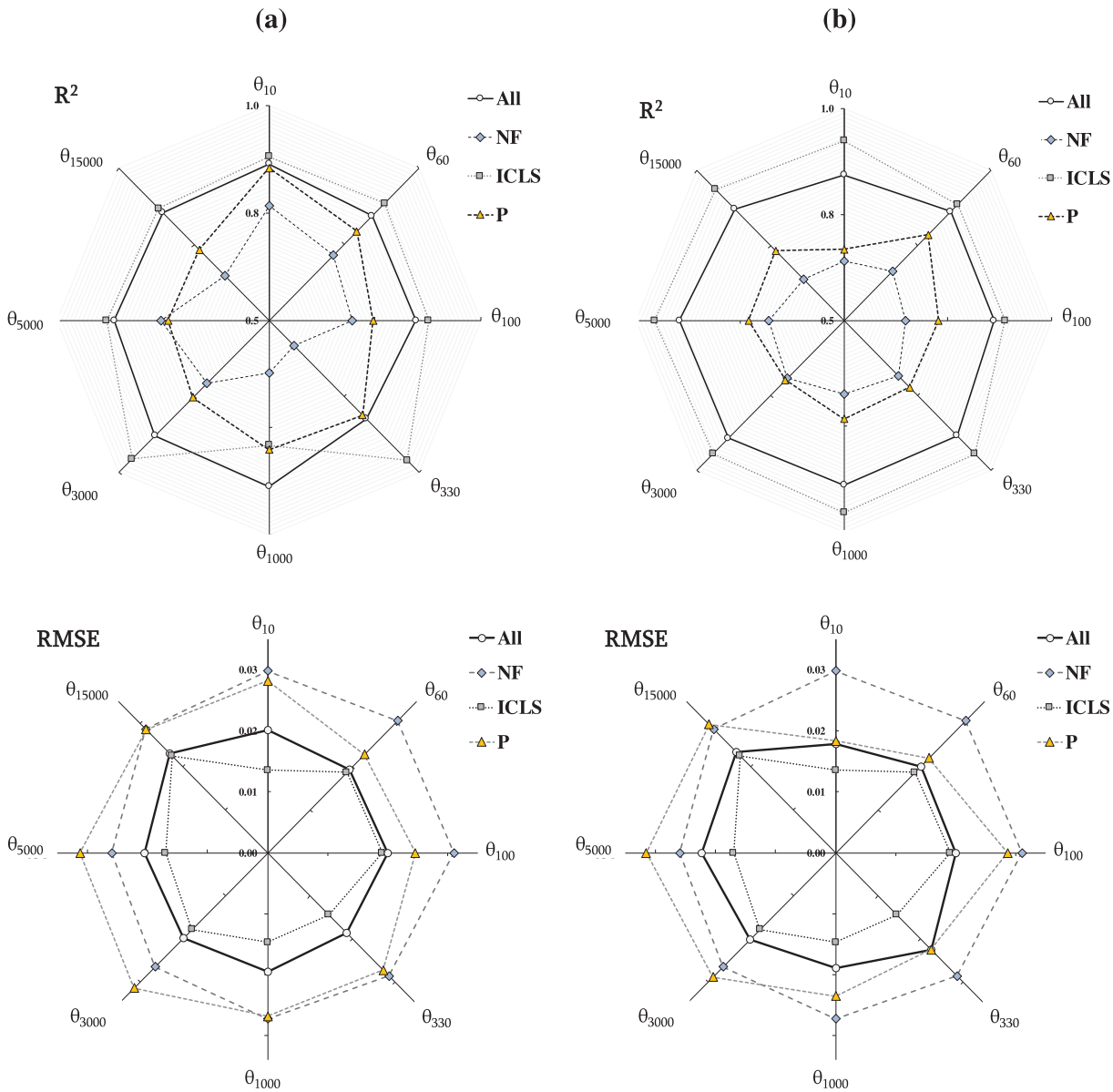

Fig. 6. Spider web diagrams representing R^2 and RMSE of predicted water content at specific pressure heads ranging from −10 to −15000 cm using SL (a) and RF (b) PTFs using data from each of the three land uses (NF, ICLS and P), together with the scenario including data from all three land uses systems (All).

Table 5
Normalized importance of predictors in the RF-PTF developed for the prediction of water contents at selected pressure heads, together with RMSE and R^2 for the AP and summarized model.

Target	Normalized predictor importance									AP-model		Summarized model	
	C	S	BD	PR	GMD	MWD	OM	CEC	θ_{sat}	RMSE	R^2	RMSE	R^2
θ_{10}	0.11	0.07	0.09	0.02	0.02	0.04	0.04	0.19	0.42	0.020	0.84	0.022	0.80
θ_{60}	0.14	0.08	0.08	0.02	0.03	0.03	0.08	0.18	0.35	0.019	0.86	0.023	0.81
θ_{100}	0.18	0.07	0.08	0.03	0.03	0.05	0.06	0.19	0.31	0.020	0.86	0.023	0.81
θ_{330}	0.19	0.10	0.06	0.02	0.03	0.04	0.07	0.22	0.26	0.019	0.88	0.021	0.85
θ_{1000}	0.22	0.10	0.08	0.04	0.05	0.05	0.06	0.22	0.18	0.020	0.89	0.022	0.85
θ_{3000}	0.27	0.09	0.07	0.03	0.04	0.04	0.08	0.20	0.17	0.020	0.89	0.024	0.84
θ_{5000}	0.26	0.09	0.06	0.03	0.05	0.06	0.08	0.21	0.17	0.020	0.90	0.025	0.84
θ_{15000}	0.30	0.08	0.06	0.02	0.04	0.07	0.07	0.19	0.17	0.023	0.87	0.028	0.81

AP-model: a scenario including all predictors; C: clay; S: sand; BD: bulk density; PR: penetration rate; GMD: geometric mean diameter; MWD: mean weight diameter; OM: organic matter; CEC: cation exchange capacity; θ_{sat}: volume-based saturated water content.
Gray boxes show the most important predictors for AP-model.

Table 6
Performance (RMSE and R^2) of developed RF and SL-PTFs using sand, clay and organic matter contents and bulk density for the prediction of all water contents.

PTF	Evaluation Criteria	θ_{10}	θ_{60}	θ_{100}	θ_{330}	θ_{1000}	θ_{3000}	θ_{5000}	θ_{15000}
RF	RMSE	0.028	0.025	0.025	0.022	0.021	0.023	0.021	0.024
	R^2	0.64	0.73	0.75	0.82	0.85	0.84	0.87	0.84
SL	RMSE	0.036	0.036	0.027	0.025	0.024	0.024	0.027	0.029
	R^2	0.41	0.47	0.71	0.77	0.81	0.82	0.78	0.76

importance of θ_{sat} from wet water contents to drier ones is compensated by increasing the impact of the clay fraction in the prediction, although the importance of CEC remained roughly constant for all water contents (Table 5). Residual water contents or points in the dry part are typically estimated by the clay content and these findings are compatible with studies by Lal (1978), van den Berg et al. (1997), Abbasi et al. (2011) and Santra et al. (2018) where clay content accounted for more than 80% of the variance in water content at wilting point.

As reviewed by Vereecken et al. (2010), Patil and Singh (2016) and Van Looy et al. (2017), particle size fractions, BD and in some cases OM may contribute to develop water content PTFs from a soil data base. Therefore, either SL or RF PTFs were trained and tested using only sand, clay and organic matter contents and bulk density (referred to as 'basic') and their performances are reported in Table 6. Compared to the models using all predictors (the AP-model, Table 5), RMSE values increased on average by 15 ± 9% while R^2 reduced by 10 ± 7% in the summarized model. Basic RF-PTF was still robust for the prediction of water contents at higher tensions (–1000 to –15000 cm pressure head). R^2 values for θ_{1000}, θ_{3000}, θ_{5000} and θ_{15000} were higher than 0.84 and better than the ones predicted by the summarized model using clay content, CEC and θ_{sat} as predictors (Table5). Basic SL-PTFs are not as precise as basic RF-PTF, especially for higher water contents. Basic SL-PTF explained only 0.4 and 0.5 of θ_{10} and θ_{60} (Table 6) their corresponding RMSEs were about 51 and 44% larger than RMSEs from the RF-PTF.

4. Conclusion

In this study, soil data from a region in Acre State, Brazil where exceptionally high silt contents are predominant were used to develop and evaluate pedotransfer functions for the prediction of water contents at specific pressure heads, distinguishing three land use systems. From the results we conclude that

(i) Determining some water contents in the pressure head range between 0 and –100 cm, together with θ_{15000} is enough to yield an accurate water retention curve for the entire range. This may reduce time and costs to obtain retention data for the studied soils.
(ii) Currently available PTFs trained based on other Brazilian soils fail to predict water contents in soils from Acre with a high silt content.
(iii) PTFs developed using data from all land uses together resulted in a better prediction of water contents, while using data only from the individual sets for native forest and pasture performed the worst.
(iv) The best PTFs for the prediction of water contents at specific pressure heads were developed by the random forest method, with an average RMSE of 0.020 and an R^2 of 0.88. The stepwise linear regression PTF was a robust model as well, but required more predictors.
(v) The developed PTFs using only sand, clay and organic matter contents and bulk density lead to an acceptable prediction of water contents in the dry range (pressure heads below −1000 cm). For the wet range, a robust performance was obtained when clay content, CEC and saturated water content were used as predictors.
(vi) The predicted available water capacity in silty soils from Acre State is in the range between 5 and 10%, far below the amount required for optimum crop growth.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2019.114098.

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