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Original Article

Determination of field capacity in Oxisols using the flux density method, Arya–Paris model, and pressure chamber[1]

Determinação da capacidade de campo em Latossolos usando o método de densidade de fluxo, modelo Arya-Paris e câmara de pressão

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HIGHLIGHTS:

Field capacity in Oxisols can be determined using undeformed samples under 10 kPa pressure.
Arya-Paris model is suitable to calculate the soil water content at field capacity in Oxisols.
Water retention curve of Oxisols can be determined using the Arya-Paris model.

ABSTRACT: The field capacity of Oxisol was evaluated using the flux density in the field, Arya-Paris model, and Richards pressure chamber with non-deformed samples, and the water retention curve and soil moisture were determined using the Arya-Paris model at a pressure of 10 kPa. The research was conducted at the Federal University of Rondonópolis, Mato Grosso state, Brazil. The soil evaluated was Oxisol at depths of 0-10 and 10-20 cm. Using the flux density method, at a water flux density q = 0.10 mm per day and 1.0 mm per day, soil moisture values at field capacity were 0.30 and 0.32 $m^3\ m^{-3}$, respectively, at a depth of 0-10 cm and 0.28 and 0.31 $m^3\ m^{-3}$, respectively, at a depth of 10-20 cm. Comparing the results obtained with the pressure chamber with those of the field capacity obtained for q = 0.1 mm per day, the mean absolute error and bias were 0.880 and -0.218, respectively, for the 0-10 cm depth and 2.57 and -2.57, respectively, for the 10-20 cm depth. Field capacity of Oxisol can be obtained by subjecting undeformed 50 cm^3 samples to a pressure of 10 kPa. The Arya-Paris model is an alternative for determining the soil water retention curve and the field capacity of Oxisol.

Key words: internal drainage, soil-water characteristic curve, water redistribution

RESUMO: A capacidade de campo do Latossolo foi avaliada usando os métodos de densidade de fluxo de água em campo, modelo Arya-Paris e câmara de pressão de Richards com amostras não deformadas, e a curva de retenção de água e a umidade do solo foram determinadas usando o modelo de Arya-Paris a uma pressão de 10 kPa. A pesquisa foi desenvolvida na Universidade Federal de Rondonópolis, Mato Grosso. O solo avaliado foi Latossolo nas camadas 0-10 e 10-20 cm. Usando o método da densidade de fluxo, a uma densidade de fluxo de água q = 0,10 mm por dia e 1,0 mm por dia, os valores de umidade do solo na capacidade de campo foram de 0,30 e 0,32 $m^3\ m^{-3}$, respectivamente, para uma profundidade de 0-10 cm, e 0,28 e 0,31 $m^3\ m^{-3}$, respectivamente, para uma profundidade de 10-20 cm. Comparando os resultados obtidos com a câmara de pressão com os da capacidade de campo obtidos para q = 0,1 mm por dia, o erro absoluto médio e o viés foram 0,880 e -0,218, respectivamente, para a profundidade de 0-10 cm, e 2,57 e -2,57, respectivamente, para a profundidade de 10-20 cm. A capacidade de campo do Latossolo pode ser obtida submetendo amostras não deformadas de 50 cm^3 a uma pressão de 10 kPa. O modelo Arya-Paris é uma alternativa para determinar a curva de retenção de água do solo e a capacidade de campo do Latossolo.

Palavras-chave: drenagem interna, curva característica solo-água, redistribuição de água

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Introduction

Soil moisture is a limiting factor in agricultural production and is essential for proper irrigation management in production systems (Gutierres & Neves, 2021). One method for determining soil moisture is field capacity, a parameter that identifies the maximum water storage capacity that the soil makes available to crops (Sousa & Assunção, 2021).

Knowledge of field capacity is important in various fields, especially in agriculture, where it guides efficient irrigation practices, optimizes crop performance and the use of water resources, as well as provides a scientific basis for agricultural management (He & Wang, 2019; Sousa & Assunção, 2021).

In the laboratory, field capacity is traditionally determined using the Richards pressure chamber in which undeformed soil samples are subjected to predefined pressures according to the soil type. Determining field capacity is time-consuming and has a high operating cost (Veloso et al., 2023). As a result, alternatives that reduce the cost of equipment and materials and facilitate the determination process are being explored to estimate field capacity.

Pedotransfer equations based on easily obtained physical measurements of the soil, such as soil density, texture, and organic matter content (Andrade et al., 2020; Rosseti et al., 2022) are one such alternative. The set of field data, together with laboratory measurements, enables the choice of the mathematical function that performs best according to the type of soil (Amorim et al., 2022).

Mathematical models designed to quantify water retention in soils are another alternative. The Arya-Paris model determines the water retention curve based on soil density, particle density, and the soil granulometric curve (Andrade et al., 2021). The main advantage of this model is its simplicity and the approach based on physical principles used to construct the equations (You et al., 2022).

Thus, in the current study, the hypotheses tested were whether the Arya-Paris model is an alternative for determining the water retention curve and the field capacity of Oxisols, and whether the field capacity of Oxisols can be determined using undeformed samples at a pressure of 10 kPa.

This study aimed to evaluate the field capacity of Oxisols using the flux density in the field, Arya-Paris model, and Richards pressure chamber with non-deformed samples and to determine the water retention curve and soil moisture using the Arya-Paris model at a pressure of 10 kPa.

Material and Methods

The experiment was conducted in the experimental area of the Federal University of Rondonópolis, Mato Grosso state, Brazil, located at 16° 46′ 43″ South, 54° 58′ 88″ West, and altitude of 290 m. According to the Köppen & Geiger classification, the region's climate is Aw, and the soil is classified as Latossolo Vermelho distrófico (EMBRAPA, 2018) or Oxisols (USDA-NRCS Soil Survey Staff, 2014).

Soil moisture was measured between July and August 2020, and after the measurements, undeformed soil samples were taken from the experimental area to determine field capacity in the laboratory.

Field capacity was determined by three methods: 1) flux density, 2) Richards pressure chamber with undeformed samples of 50 cm^3, and 3) Arya-Paris model. The methods are described below:

The determination of field capacity was based on the analysis of soil water flux density (Twarakavi et al., 2009; Brito et al., 2011; van Lier, 2017; Inforsato & Van Lier, 2021; Phogat et al., 2022). Three 4.0 m^2 (2.0 × 2.0 m) experimental plots were delimited using polyvinyl chloride (PVC) plates inserted to a depth of 10 cm. This analysis was carried out at depths of 0.0-0.10 m, 0.10-0.20 m.

An access tube was inserted into the center of each experimental plot to measure soil moisture with the Diviner 2000 (Sentek Sensor Technologies, Stepney, South Australia) capacitance probe calibrated for the local soil (Duarte et al., 2020).

During the experimental setup, the soil in the experimental plots was saturated by constantly adding a layer of water through a water tank, and the soil moisture monitored. Whenever a variation in the height of the water was observed, the water was replaced. On average, a total of 2.0 m^3 of water was added to each experimental plot, which theoretically would be enough to fill all pores with water up to a depth of 1.0 m, considering an average total porosity of 0.5 $m^3\ m^{-3}$.

After saturation, the plots were covered with waterproof plastic and a depth of straw approximately 10 cm in thickness to reduce thermal fluctuation. Immediately after covering the soil, soil moisture measurements were taken for 30 days or 721 hours.

Water flux density was calculated using the continuity equation, which takes soil depth into consideration (Eq. 1).

$$q_z = -\int_0^z \frac{\partial \theta}{\partial t}\, dz \tag{1}$$

where:

θ - soil moisture ($m^3\ m^{-3}$);

t - water redistribution time (days); and,

q_z - water flux density (mm per day) at soil depth Z. Field capacity was assessed at flux densities of 0.1 and 1.0 mm per day (Jong van Lier, 2017; Inforsato & Van Lier, 2021; Phogat et al., 2022).

Undeformed soil samples were collected at depths of 0.0-0.10 and 0.10-0.20 using 50 cm^3 volumetric rings (4.9 × 2.6 cm) to determine field capacity in the laboratory. Five samples were collected for each ring volume at each depth, totaling 15 samples.

The samples were subjected to pressures of 0, 6, 10, 33, and 50 kPa in the Richards pressure chamber to determine the initial water retention curve. At each pressure, the soil moisture was considered to have stabilized when no more water drained out of the equipment after 48 hours.

Soil moisture was determined at each pressure, and the initial water retention curve was adjusted to the Van Genuchten (1980) model. The adjustment was made for the parameters θr, α, and n. The parameter θs was taken as the highest moisture measured experimentally, and the parameter m was calculated as m = 1 - 1/n. The Microsoft Excel solver function was used to adjust and minimize the sum of squares of the deviations. The field capacity was considered to be the balanced moisture at a pressure of 10 kPa, as commonly adopted for tropical soils (Reichardt, 1988).

To determine the water retention curve using the Arya-Paris model, the soil particle size curve was initially drawn for depths of 0.0-0.10 and 0.10-0.20 m using the ABNT 7181 standards (Figure 1).

The logistic model was fitted to represent the relationship between particle diameter (mm) and cumulative percentage (Eq. 2):

$$y = A_{min} + \frac{\left(A_{max} - A_{min}\right)}{\left[1+\left(\frac{x}{x_0}\right)^{-h}\right]^{s}} \qquad (2)$$

where:

y - cumulative percentage (%);
A_{min} and A_{max} - lower and upper asymptotes, respectively;
x - particle size (mm);
x0 - point of inflection;
h - slope; and,
s - asymmetry factor.

The particle size curve was divided into 20 fractions, according to the methodology described by Arya et al. (1999). The soil moisture, volumetric water content, and tension inside the pores were determined according to Eq. 3 (Arya & Paris 1981), Eq. 4, and Eq. 5, respectively.

$$V_{vi} = \left(\frac{W_i}{\rho_s}\right)e;\; i = 1, 2, \ldots, n \qquad (3)$$

where:

V_{vi} - pore volume (cm^3);
W_i - particle mass (g);
ρ_s - particle density (g cm^{-3});
n - number of samples;
e - void ratio (cm^3 cm^{-3}); and,
i - sample number.

$$V_{pi} = \frac{n4\pi R^3}{3} = \frac{W_i}{\rho_s} \qquad (4)$$

where:

V_{pi} - total volume of particles (cm^3);
n - number of particles;
R - average radius of the particles;
W_i - particle mass (g); and,
ρ_s - particle density (g cm^{-3}).

$$\psi_i = \frac{2\sigma\cos\alpha}{\rho_w g r i} \qquad (5)$$

where:

ψ_i - water pressure in the soil;
σ - surface tension of water;
α - contact angle;
ρ_w - water density;
g - acceleration due to gravity; and,
ri - pore radius (cm).

Originally, the Arya-Paris model (1981) estimated the pore radius value from the average radius of soil particles and the number of particles in each fraction of the soil particle size curve. Following the methodology adapted from Mohammadi (2018), the average pore radius was determined using Eq. 6.

$$r_i = \frac{0.1592\phi\left(\frac{W_1}{\rho_b}\right)}{\sqrt{n_i R_i}} \qquad (6)$$

where:

r_i - pore radius (cm);
ϕ - porosity (cm^3 cm^{-3});
W_1 - fraction solid mass (g);
ρb - bulk density (g cm^{-3});
n_i - number of spherical particles; and,
R_i - particle radius (g).

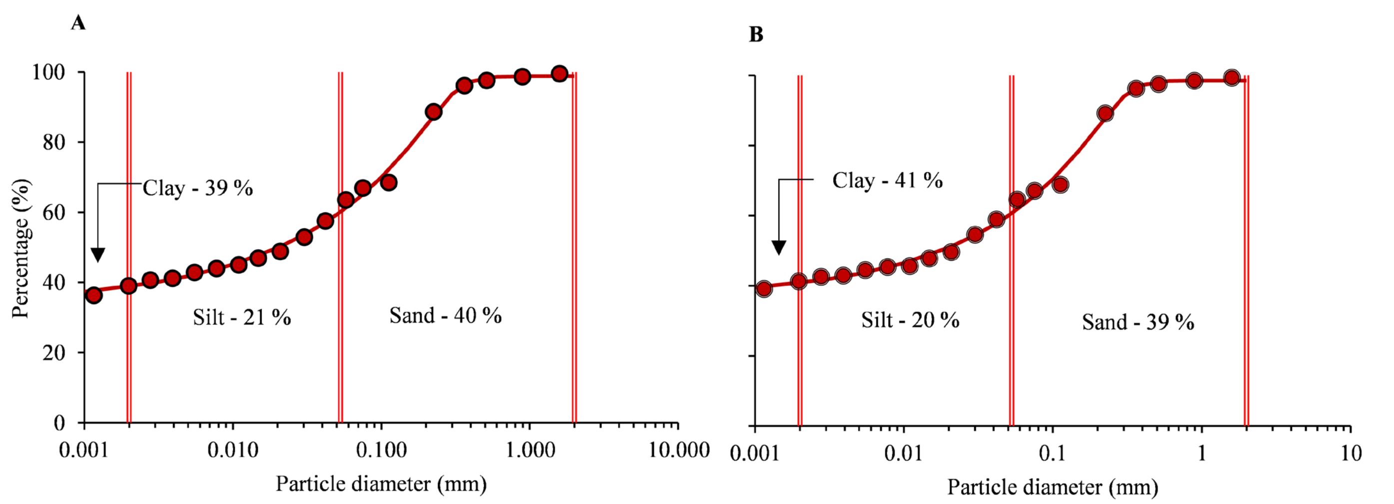


Figure 1. Particle size distribution for Oxisol in the 0.0-0.10 m (A) and 0.10-0.20 m (B) depths

The n_i can be obtained from Eq. 7:

$$n_i = \frac{3w_i}{4\pi\rho_s R_i^3} \quad (7)$$

where:

n_i - number of spherical particles;

W_i - solid mass (g);

ρ_s - particle density (g cm^{-3}); and,

R_i - particle radius (cm).

Particle density was determined using the volumetric flask method, and soil density was obtained from the ratio between dry soil mass and soil volume, considering undeformed samples of 50 cm^3 (EMBRAPA, 2018).

Moisture values at field capacity were compared using the paired Student's t-test at a statistical significance level of $p \leq 0.05$, using the flux density method as the standard. The quality of the simulation obtained with the Arya-Paris model was checked using the indices described below:

$$MAE = \frac{\sum_{i=1}^{n}|Y_i - O_i|}{n} \quad (8)$$

$$Bias = \frac{\sum_{i=1}^{n}(Y_i - O_i)}{n} \quad (9)$$

where:

MAE - mean absolute error;

Bias - error;

Y_i and O_i, - model simulated and measured values, respectively; and,

n - number of observations.

The data were subjected to analysis of variance, and when significant, to the Student's t-test with statistical significance set at $p \leq 0.05$. Analysis was performed using the statistical software R version 4.4.1 (R Core Team, 2024).

Results and Discussion

The physical characteristics of soil density and porosity by depth are listed in Table 1. The highest soil density was observed at 0.10-0.20 m, and this depth had the lowest total porosity (50.51%). In the surface depth (0.00-0.10 m), the density (1.20 g cm^{-3}) was lower with a higher total porosity (54.60%).

The higher density found in the subsurface depth may indicate a tendency towards compaction because of mechanized management. In this case, as compaction in field conditions can alter the distribution of pores (Fu et al., 2019), this occurrence may influence the quality of the simulation of soil water content with the Arya-Paris model.

The field capacity values obtained using the soil water flux density method for the 0-10 cm and 10-20 cm depths are listed in Table 2 and illustrated in Figure 2. For the initial depth, the soil moisture value considering a flux density of 1.0 mm per day was 0.32 m^3 m^{-3}, whereas for a flux of 0.10 mm per day, the value was 0.30 m^3 m^{-3}. The soil moisture values for the 0.10-0.20 m depth were 0.31 and 0.28 m^3 m^{-3}, respectively.

At 0.0-0.10 m, when flux density q = 1 mm per day was used, it took 26 hours to achieve field capacity. However, when flux density q = 0.1 mm per day was used, field capacity was achieved after 264 hours, in other words, stabilization took approximately 11 days (Table 2 and Figure 2A).

At the deeper depth of 0.10-0.20 m, with flux density q = 1.0 mm per day, the time taken to reach field capacity was

Table 1. Soil density and total porosity of undeformed samples collected at two depths

Soil depth (m)	Soil bulk density (g cm^{-3})	Total porosity (%)
0-0.10	1.20 ± 0.07	54.60 ± 0.019
0.10-0.20	1.31 ± 0.09	50.51 ± 0.018

Table 2. Results of determining field capacity using the soil water flux density method

Soil depth (m)	Flux density (mm per day)	Hour (h)	Water content (m^3 m^{-3})
0-0.10	1.0	26	0.32
	0.1	264	0.30
0.10-0.20	1.0	23	0.31
	0.1	232	0.28

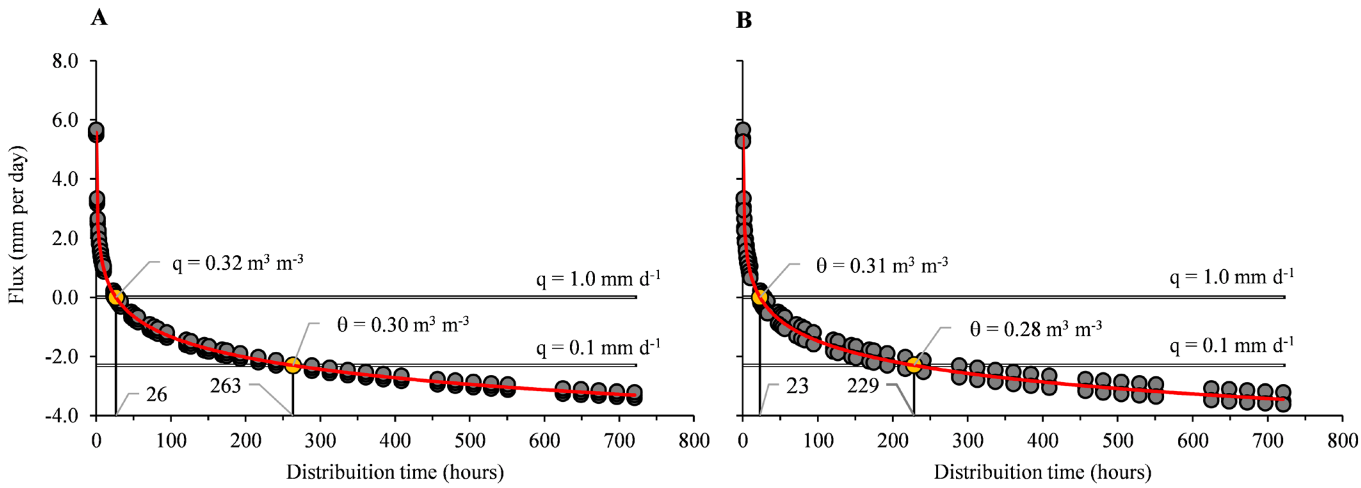


Figure 2. Variation in soil water flux density in an Oxisol in the (A) 0.0-0.10 cm, and (B) 0.10-0.20 cm depths

23 hours, whereas with flux density q = 0.1 mm per day, field capacity was achieved only after 232 hours, or approximately 10 days (Table 2 and Figure 2B).

Therefore, for both depths (0.0-0.10 and 0.10-0.20 m), if a low flux density is used, the time taken to reach field capacity will be longer. It is worth noting that the flux density q = 0.1 mm per day is generally used to determine field capacity in the literature (Twarakavi et al., 2009; Brito et al., 2011).

Considering a flux density of 1.0 mm per day, field capacity would be reached in approximately only 24 hours at both depths after the excess water begins to drain away, corroborating the time estimated by Veihmeyer & Hendrickson (1931) as being generally 2 or 3 days when determining values in situ.

Using a flux density of 1.0 mm per day, De Jong van Lier (2017), reported times of 2-6 days at a depth of 0.30 m. In contrast, for 2-3 days, which is the time considered by Veihmeyer & Hendrickson (1931), the flux density used was 5 mm per day.

In the study by Brito et al. (2011) with Hapludox (0.00-0.20 m depth), water flux density values of 0.1 mm per day were verified for 455 hours after redistribution began; the observed times were 52, 97, 152, and 205 hours at depths of 0.2, 0.4, 0.6, and 0.8 m, respectively.

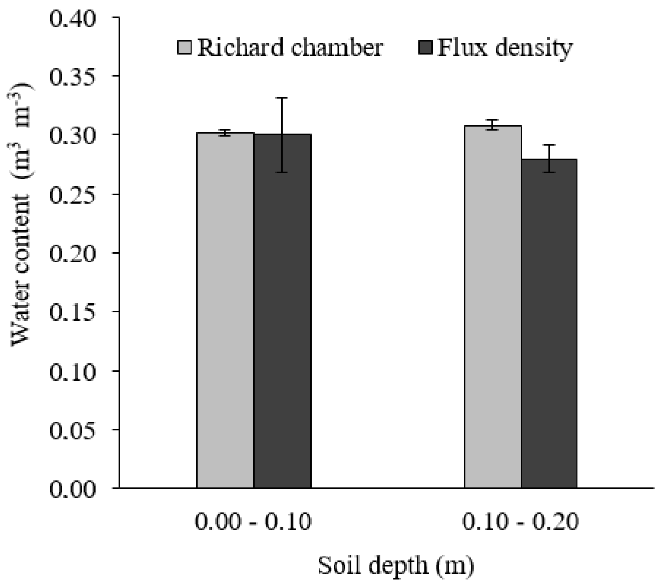
Sandy-textured soils reach field capacity in approximately 3 days because sand drains very quickly; in medium-textured and clayey soils, the moisture value at field capacity can be reached in 6-8 days (Twarakavi et al., 2009). This corroborates the results obtained in the present study for q = 0.1 mm per day, i.e., it takes longer to reach field capacity because clay drains more slowly owing to its low hydraulic conductivity.

In the study by Turek et al. (2020) with Brazilian soils (0-0.60 m depth), water flux density values of 1.0 mm per day were observed after approximately 10 days (240 hours).

According to De Jong Van Lier (2017), the simulations carried out to determine field capacity using flux density depend on the density used and the soil profile depth; greater depths take longer to reach field capacity.

In the analysis in Figure 3 and Table 3, the results for water flux density (q = 0.1 mm per day) and 50 cm^3 undeformed sample stabilized at 10 kPa in the Richards pressure chamber were compared. The moisture values in the initial depth (0.0-0.10 m) were 0.302 and 0.299 $m^3\ m^{-3}$ for the undeformed 50 cm^3 samples and the water flux density methods, respectively. The results for the 0.10-0.20 m depth were similar to those of the initial depth, with values of 0.309 and 0.283 $m^3\ m^{-3}$ for the field capacity determined in the Richards chamber and by the water flux density method, respectively.

According to Silva et al. (2018), the height of the soil sample used to determine the water retention curve should be as low as possible. The researchers compared the water retention curve in two types of soil (Hapludox and Kandiudalfic Eutrudox) using samples of different heights: 25, 50, and 75 mm. After analysis, they found that sample size influenced the water retention curve, especially in the soil with the highest clay content.



Bars represent confidence intervals

Figure 3. Comparison between the field capacity determined by the flux density method and that determined in the Richards pressure chamber at a pressure of 10 kPa

When comparing the water retention capacity based on a matric potential of 10 kPa, using both the retention curve derived from data collected in the field and those obtained in the laboratory with undeformed samples, Brito et al. (2011) observed significant differences between the samples, noting that the value of the retention curve generated from the laboratory data overestimated that derived from the data collected in the field.

Thus, the difference between the field and laboratory methods can be attributed, in part, to the use of the Richards chamber in the analysis of undeformed samples. This is possibly owing to the contact between the soil sample and porous plate and the possible heterogeneity of the samples, which can result in an imbalance in the equilibrium time between them (Silva et al., 2014).

Figure 4 shows the simulated data of the water retention curve with the Arya-Paris model and the data measured in the Richards pressure chamber at pressures of 0, 6, 10, 33, and 50 kPa, at two investigated soil depths. In addition, the adjustment parameters of the van Genuchten (1980) model for the soil retention curve obtained using the Arya-Paris method are listed in Table 4.

A significant difference ($p \leq 0.05$) was observed at the depth of 0.10-0.20 m when comparing the data obtained with the model (between 0 and 50 kPa) with those obtained in the laboratory (Table 5). A mean absolute error of 0.0273 and a bias

Table 3. Statistical analysis between the methods for determining field capacity at a flux density of 0.01 mm per day

Soil depth (m)	Method	θ ($m^3\ m^{-3}$)	MAE	Bias	P_{value}
0-0.10	Richard chamber	0.302 ± 0.002	0.0088	-0.002	0.755^{ns}
	Flux density	0.299 ± 0.032	-	-	-
0.10-0.20	Richard chamber	0.309 ± 0.004	0.0257	-0.02570	0.042*
	Flux density	0.283 ± 0.012	-	-	-

* - Significant by paired t test ($p \leq 0.05$). ns - Not significant by paired t test ($p > 0.05$)

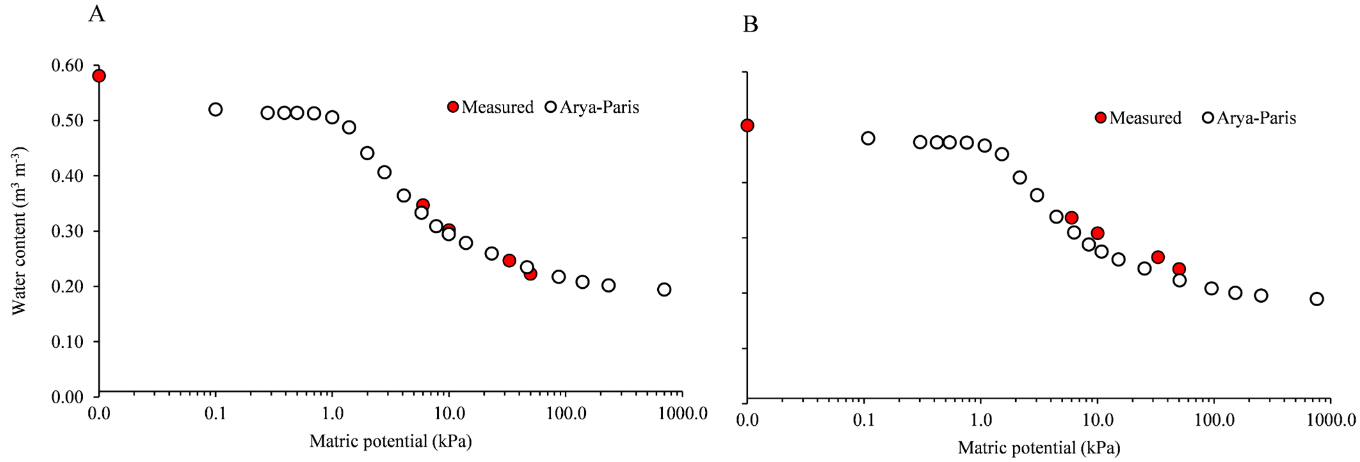


Figure 4. Soil water retention in undeformed samples simulated with the Arya & Paris model in the 0.0-0.10 m depth (A); and 0.10-0.20 m depth (B)

Table 4. Fitting parameters of the van Genuchten model (1980) to the soil water retention curve obtained by the Arya & Paris model (1981) in 50 cm³ samples of different soil depths

Depth (m)	θs	θr	α	n	m	R^2
0-0.10	0.520	0.189	0.4524	1.7377	0.4245	0.996
0.10-0.20	0.480	0.187	0.4182	1.7713	0.4354	0.996

θs - Saturated soil water content (m^3 m^{-3}); θr - Residual soil water content (m^3 m^{-3}); α, n e m - Model parameters

Table 5. Statistical analysis comparing the initial water retention curve (0 to 50 kPa) measured and determined by the Arya-Paris model for different soil depths

Depth (m)	MAE[a]	Bias	P-value[b]
0-0.10	0.0191	-0.0179	0.181162
0.10-0.20	0.0273	-0.0273	0.00130*

[a] Mean absolute error. [b] Significant by paired *t*-test ($p \leq 0.05$)

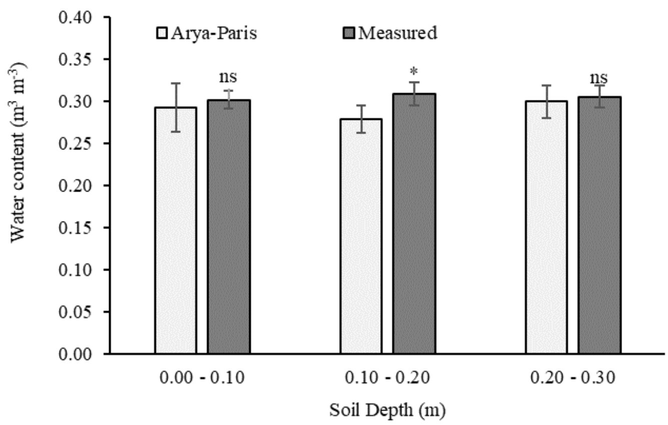
error of -0.0273 was observed at the depth of 0.10-0.20 m. At 0.00-0.10 m, the difference when comparing the initial water retention curve (0 to 50 kPa) measured and that determined by the Arya-Paris model was not significant.

Satisfactory results were obtained in a study on water retention model for Brazilian soils when comparing the Arya-Paris model with laboratory methods in the retention curves, including the pressure of 10 kPa using α = 0.977 (Vaz et al., 2005).

When comparing the Arya-Paris method with the Richards chamber method in Entisols (Quartzipsamments), Nascimento et al. (2010) found divergent results between the two methods. The authors report that this difference may be because of the particle size used to obtain the Arya & Paris (1981) retention curve as in their study, a standardized particle size analyzer was used.

Evaluating the data obtained in the Richards pressure chamber for a pressure of 10 kPa (Figure 5) with the values obtained with the Arya-Paris model, a significant difference was found only for the 0.10-0.20 m depth. The measured and simulated values were 0.31 and 0.28 m^3 m^{-3}, respectively, at this depth.

The water content at 10 kPa for the two soil depths (0-0.10 m and 0.10-0.20 m) measured and determined by the Arya-Paris model were compared (Table 6). At 0.00-0.10 m, the mean absolute error was lower than that at 0.10-0.20 m, 0.0104 and 0.0296, respectively. Regarding bias, lower values for the 0.0-0.10 m depth than at 0.10-0.20 m, -0.0088, and -0.0296, respectively, were obtained.



*, ns - Significant and not significant by paired t test ($p \leq 0.05$); Bars represent confidence intervals

Figure 5. Determination of field capacity (10 kPa) using the Arya & Paris model and the Richards pressure chamber with undeformed samples

Table 6. Statistical analysis comparing the water content at 10 kPa pressure measured and determined by the Arya-Paris model for different soil depths

Depth (m)	MAE[a]	Bias
0-0.10	0.0104	-0.0088
0.10-0.20	0.0296	-0.0296

[a] Mean absolute error

The results showed that the most significant errors occurred in the subsurface layer (0.10-0.20 m), probably because it is a depth prone to compaction. Considering that the errors (bias) were only -0.02570 (Table 3) and -0.0296 (Table 6), the field capacity can be determined at a pressure of 10 kPa by the Richards pressure chamber or calculated using the Arya-Paris model.

Conclusions

1. Field capacity can be determined at a pressure of 10 kPa using the Richards pressure chamber with undeformed samples.

2. The Arya-Paris model is an alternative for determining the water retention and soil moisture curve and calculating field capacity at a pressure of 10 kPa.

Contribution of authors: Conceptualization - T.F.D. Methodology - T.F.D. Collected the data - T.F.D and G.F.L. Software - T.F.D and G.F.L. Analyzing and interpreting the data - T.F.D.; G.F.L and L.A.M.M. Validation - T.F.D. and G.F.L. Writing (original draft preparation) - G.F.L; L.A.M.M.; A.S.C.C.; X.D. and T.F.D. Writing (review and editing) - E.M.B.S; T.J.A.S. and X.D. Supervision - T.F.D. Administering and acquiring funding - T.F.D.

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