Journal of Agricultural Science; Vol. 14, No. 3; 2022
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

In situ Field Capacity in Brazilian Soils and a Derived Irrigation Management Practice Based on Water Suction

T. B. Ottoni Filho[1], A. R. Caetano[1] & M. V. Ottoni[2]

[1] Department of Water Resources and Environment, Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, RJ, Brazil

[2] Geological Survey of Brazil, Companhia de Pesquisa de Recursos Minerais (CPRM), Rio de Janeiro, RJ, Brazil

Correspondence: T. B. Ottoni Filho, Department of Water Resources and Environment, Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, RJ, Brazil. E-mail: teottoni@poli.ufrj.br

Received: December 15, 2021 Accepted: January 16, 2022 Online Published: February 15, 2022

doi:10.5539/jas.v14n3p23 URL: https://doi.org/10.5539/jas.v14n3p23

Abstract

Field capacity (FC) is a fundamental parameter in soil and water engineering and hydrologic modeling. Despite its relevance, the *in situ* determination of this parameter is not standardized and its determination by indirect methods is dubious. This study presents a method of calculation of *in situ* FC and its corresponding water suction (h_{FC}), using the van Genuchten equation for water retention and the pedotransfer function by Ottoni Filho et al. (2016) for standardized *in situ* determination of FC. The methodology was applied to HYBRAS, a database of hydrophysical data for Brazilian soils with 1,075 soil samples from 15 Brazilian states. FC and h_{FC} were confirmed to depend on textural class and pedogenetic origin (weathered and unweathered soils). Our analysis justified why FC must not be determined based only on a single predetermined water suction value. A simplified method is proposed for the management of irrigated soils through the determination of water suction in the root zone and the mode and confidence interval values of h_{FC} corresponding to soil groups formed from textural classes and pedological nature. Various statistical calculations of FC and h_{FC} are presented for these groups.

Keywords: hydrophysical soil data, pedotransfer function, weathered soils, field capacity suction

1. Introduction

According to the Soil Taxonomy (1975), a soil is characterized by an arrangement of pores formed by inorganic and organic matter that serves as a support to plants in the field. It is an environment capable of having the air of its pores renewed with air from the atmosphere or filled with water. In irrigation engineering, soil is interpreted as being a reservoir of water and nutrients for crops. The main objective of its agricultural management is to provide optimum conditions for the development of plants with minimum impact to the environment. In this context, the concept of field capacity (FC) was introduced by Veihmeyer and Hendrickson (1931, 1949) as the soil moisture that corresponds to the maximum capacity of the soil to hold water available for use by plants, also characterized as the water content stabilized in the soil pores after the soil profile has been drained following an irrigation or rain event. This parameter has been largely used in hydrodynamic and hydrologic models involving soils (Kannan, White, Worral, &Whelan, 2007; Nasta & Romano, 2016; De Jong Van Lier, 2017), as well as in projects of irrigation and drainage systems and in water and soil management in general, including studies of groundwater recharge.

More specifically, Veihmeyer and Hendrickson (1931, 1949) defined FC as “the water content retained by the soil after an infiltration event and the drainage of the excess water, with a sharp decrease in the rate of downward water percolation”. In their definition, these authors commented that this usually occurs two or three days after a rain or irrigation event. Similarly, the Glossary of Soil Science Terms (Soil Science Society of America, 2008) defines FC as “the water content retained in a uniform soil profile two or three days after it has been fully wetted and when free drainage in the root zone has become negligible”.

Despite the high applicability of FC, the definitions above are considered to be inaccurate (Hillel, 1998; Reichardt & Timm, 2004; Ottoni Filho, Ottoni, Oliveira, Macedo, & Reichardt, 2014; De Jong Van Lier, 2017), resulting in uncertainties in its determination. For example, the term “negligible” in the definition from the Glossary of Soil Science Terms is absolutely vague, since the movement of water in the soil profile remains even after a few days of drainage due to the fact that hydraulic equilibrium is not usually fully reached (Reichardt, 1988; Hillel, 1998; Romano & Santini, 2002; Reynolds, 2018). The main criticism falls on the lack of clarity and standardization of the explanation of hydraulic processes and field procedures related to the FC definition, which leads to significant differences between reported FC values, depending on the determination method used (Richards, 1960; Reichardt & Timm, 2004; Silva, Silva, Oliveira, Ferreira, & Serafim, 2014; Reynolds, 2018; Ribeiro, Costa, Silva, Franco, & Borges, 2018, Turek, Armido, Wendroth, & Santos, 2018).

As a result, to maximize the standardization of a Veihmeyer and Hendrickson's reference method of determination of FC, Ottoni Filho et al. (2014) redefined the FC concept as being "the vertical distribution of the volumetric water content in the upper part of a soil profile that, in the course of ponded infiltration (of water from any source and with ponding depth smaller than 10 cm), becomes fully wetted at the end of infiltration and remains exposed to the subsequent process of drainage without evapotranspiration or rain for 48 h".

The definition above is considered more adequate because it keeps the original meaning of the FC concept expressed by the Glossary of Soil Science Terms at the same time that it establishes the drainage time and minimizes the inaccuracies and inconsistencies related to the expressions "uniform soil profile", "two or three days", " negligible drainage", "free drainage" that appear in the definition from the Glossary, which also omits the specification of the water application event in the soil profile, as well as the inexistence of rain or evapotranspiration after wetting. A consequence of the definition by Ottoni Filho et al. (2014) is that it leads to a greater standardization of the field test and of the method of determination of a reference FC.

FC has been determined by the *in situ* direct method, that is, through experimental field infiltration and drainage or, generally, by the two following main subtypes of indirect methods: either pedotransfer functions (PTFs) or laboratory tests based mainly on the concept that FC is the soil water content associated with an arbitrary predetermined suction value.

To determine the FC value *in situ*, Embrapa (1979) advises the full wetting of the soil profile, that is, saturating it by inundation by applying a water depth to a 1mx1m soil area without vegetation. After wetting, the area must be covered with a piece of canvas or plastic to prevent further wetting by rain or water loss by evaporation, and until the FC is measured directly along the profile.

Because of the operational difficulties of the *in situ* direct method, the indirect method using PTFs has been applied to estimate *in situ* FC(z) using only easily available and measured soil properties at soil depth z (Fabian, 1995; Fabian & Ottoni Filho, 2000; Thurler, 2000; Macedo, Menegueli, Ottoni Filho, & Souza Lima, 2002; Nemes, Pachepsky, & Timlin, 2011; Ottoni Filho, Ottoni, Oliveira, Macedo, & Reichardt, 2014; Ottoni Filho, Leal, Macedo, & Reis, 2016; Ribeiro, Costa, Silva, Franco, & Borges, 2018), as will be detailed in Section 2.2.

However, the indirect method most used to determine FC is the one that considers it to be the water content at a predetermined suction value, a moisture value frequently determined in the laboratory. Alternatively, this water content at a predetermined suction can also be obtained by PTFs. Usually, water suction values of 60, 100 or 330 cm associated with FC are adopted (Mello, Oliveira, Ferreira, & Lima, 2002; Reichardt & Timm, 2004; Ottoni Filho, Ottoni, Oliveira, Macedo, & Reichardt, 2014; Silva, Silva, Oliveira, Ferreira, & Serafim, 2014; De Jong Van Lier, 2017). In the laboratory, the method of equivalent moisture is also used. By this method, a centrifuge force one thousand times greater than the gravity force is applied for 30 min to previously saturated samples, which produces a water content called moisture equivalent that some researchers consider to be the FC (Cassel & Nielsen, 1986; Hillel, 1998; Ruiz, Ferreira, & Pereira, 2003).

Although the indirect method above, which equates FC to a water content associated with a predetermined suction value, is largely used by the scientific community, Reichardt (1988), Hillel (1998), Netto et al. (1999), Reichardt and Timm (2004), Ottoni Filho et al. (2016) and Reynolds (2018), among others, point out that these results are not representative of the actual FC of the soil profile and can at best be correlated to it. The reason is that the FC concept is derived from a specific water movement process by drainage through the soil profile and not from hydrostatic characteristics of the soil. The suction values of 60, 100 and 330 cm usually adopted in the determination of FC are considered arbitrary in the literature above and incompatible with the very definition of FC given by the Glossary of Soil Science Terms, not having any scientific grounds to be considered FC suction values. For example, Ottoni Filho et al. (2016) demonstrated that none of these three suction values in isolation represented *in situ* FC in their database adequately. Turek et al. (2018) analyzed various approaches of indirect determination of FC based on hydrodynamic and hydrostatic criteria, also adopting the suction values of 60, 100 and 330 cm. Their results showed that the FC values in general varied significantly depending on the determination criterion used.

The objective of the present study was to propose a method of calculation of a standardized *in situ* FC and its related suction value and test it with Brazilian soils. It also presents a proposal of soil management in irrigated agriculture using statistical data of the suction associated with FC for a Brazilian soil database.

2. Material and Methods

2.1 Soil Database

HYBRAS (HYdrophysical database for BRAzilian Soils) (Ottoni, Ottoni Filho, Schaap, Lopes-Assad, & Rotunno Filho, 2018) is a database of hydrophysical data for Brazilian soils containing consistent and reliable hydraulic and physical information from 1,075 weathered and unweathered soil samples from 15 Brazilian states. HYBRAS was selected due to its availability for consultation, scope and representativeness of Brazilian soils. Figure 1 depicts the 445 sampling sites of the 1,075 samples. A more detailed description of HYBRAS and its data availability can be found in Ottoni et al. (2018).

Figure 1. HYBRAS sampling sites in the Brazilian territory

Source: Ottoni et al. (2018).

Figure 2 shows the distribution of the 1,075 samples in the FAO/USDA textural triangle and highlights the predominant soil types. Ferrasol, Acrisol and Nitisol, according to the World Reference Base for Soil Resources (WRB, 2015) nomenclature, are three classes of typical intensely weathered tropical climate soils, here called weathered soils; the percentages of samples in each soil textural class are given in Figure 2b. The other soils from HYBRAS, here called unweathered, correspond to the other WRB classes: Regosol, Gleysol, Cambisol, Histosol, Podzol, Fluvisol, Planosol and Chernozem.

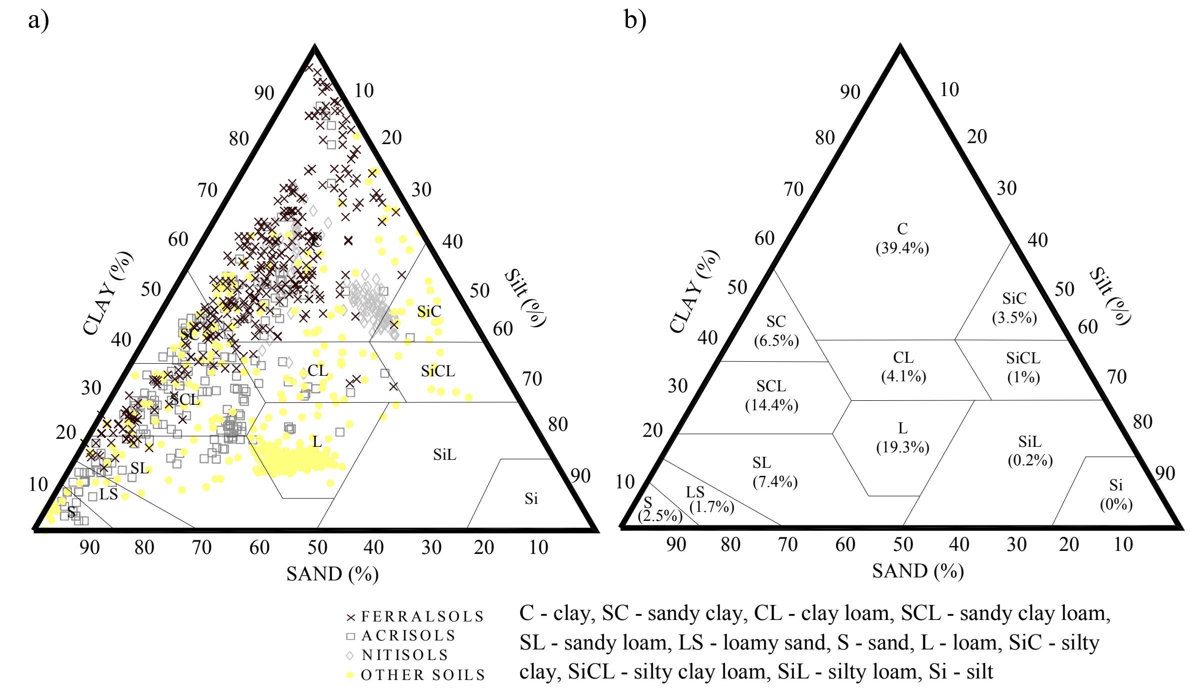

Figure 2. a) 1,075 soil samples from HYBRAS distributed in the FAO/USDA textural triangle with differentiation of Ferrasols, Acrisols and Nitisols and b) Percentage of samples from HYBRAS in each textural class

Source: Ottoni et al. (2018).

To analyze the results, the 1,075 samples were separated into two groups – weathered and unweathered soils, as described above. In addition, the soils were separated again taking into account their textural classes. Three great textural class groups were considered, according to Cassel et al. (1983): fine texture, FT (silty clay loam, clay loam, silty clay, sandy clay and clay classes); mean texture, MT (sandy loam, loam, sandy clay loam, silt loam and silt classes); coarse texture, CT (sand and loamy sand classes). The textural classes in parenthesis are the same as in Figure 2.

Among other data, HYBRAS contains information on the five parameters (θs, θr, α, n, m) of the van Genuchten (VG) equation (Equation 1), which models the volumetric soil water content, θ (m^3/m^3), as a function of suction h (cm):

$$\theta\ (h) = \theta_r + (\theta_s - \theta_r)\cdot[1 + (\alpha h)^n]^{-(m)} \quad (1)$$

Where, θ_s and θ_r are the saturation and the residual water contents, respectively, and α (cm^{-1}), n (dimensionless) and m (dimensionless) are shape parameters of the water retention curve, θ(h).

2.2 Determination of the in situ Field Capacity (FC) and Its Associated Suction (h_{FC})

The *in situ* field capacity (FC) and the associated suction (h_{FC}) are determined using Equation 1 and the PTF by Ottoni Filho et al. (2016), which is better described next. Ottoni Filho et al. (2014, 2016) standardized the process for obtaining *in situ* FC using the FC definition expressed in their study and following the recommendations of Embrapa (1979), as was mentioned in the Introduction. FC data were collected at different depths of 29 soils from the state of Rio de Janeiro (Brazil) (207 samples) based on the direct measurement of FC from the soil profile and always following the same laboratory methodological protocol in all tests, thus reducing experimental inconsistencies. The pedological classification of the 29 profiles, with varied pedogenesis, is given in Ottoni Filho et al. (2016). The profile lengths where FC was monitored varied from 30 cm to 70 cm. Using this database (N = 207), a PTF was developed and the estimation of the *in situ* FC was made using only the soil moisture for the 60 cm-suction value (θ_{60}—called microporosity in the Brazilian nomenclature). The results obtained demonstrated that the PTF from Ottoni Filho et al. (2016) (Equation 2 and Figure 3 in the present work) successfully calculated the *in situ* FC with small errors and without bias; the root mean square error (RMSE) of the FC calculated with Equation 2 for the 207 samples was only 0.026 m^3/m^3. Other studies have used PTFs to determine *in situ* FC based on the soil granulometry, bulk density, organic matter content and/or soil moisture at a given suction (Macedo, Menegueli, Ottoni Filho, & Souza Lima, 2002; Nemes, Pachepsky, & Timlin, 2011; Ottoni Filho, Ottoni, Oliveira, Macedo, & Reichardt, 2014; Ottoni Filho, Leal, Macedo, & Reis, 2016; Ribeiro, Costa, Silva, Franco, & Borges, 2018), however, in general, with smaller efficiency than that given by Equation 2 with the 207 samples (Figure 3).

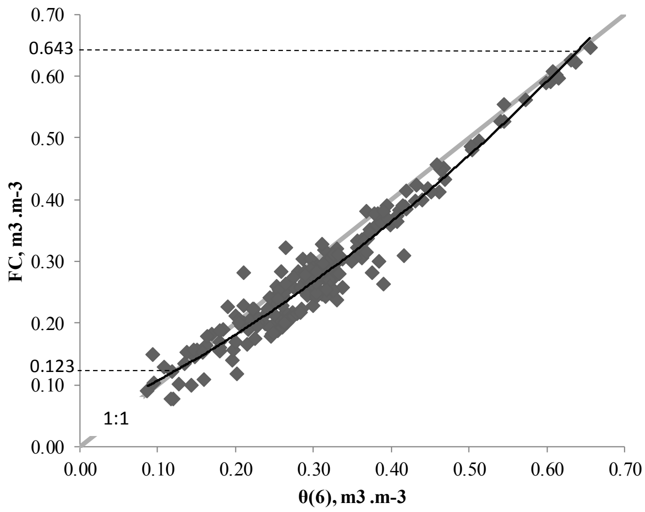

Figure 3. Field capacity measured *in situ vs.* θ_{60} (N = 207) and plot of the corresponding pedotransfer function using a quadratic model—Equation 2

Source: Ottoni Filho et al. (2016).

$$FC = 0.560 \cdot \theta_{60}^2 + 0.576 \cdot \theta_{60} + 0.0436 \tag{2}$$

Where, FC and θ_{60} are given in m³/m³ and θ_{60} is the water content for the 60-cm suction.

We show below how FC and h_{FC} can be calculated using the five parameters of Equation 1 and the three constants of Equation 2. Using Equation 2 requires that θ_{60} be calculated with Equation 1:

$$\theta_{60} = \phi_e f_{60} + \theta_r \tag{3}$$

Where,

$$\phi_e = \theta_s - \theta_r \tag{4}$$

$$f_{60} = [1 + (60\alpha)^n]^{-m} \tag{5}$$

Substituting Equation 3 in Equation 2 gives the expression that calculates FC using Equations 4 and 5, the parameters of Equation 1 and the constants of Equation 2:

$$FC = A\phi_e^2 f_{60}^2 + (2A\theta_r + B)\phi_e f_{60} + A\theta_r^2 + B\theta_r + C \tag{6}$$

Where, A = 0.560, B = 0.576, C = 0.0436 are the constants of Equation 2.

Considering in Equation 1 that θ = FC calculated with Equation 6, h = h_{FC}, one obtains Equation 7 that calculates h_{FC} from Equations 6 and 8:

$$h_{FC} = \frac{(S_{FC}^{(-1/m)} - 1)^{1/n}}{\alpha} \tag{7}$$

$$S_{FC} = \frac{FC - \theta_r}{\theta_s - \theta_r} \tag{8}$$

Where, S_{FC} is the effective saturation at FC.

For greater reliability of the results of Equations 6 (which calculates FC) and 7 (which calculates h_{FC}), two criteria were used to select and reject HYBRAS soil samples. The first criterion was related to the RMSE values (Equation 9) of the optimization of the parameters of the VG equation (Equation 1) for each sample of the HYBRAS database. The objective of this was to eliminate all the samples with an RMSE greater than 0.015 m³/m³. It must be said that for all the HYBRAS samples (always undisturbed samples), N > 4 and the measured water contents encompassed large suction ranges, usually from 30 cm to 15,000 cm (with few data in the 0-30-cm range). The water content at zero suction was always characterized in HYBRAS.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N - p}\sum_{j=1}^{N}\left(\theta_{j\ \mathrm{calculated}} - \theta_{j\ \mathrm{measured}}\right)^2} \quad (9)$$

Where, $\theta_{j\ \mathrm{calculated}}$ and $\theta_{j\ \mathrm{measured}}$ are the calculated and measured water content associated with the N values of suction measured in the sample; the p value represents the number of optimized parameters of the VG equation, which, in the case of HYBRAS, was p = 4 (5-1), since parameter m was not optimized, but obtained from parameter n (m = 1 – 1/n), as is usual.

The second sample rejection criterion used aimed at eliminating all the samples with calculated h_{FC} or with the 60-cm suction (used in Equation 2) out of the range of measured non-zero suctions in the sample, in order to avoid h_{FC} being determined by extrapolation of the optimized water retention curve, θ(h).

The FC values measured *in situ* for 77 samples from HYBRAS (Appendix A) were known [personal communication with Dr.Marta Ottoni, the main author of Ottoni et al. (2018), where HYBRAS was described] and are shown in Figure 4. These 77 values are included in the database (N = 207) of Ottoni Filho et al. (2016) described in the first paragraph of Section 2.2. To evaluate the suitability of the FC calculation proposed here, the non-parametric Wilcoxon test for paired groups (Bradley, 1968; Zar, 1984) was used, as well as the RMSE value calculated from Equation 10:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(FC_{j\ \mathrm{calculated}} - FC_{j\ \mathrm{measured}}\right)^2} \quad (10)$$

Where, $FC_{j\ \mathrm{calculated}}$ and $FC_{j\ \mathrm{measured}}$ are the calculated and measured FC values of the N samples (N = 77).

Considering only samples not eliminated by the two criteria above, the distribution of the calculated values of h_{FC} and FC in the various possible groups of soils in HYBRAS, mentioned in Section 2.1, was described statistically taking into account all the combinations of the four textural groups (all soils, fine texture (FT), mean texture (MT) and coarse texture (CT)), with the three groups of pedological classes (all soils, weathered and unweathered). Traditional statistical measures were used in the description: mean, coefficient of variation (CV), median, mode, minimum, maximum and confidence interval. The Mann-Whitney non-parametric test for unpaired groups (Field, 2005) was used to compare the median values of h_{FC} or FC involving pairs of subgroups of soils above. The normality of the statistical distribution was verified with the Shapiro-Wilk test (Shapiro & Wilk, 1965).

3. Results and Discussion

3.1 Field Capacity and Its Corresponding Suction in HYBRAS

To evaluate the quality of the FC results calculated with Equation 6, we compared the FC measured *in situ* with the calculated FC of the 77 samples from HYBRAS mentioned in the explanation of Equation 10. The results demonstrated that Equation 6 estimated FC well, since RMSE = 0.0255 cm^3/cm^3 (Equation 10) was not high and the Wilcoxon test showed that the measured FC was statistically indistinguishable from the calculated FC ($p < 0.05$), which indicates the inexistence of an estimation bias. The good performance of Equation 6, and, therefore, of Equation 2, in the calculation of *in situ* FC of the 77 samples is shown in Figure 4.

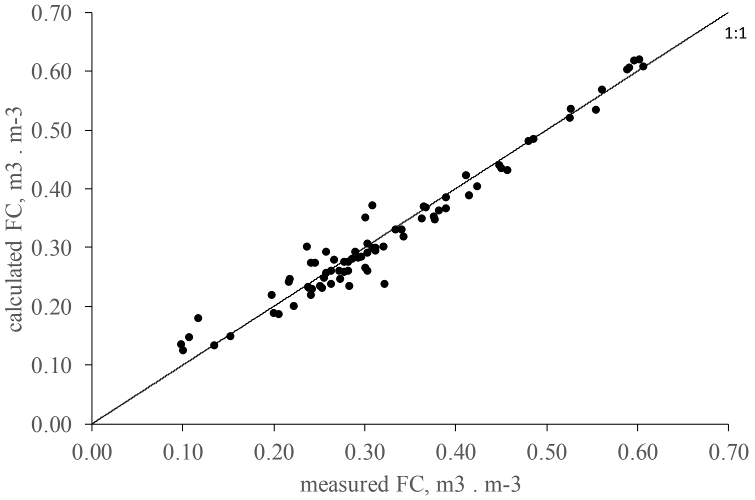

Figure 4. Comparison of the *in situ* field capacity values of 77 samples to those calculated using Equation 6 based on the parameters of the van Genuchten equation (Equation 1) from HYBRAS.

However, the good performance of Equation 2 above does not necessarily imply a full validation of the equation for HYBRAS, since the 77 samples used belong to a group of 207 samples used in the calibration of Equation 2. Yet, we can affirm that the result of the previous paragraph validates the calculation procedure used (Equation 6) for the calculation of FC using the parameters of the VG equation.

Filtering the HYBRAS data using the two sample rejection criteria described in Section 2.2 allowed 842 samples for analysis of the results, approximately two thirds of which were weathered (554 samples) and one third unweathered (288 samples). These fractions roughly correspond to the total fractions of weathered and unweathered soils in the Brazilian territory (Embrapa-Spi, 2006). In the total, 474 samples had fine texture, 349 mean texture and 19 had coarse texture.

Table 1 gives the values of median, mean, coefficient of variation, minimum and maximum of h_{FC} (calculated with Equation 7) and FC (calculated with Equation 6), as well as the number of samples from the various possible soil subgroups according to the combinations of pedological classes (all soils, weathered and unweathered soils) with textural classes (all soils, FT, MT and CT soils). An unweathered FT soil sample that gave a rather atypical result of h_{FC} = 15,100 cm was excluded from the mean and CV calculation of h_{FC} so that these two statistics were not strongly influenced by a rather distinct single result. After the exclusion of this sample, the maximum was 1,180 cm. The sample with this rather unusual value was a clay (horizon B2 from the Chernozem class) which was practically impermeable to air, with θ (h = 0) = 0.43 m^3/m^3, θ (h = 15,100 cm) = 0.41 m^3/m^3 and a calculated FC of 0.41 m^3/m^3.

The CT soil class, with only 19 samples, was not submitted to pedogenetic subdivision because of its inadequate number of data. Anyhow, the CT soil statistics presented in Table 1 must be analyzed with caution due to the small number of samples. All the other subgroups had over 80 samples and their statistics were calculated. At the two last paragraphs of Section 3.1 we will comment further on the CT data from HYBRAS.

Table 1. Statistics for field capacity (FC) and suction at field capacity (hFC) for HYBRAS

		All textural classes			Fine Texture			Mean Texture			Coarse Texture
		All Soils	Weathered Soils	Unweathered Soils	All Soils	Weathered Soils	Unweathered Soils	All Soils	Weathered Soils	Unweathered Soils	All Soils**
hFC (cm)	Mean	189*	188	191*	217*	209	251*	159	143	171	79
	CV (%)	65*	64	66*	64*	62	70*	55	55	53	21
	Minimum	60	62	60	64	71	64	66	66	71	60
	Median	157	157	156	179	173	219	137	118	147	74
	Maximum	15100	1178	15100	15100	1178	15100	761	606	761	121
FC ($m^3.m^{-3}$)	Mean	0.315	0.314	0.317	0.358	0.347	0.411	0.264	0.241	0.281	0.193
	CV (%)	25	23	27	19	16	23	18	20	15	31
	Minimum	0.119	0.125	0.119	0.215	0.215	0.237	0.149	0.149	0.162	0.119
	Median	0.306	0.319	0.295	0.358	0.348	0.388	0.266	0.239	0.283	0.185
	Maximum	0.628	0.479	0.628	0.628	0.479	0.628	0.519	0.433	0.519	0.344
Number of samples		**842**	**554**	**288**	**474**	**392**	**82**	**349**	**150**	**199**	**19**

Note. * One sample with h_{FC} = 15,100 cm (h_{FC} maximum) was eliminated from the calculation.

** Analysis not performed for CT soils in the weathered and unweathered soil classes due to insufficient data.

The h_{FC} results considering all the textural classes (Table 1) gave a median of 157 cm, a mean of 188 cm and a CV of 64% for weathered soils (554 samples), in comparison to a median of 156 cm, a mean of 191 cm and a CV of 66% for unweathered soils (288 samples). The similarity between the statistics of weathered and unweathered soils indicates that the h_{FC} distribution was little influenced by pedological class when texture was not considered. The same was observed for the FC results (Table 1). This fact is illustrated in Figure 5 by the great proximity of the plots of probability distribution of h_{FC} for weathered and unweathered soils.

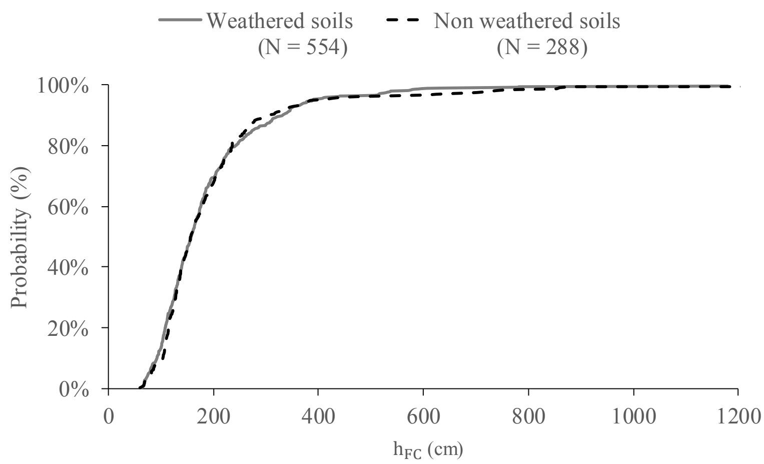

Figure 5. Comparison of the curves of probability distribution of suction at field capacity (h_{FC}) of weathered and unweathered soils from HYBRAS

On the other hand, considering all the 842 soil samples, the FC median varied with the textural classes, being greater in the FT group (0.358 m³/m³) and smaller in the groups MT (0.266 m³/m³) and CT (0.185 m³/m³), as shown in Figure 6a, which presents the clear influence of textural class on FC values, as expected. This textural influence is confirmed by the comparison of the medians with the Mann-Whitney test involving the three groups, corroborating ($p < 0.001$) a decreasing tendency of FC values from the FT group to the CT group. We can also see that the FC means practically coincided with the medians above in the three textural groups (Table 1 and Figure 6a).

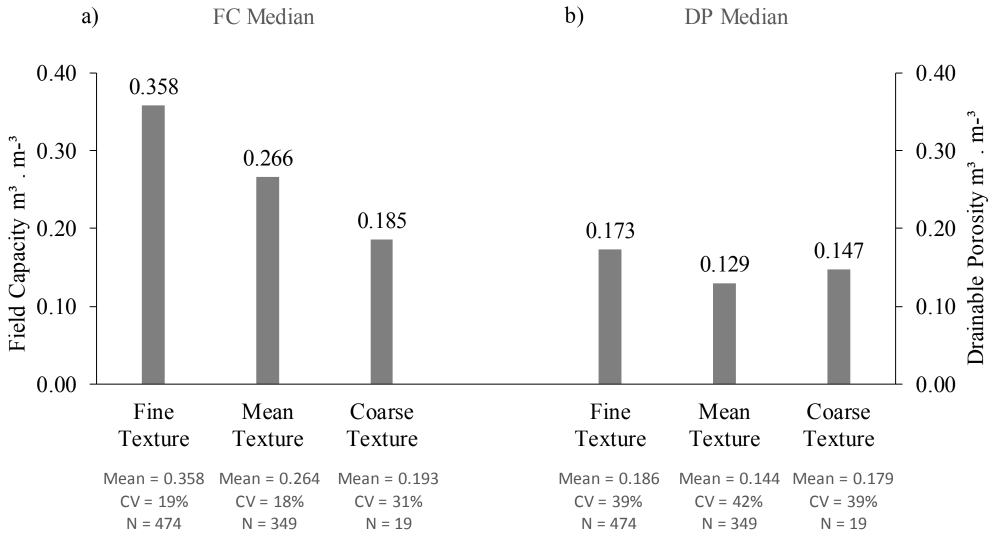

Figure 6. a) Field capacity (FC) medians and b) drainable porosity (DP) medians, both for HYBRAS, as a function of textural classes. Below the bars are the values of the means, coefficients of variation (CV) and the numbers of samples (N)

A relevant hydraulic parameter associated with FC is drainable porosity (DP) (also called field air capacity or specific yield), defined as the volumetric part of the total porosity of a fully saturated soil that percolates by drainage until the soil moisture reaches FC. That is, DP = total porosity − FC. The total porosity was considered here to be the water content at zero pressure in HYBRAS. Figure 6b depicts the DP median results for the three textural classes (along with the mean and coefficient of variation values). The results confirm that DP (0.147 m^3/m^3) was greater for CT soils than for MT soils (0.129 m^3/m^3), which is expected and confirmed by the Mann-Whitney test ($p = 0.016$). However, the DP median of FT soils (0.173 m^3/m^3) was greater than that of CT soils, which is unexpected, since in general sandy soils are thought to drain a greater volume of water than clayey soils (Davis & DeWiest, 1966; Hillel, 1998). This unexpected result was also confirmed by the Mann-Whitney test, as it did not show any statistical difference ($p = 0.528$) between the DP medians of subgroups CT and FT. It also confirmed ($p < 0.001$) that the DP values of the FT group tend to be greater than those of the MT group (0.173 m^3/m^3 *vs.* 0.129 m^3/m^3).

To clarify the two unexpected results above, we hypothesized that the nature of the clay fraction in weathered Brazilian soils influences DP, since drainability greatly depends on the saturated hydraulic conductivity and water retention of the soil, which are acknowledged to differ between weathered tropical soils and temperate climate soils, as demonstrated by Tomasella et al. (2000) and Ottoni et al. (2018, 2019). According to these authors, the distinct nature of weathered clays from tropical climate in relation to temperate climate clays results in a peculiar granular aggregation of clayey weathered soils, forming a pore structure somewhat similar to that of coarse textured soils. This characterizes the so-called hybrid behavior of weathered tropical clayey soils, which gives them aeration, permeability and water availability characteristics similar to those of sandy soils. This would justify the fact that FT soils in HYBRAS tend to have DP values similar or even higher than the DP values of CT and MT soils, as confirmed in the previous paragraph. To test the hypothesis made in this paragraph, Table 2 gives the DP statistics for a subdivision of the FT subgroup of weathered soils considering only the clay textural class (311 samples). In Table 2, DP5 and DP95 represent the drainable porosity which is exceeded at 95% and 5% of probability, respectively. That is, according to Table 2 there is just a small chance of 5% of DP values being smaller than 0.10 m^3/m^3 in weathered clays from HYBRAS, which would be a surprising result in a database of clays from temperate climate. Table 2 also shows that both the median and the mean of DP of these clays are around 0.20 m^3/m^3, a value typical of sandy materials reported in the literature on temperate climate soils (Davis & DeWiest, 1966; Hillel, 1998). All this indicates that the nature (weathered or unweathered) of Brazilian clays influences soil drainability, that is to say, FC values.

Table 2. Drainable porosity (DP) statistics for the clay textural class in weathered soils from HYBRAS (N = 311)

Mean (m^3/m^3)	CV (%)	Minimum (m^3/m^3)	Median (m^3/m^3)	Maximum (m^3/m^3)	DP5* (m^3/m^3)	DP95* (m^3/m^3)
0.20	36	0.07	0.18	0.45	0.10	0.32

Note. * DP5 and DP95 represent the drainable porosity exceeded at 95% and 5% of probability, respectively.

Evaluating the statistics in Table 1 and consistently with that pointed out in the previous paragraph, we observe that the median of h_{FC} for FT samples of unweathered soils (219 cm) is greater than the median of weathered soils (173 cm), which also applied to the means (251 cm and 209 cm, respectively). The same was observed for FC in the FT group, which had a greater median (0.388 m^3/m^3) and mean (0.411 m^3/m^3) in unweathered soils than in weathered soils (0.348 m^3/m^3 and 0.347 m^3/m^3, respectively). The h_{FC} and FC medians and means of MT soils were also greater in unweathered soils than in weathered soils (Table 1), which demonstrates the influence of pedogenetic origin on the h_{FC} and FC values in soils of similar texture. The Mann-Whitney test of comparison of medians also confirmed that the h_{FC} and FC values tended to be greater ($p < 0.011$) in unweathered soils in relation to the corresponding weathered soil subgroups in the comparisons above.

As to FC, while the mean and median values were close in HYBRAS (Table 1), this did not happen for h_{FC}, which had means about 20% greater than the medians, except in the CT soil group. This implies an asymmetrical statistical distribution of h_{FC} values, with the distribution tail tending to high values, as shown in Figure 7. However, the proximity of the mean and median values of FC did not imply a normal statistical distribution of FC in HYBRAS, according to the Shapiro-Wilk test (N = 842, $p < 0.001$).

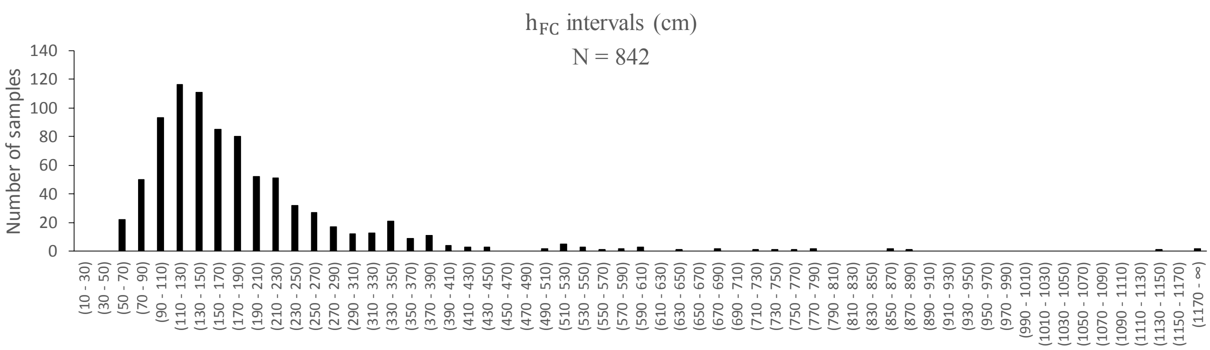

Figure 7. Distribution of the frequencies of the suction values at field capacity (h_{FC})
(in the 20-cm range) for HYBRAS

The h_{FC} values were rather variable in all soil subgroups of HYBRAS, with coefficients of variation around 60% (Table 1), except in the CT class (CV = 21%). This makes h_{FC} a highly variable property (Warrick, 1998) and points to great errors of estimation of FC when the indirect method of estimation with a single arbitrary and predetermined value of h_{FC} is used. The FC values in general had a smaller variation in HYBRAS than h_{FC}, with a CV around 25% in all the subgroups (Table 1). The minimum FC value in HYBRAS was 0.119 m^3/m^3 (a sand from the Podzol class, with a high DP value of 0.315 m^3/m^3), and a maximum of 0.628 m^3/m^3 (a clay from the Gleysol class, with a low DP value of 0.064 m^3/m^3). The minimum value of h_{FC} was 60 cm (for the same sand above) and the maximum was 15,100 cm, as previously mentioned. Further information on h_{FC} in HYBRAS is given in Section 3.2.

We previously mentioned that the statistical measures calculated for FC and h_{FC} in CT soils (Table 1) must be taken with caution due to the small number of samples (N = 19) in this group. In order to evaluate the quality of these statistical data in HYBRAS, all the methodology described here for the determination of FC and h_{FC} was repeated in CT soils from HYPRES (Hydraulic Properties of European Soils) database (Wösten, Lilly, Nemes, & Le Bas, 1999; personal communication with Dr. Allan Lilly, one of the authors of the paper above, who kindly granted us access to HYPRES data). As its name suggests, HYPRES is a database with only European soils. Its CT soils, such as those in HYBRAS, also have N > 4, where N is the number of experimental data pairs in the water retention curve. Because the clay content of CT soils is rather low (lower than 15%), these soils are expected to present a pore structure simpler and less dependent on pedological conditions than those of other textural classes. Thus, we hypothesized that the pedogenetic conditions of CT soils from HYPRES do not exert a significant influence on the efficacy of determination of FC using the methodology adopted in this study, based on an equation (Equation 2) developed for Brazilian soils. This would justify using Equations 6 and 7 to determine FC and h_{FC} in all CT soils from HYPRES, and would enable the comparison of statistics of CT soils from HYBRAS and HYPRES.

When the same sample selection criteria described in Section 2.2 were applied to HYPRES CT soils with the VG equation parameters of HYPRES, it was possible to calculate the FC and h_{FC} values of 52 samples, a much larger number than the 19 CT HYBRAS soil samples. Table 3 compares the FC and h_{FC} statistics of CT soils from HYBRAS and HYPRES. We can see that the median, mean and CV values of the two databases are very close. The Mann-Whitney test confirmed that the FC and h_{FC} medians of CT soils from HYBRAS and HYPRES are statistically equal ($p > 0.682$). This lends further support to the statistical values of CT soils presented in Table 1.

Table 3. Statistics of field capacity (FC) and suction at field capacity (h_{FC}) calculated for coarse textured soils from HYBRAS and HYPRES

	h_{FC} (cm)					FC ($m^3 m^{-3}$)					No. of samples
	Mean	CV (%)	Minimum	Median	Maximum	Mean	CV (%)	Minimum	Median	Maximum	
HYPRES											
All soils coarse texture	81	24	51	75	144	0.201	38	0.111	0.180	0.464	52
HYPRAS											
All soils coarse texture	79	21	60	74	121	0.190	31	0.119	0.185	0.344	19

3.2 Proposal for the Management of Irrigated Soils

For the use of FC and h_{FC} in mathematical modeling or soil management, it is recommended that the FC value be measured preferably through *in situ* testing employing a standard experimental procedure, such as that suggested by Ottoni Filho et al. (2014, 2016), so that more appropriate and consistent values of FC and h_{FC} can be obtained. If a direct determination of FC and h_{FC} is not viable due the complexity of *in situ* testing, a second option is presented here. Undisturbed soil samples from the soil horizons of interest can be taken to the laboratory for analysis and their water contents can be determined at different suction values, but preferably in the 50-1,000-cm range, the predominant range where h_{FC} was determined in this study. Next, the parameters of an appropriate ~~E~~ equation of representation of the water retention curve (such as Equation 1) of each sample must be provided. After that, the methodology of this study can be applied to determine the values of FC and h_{FC} in the horizons wanted. Due to the great variability of h_{FC}, as demonstrated in Section 3.1, we strengthen the inconvenience of adopting the usual method with a single arbitrary value of h_{FC} in the estimation of FC, a method also largely criticized in the literature, as already mentioned.

If both options of the previous paragraph are unviable, a simplified method of irrigated soil management is proposed using only the *in situ* determination of water suction (using a tensiometer, for example) at a depth of relevant water extraction in the root zone, and some h_{FC} statistics from HYBRAS. Our intention is to propose a simplified soil management tool that is easy to use, since specific plant and climate conditions are not taken into account, but rather, as we shall see, only textural and pedological characteristics of the soil.

The method is based on the 90%-probability confidence interval of h_{FC} and on the most probable h_{FC} value (mode), for eight subgroups of soils from HYBRAS already analyzed, organized according to their textural and pedogenetic characteristics (Figure 8). According to a previous analysis (former paragraph where Figure 5 was mentioned), in Figure 8 it is not necessary to differentiate soils in the weathered and unweathered subgroups when textural class information is unknown. Pedogenesis subdivisions are not presented for coarse soil texture either, due to a lack of data.

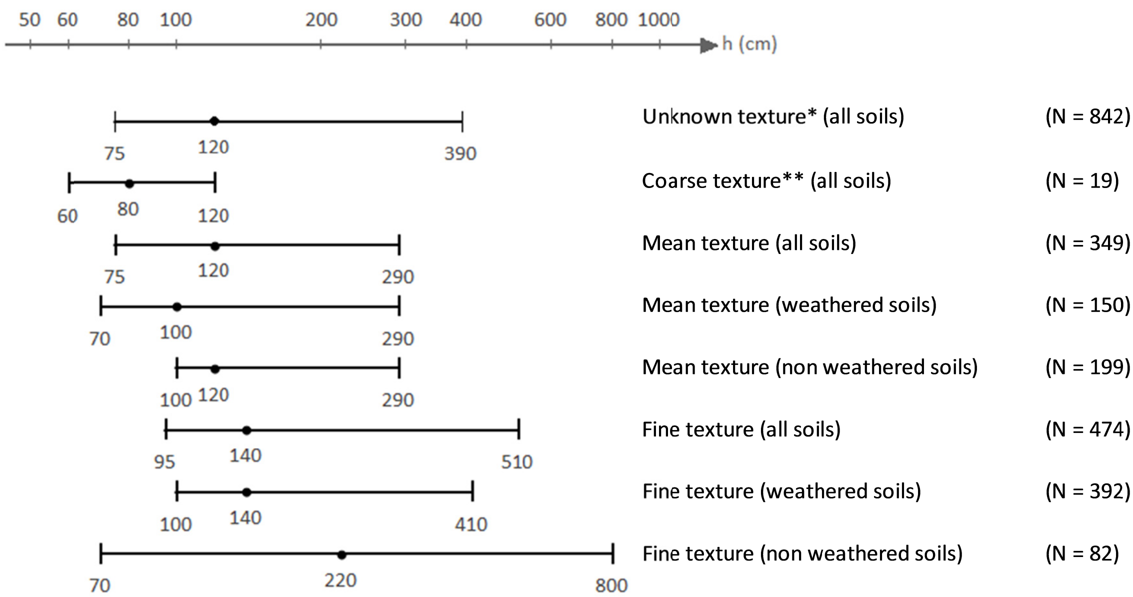

Figure 8. Confidence interval at 90%-probability (bars) and most probable value (dots) of suction at field capacity (h_{FC}) for different textural classes in HYBRAS and considering the pedological nature of the soils

Note. * Pedogenesis is irrelevant when the soil texture is unknown; ** Insufficient data for the characterization of the influence of the pedological nature.

Firstly, when the textural class is unknown (which is possibly rare) and regardless of the pedological class, we propose soil management considering the suction range of 75-390 cm, which corresponds to the confidence interval of h_{FC} (Figure 8), the 120-cm suction being the most probable for FC in this case. Following this criterion, if the suction determined in the field is higher than the limit h_{FC} = 390 cm, irrigation is advisable, since there is at least 95% chance that the soil water content in the field is smaller than FC. As a result, with certainty greater than 95%, the user would not apply water unnecessarily when irrigating, which means that this soil irrigation management technique is water efficient. On the other hand, if the suction determined in the field is smaller than 75 cm for more than two or three consecutive days after irrigation, apparently the drainage in this soil profile is insufficient, since the suction value determined is smaller than the lower limit of the confidence interval of h_{FC} and, consequently, the water content in the field most probably (with 95% probability) is greater than FC for a long time after irrigation, which must raise an alarm of drainage problem. As an irrigation criterion, it is also proposed irrigating to raise the suction determined in the field at the start of wetting to a value close to the h_{FC} mode, which, in the present case (when the textural class is unknown), is 120 cm. Obviously, the latter is just a guideline for the direct application of irrigation water because the mode is the most probable value and not the suction value at FC per se in the studied soil, which is the desirable value of h_{FC} under irrigation.

On the other hand, Figure 8 shows that when the textural class is known, it can alter the confidence interval of h_{FC} significantly, the most probable value of h_{FC} when the user does not know the pedological nature of the soil being 140 cm for the FT group, 120 cm for MT, and 80 cm for CT. As previously mentioned, these must be the respective guideline suctions to be attained in the field through irrigation when the soil belongs to any of the groups above. These mode values obtained with an equation (Equation 2) based on values from *in situ* FC tests, challenge the arbitrary values usually adopted in the determination of FC in irrigation engineering (60 cm, 100 cm or 330 cm) without taking the soil texture or pedological nature into account. These three mode values of h_{FC} also confirm the expectation that soils with a finer texture reach FC at higher suction values than those of soils with a coarser texture. The medians and means of h_{FC} also decreased in subgroups FT, MT and CT, in this order (Table 1, all soils), as expected.

The influence of the pedological origin (weathered and unweathered soils) can be observed in Figure 8; however, it is not very significant when the user knows that the soil under study belongs to the MT class. In this case, the results demonstrate that the most probable h_{FC} values varied from 100 cm in weathered soils to 120 cm in unweathered soils. Using the management method proposed based on the determination of water suction in the field to verify if it is within the confidence interval of h_{FC}, irrigation of MT soils is recommended when the suction value is greater than 290 cm (Figure 8), regardless of the pedological class. A field suction lower than 70 cm for two or more days after irrigation (weathered soils), 100 cm (unweathered soils) or 75 cm (pedological nature unknown) indicates that drainage is insufficient. As proposed, suctions of 100 cm (weathered soils) or 120 cm (unweathered soils) must be the guideline values to be attained in the field resulting from the irrigation of MT soils.

The influence of the pedological nature shown in Figure 8 can be better observed in FT soils, which have greater clay contents, and, in turn, most influence the soil structure. Considering this, the recommended range of irrigation management, corresponding to the confidence interval of h_{FC}, varied from 95 cm to 510 cm when the pedological nature is unknown, and from 100 cm to 410 cm in weathered soils or 70 cm to 800 cm in unweathered soils. In the latter case, if tensiometers are used, it is recommended to irrigate unweathered FT soils only when the instrument reading is nearly at its practical highest limit of use, which is around 800 cm. Likewise, the mode of h_{FC} in this textural class changed from 140 cm in weathered soils to 220 cm in unweathered soils; these must be the guideline suction values for wetting the soil in the field in both cases. These results justify the differentiation in subgroups according to the pedological nature.

The analysis above reveals that the pedological class has a greater influence on the h_{FC} mode and confidence interval in the textural group with a greater clay content (FT soils) than in the group with a smaller clay content (MT soils), which is expected. Therefore, it is reasonable to hypothesize that the influence of pedological class on CT soils, which have very low clay contents, is secondary with respect to the irrigation management method proposed, especially considering that the confidence interval of h_{FC} has a reduced amplitude (from 60 cm to 120 cm) in CT soils when the pedogenetic origin is unknown.

4. Conclusions

When field capacity (FC) is not determined *in situ* it has been calculated using various methodologies usually inconsistent with each other, which is unfortunate. The most popular method is that which estimates FC from a predetermined arbitrary value of suction without any theoretical or experimental basis. In the present work we have calculated an standardized *in situ* FC and its corresponding suction (h_{FC}) for 842 soils from HYBRAS, a broad database of hydrophysical data of Brazilian soils, using the van Genuchten water retention equation (Equation 1) and the PTF of Equation 2. This PTF was calibrated for 207 samples of Brazilian soils with varied pedogenesis in order to estimate *in situ* FC values measured by a standard field test of water application and drainage. The methodology proposed in our work calculated *in situ* FC successfully for 77 samples from HYBRAS with small errors and without bias. As the PTF of Equation 2 was developed for Brazilian soils, for caution, it is recommended to apply this methodology to determine FC and h_{FC} only in these soils. However, as the PTF above is based only on $\theta_{60} = \theta$ (h = 60 cm), a variable dependent mainly on the soil pore structure, we can argue that this methodology also applies to other pedological environments, which must be evaluated experimentally.

The statistical analysis of the distribution of FC and h_{FC} values in various soil groups of HYBRAS taking three textural classes (fine, mean and coarse texture) and two pedological groups (weathered and unweathered soils) into account leads to the conclusion that both soil granulometry and pedological nature influenced the FC and h_{FC} values. The FC and h_{FC} means ranged from 0.19 m^3/m^3 and 79 cm for the coarse texture group to 0.41 m^3/m^3 and 251 cm for the unweathered fine texture group. The h_{FC} varied greatly within groups, with coefficients of variation around 60% in general, which confirms the lack of consistency of the method used to determine FC from an arbitrary predetermined h_{FC} value. The most probable value (mode) of h_{FC} also varied among groups, from 80 cm (coarse texture) to 220 cm (unweathered fine texture).

When the methodology proposed for the determination of FC and h_{FC} cannot be applied, we suggest a simplified method of management of irrigated soils through the determination of suction in the field (using tensiometers, for example) and the knowledge of the group of the soil in hand. This simplified management is based on the confidence interval of h_{FC} (at 90% probability) and on the mode value of h_{FC}, corresponding to the specific soil group (Figure 8). The high limit of these confidence intervals ranged from 120 cm in the coarse texture group to 800 cm in the unweathered soils of fine texture. The low limit ranged from 60 cm (coarse textured soils) to 100 cm (weathered fine textured soils or unweathered mean textured soils). When the suction determined in the field is out of the range of the confidence interval, it is indicative that irrigation is needed or the soil profile drainage is deficient. As proposed, the mode value serve as a guideline suction to be attained for the adequate wetting of the soil profile through irrigation.

References

Bradley, J. V. (1968). *Distribution-Free Statistical Tests*. Englewood Cliffs., New Jersey: Prentice-Hall, Inc.

Cassel, D. K., & Nielsen, D. R. (1986). Field capacity and available water capacity. In A. Klute (Ed.), *Methods of Soil Analysis. Part 1, Physical and Mineralogical Methods* (2nd ed., pp. 901-926). Madison: American Society of Agronomy and Soil Science Society of Agronomy. https://doi.org/10.2136/sssabookser5.1.2ed.c36

Cassel, D. K., Ratliff, L. F., & Ritchie, J. T. (1983). Models for estimating in-situ potential extractable water using soil physical and chemical properties. *Soil Sci. Soc. Am. J., 47*, 764-769. https://doi.org/10.2136/sssaj1983.03615995004700040031x

Davis, S. N., & DeWiest, R. J. M. (1966). *Hydrogeology*. Nova Jersey: John Wiley & Sons.

De Jong van Lier, Q. (2017). Field capacity, a valid upper limit of crop available water? *Agricultural Water Management, 193*, 214-220. https://doi.org/10.1016/j.agwat.2017.08.017

Embrapa. (1979). *Manual de Métodos de Análise de Solo*. Rio de Janeiro: Empresa Brasileira de Pesquisa Agropecuária, Centro Nacional de Levantamento e Conservação de Solos.

Embrapa-Spi. (2006). *Sistema Brasileiro de Classificação de Solos* (2nd ed.). Rio de Janeiro: Empresa Brasileira de Pesquisa Agropecuária, Centro Nacional de Pesquisa de Solos.

Fabian, A. J. (1995). *Determinação de infiltração e de capacidade de campo usando uma câmara de infiltração* (M.Sc. Dissertation, UFRRJ, Itaguaí).

Fabian, A. J., & Ottoni Filho, T. B. (2000). Determinação de capacidade de campo "*in situ*" ou através de equações de regressão. *Pesq. Agropec. Bras., 35*, 1029-1036. https://doi.org/10.1590/S0100-204X2000000500022

Field, A. (2005). *Discovering Statistics with SPSS* (2nd ed.).

Hillel, D. (1998). *Environmental Soil Physics*. Academic Press.

Kannan, N., White, S. M., Worral, F., & Whelan, M. J. (2007). Hydrological modelling of a small catchment using SWAT-2000. Ensuring correct flow partitioning for contaminant modelling. *J. of Hydrology, 334*, 64-72. https://doi.org/10.1016/j.jhydrol.2006.09.030

Macedo, J. R. de, Meneguelli, N. A., Ottoni Filho, T. B., Souza Lima, J. A. de. (2002). Estimation of field capacity and moisture retention based on regression analysis envolving chemical and physical properties in Alfisols and Utilisols of the State of Rio de Janeiro. *Soil Sci. Plant Anal., 33*(13-14), 2037-2055. https://doi.org/10.1081/CSS-120005747

Mello, C. R. de, Oliveira, G. C. de, Ferreira, D. F., & Lima, J. M. de. (2002). Predição da porosidade drenável e disponibilidade de água para Cambissolos da microrregião Campos das Vertentes, MG. *Pesq. Agropeq. Bras., 37*(9), 1319-1324. https://doi.org/10.1590/S0100-204X2002000900016

Nasta, P., & Romano, N. (2016). Use of a flux-based field capacity criterion to identify effective hydraulic parameters of layered soil profiles subjected to synthetic drainage experiments. *Water Resour. Res., 52*. https://doi.org/10.1002/2015WR016979

Nemes, A., Pachepsky, Y. A., & Timlin, D. J. (2011). Towards improving global estimates of field soil water capacity. *Soil Sci. Soc. Am. J., 75*, 807-812. https://doi.org/10.2136/sssaj2010.0251

Netto, A. O. A., Nacif, P. G. S., & Rezende, J. O. (1999). Avaliação do conceito de capacidade de campo para um Latossolo Amarelo coeso do Estado da Bahia. *R. Bras. Ci. Solo, 23*, 661-66. https://doi.org/10.1590/S0100-06831999000300020

Ottoni Filho, T. B., Leal, I. F., Macedo, J. R. de, & Reis, B. C. B. (2016). An algebric pedotransfer function to calculate standardized *in situ* determined field capacity. *Journal of Agricultural Science, 8*(8), 158-170. https://doi.org/10.5539/jas.v8n8p158

Ottoni Filho, T. B., Ottoni, M. V., Oliveira, M. B., Macedo, J. R., & Reichardt, K. (2014). Revisiting field capacity (FC): Variation of definition of FC and its estimation from pedotransfer functions. *R. Bras. Ci. Solo, 38*, 1750-1764. https://doi.org/10.1590/S0100-06832014000600010

Ottoni, M. V., Ottoni Filho, T. B., Lopes-Assad, M. L. R. C., & Rotunno Filho, O. C. (2019). Pedotransfer functions for saturated hydraulic conductivity using a database with temperate and tropical climate soils. *J. of Hydrology, 575*, 1345-1358. https://doi.org/10.1016/j.jhydrol.2019.05.050

Ottoni, M. V., Ottoni Filho, T. B., Schaap, M. G., Lopes-Assad, M. L. R. C., & Rotunno Filho, O. C. (2018). Hydrophysical database for Brazilian soils (HYBRAS) and pedotransfer functions for water retention.

Vadose Zone J., 17, 170095. https://doi.org/10.2136/vzj2017.05.0095

Reichardt, K. (1988). Capacidade de campo. *R. Bras. Ci. Solo, 12*, 211-216.

Reichardt, K., & Timm, L. C. (2004). *Solo, Planta e Atmosfera: Conceitos, Processos e Aplicações*. Barueri, São Paulo: Manole.

Reynolds, W. D. (2018). An analytic description of field capacity and its application in crop production. *Geoderma, 326*, 56-67. https://doi.org/10.1016/j.geoderma.2018.04.007

Ribeiro, B. T., Costa, A. M., Silva, B. M. da, Franco, F. O., & Borges, C. S. (2018). Assessing pedotransfer functions to estimate the soil water retention. *Bioscience Journal, 34*(6). https://doi.org/10.14393/BJ-v34n6a2018-42371

Richards, L. A. (1960). Advances in soil physics (Vol. 1, pp.67-69). In: 7th International Congress of Soil Science. Madison: International Society of Soil Science.

Romano, N., & Santini, A. (2002). Field water capacity. In J. H. Dane & C. G. Topp (Eds.), *Methods of Soil Analysis, Part 4: Physical Methods* (pp.721-738). Madison: Soil Sci. Soc Am.

Ruiz, H. A., Ferreira, G. B., & Pereira, J. B. M. (2003). Estimativa da capacidade de campo de Latossolos e Neossolos Quartzarênicos pela determinação do equivalente de umidade. *R. Bras. Ci. Solo, 27*, 389-393. https://doi.org/10.1590/S0100-06832003000200019

Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika, 52*, 591-611. https://doi.org/10.1093/biomet/52.3-4.591

Silva, B. M., Silva, E. A. da, Oliveira, G. C. de, Ferreira, M. M., & Serafim, M. E. (2014). Plant-available soil water capacity: Estimation methods and implications. *R. Bras. Ci. Solo, 38*, 464-475. https://doi.org/10.1590/S0100-06832014000200011

Soil Science Society of America. (2008). *Glossary of Soil Science Terms*. Madison: Soil Science Society of America.

Soil Taxonomy. (1975). *A Basic System of Soil Classification for Making and Interpreting Soil Surveys* (Agriculture Handbook, No. 436, p. 754). Washington, D.C.: U.S. Department of Agriculture.

Thurler, A. M. (2000). *Determinação de capacidade de campo e retenção de umidade em solos do terciário da formação de barreiras, em função de suas características granulométricas e fatores estruturais* (D.Sc. Thesis, UFRRJ, Seropédica).

Tomasella, J., Hodnett, M. G., & Rossato, L. (2000). Pedotransfer functions for the estimation of soil water retention in Brazilian soils. *Soil Sci. Soc. Am. J., 64*, 327-338. https://doi.org/10.2136/ sssaj2000.641327x

Turek, M. E., Armindo, R. A., Wendroth, O., & Santos, I. dos. (2018). Criteria for the estimation of field capacity and their implications for the bucket type model. *European Journal of Soil Science, 70*(2), 278-290. https://doi.org/10.1111/ejss.12747

Veihmeyer, F. J., & Hendrickson, A. H. (1031). The moisture equivalent as a measure of the field capacity of soils. *Soil Sci., 32*, 181-193. https://doi.org/10.1097/00010694-193109000-00003

Veihmeyer, F. J., & Hendrickson, A. H. (1949). Methods of measuring field capacity and permanent wilting percentage of soils. *Soil Sci., 68*, 75-95. https://doi.org/10.1097/00010694-194907000-00007

Warrick, A. W. (1998). Spatial variability. *Environmental Soil Physics* (pp. 655-675). Hillel. https://doi.org/10.1016/B978-012348525-0/50026-4

Wösten, J. H. M., Lilly, A., Nemes, A., & Le Bas, C. (1999). Development and use of a database of hydraulic properties of European soils. *Geoderma, 90*, 169-185. https://doi.org/10.1016/S0016-7061(98)00132-3

WRB (World Reference Base for Soil Resources). (2015). *International soil classification system for naming soils and creating legends for soil maps* (p. 106). World Soil Resources Reports, FAO, Rome.

Zar, H. Z. (1984). *Biostatistical Analysis* (2nd ed.). New Jersey: Prentice-Hall Inc.

Appendix A

Measured FC for 77 samples from HYBRAS

Code HYBRAS	Measured FC (cm^3/cm^3)
139	0.267
140	0.264
141	0.301
143	0.283
144	0.258
145	0.287
147	0.304
148	0.272
152	0.117
156	0.108
160	0.099
165	0.293
166	0.241
167	0.322
171	0.29
172	0.198
173	0.246
174	0.218
175	0.217
176	0.243
178	0.237
179	0.284
181	0.301
182	0.309
200	0.451
202	0.526
203	0.591
204	0.412
206	0.274
207	0.39
208	0.304
209	0.256
210	0.321
211	0.377
212	0.258
213	0.304
214	0.312
215	0.343
216	0.283
217	0.297
218	0.312
219	0.341
220	0.39
221	0.449
222	0.238
223	0.254
224	0.368
225	0.239

226	0.2
227	0.264
228	0.555
229	0.457
230	0.424
231	0.415
232	0.378
233	0.382
234	0.481
235	0.486
236	0.561
237	0.527
238	0.602
242	0.589
243	0.607
245	0.597
246	0.365
247	0.363
248	0.334
249	0.309
250	0.278
251	0.278
252	0.251
253	0.241
254	0.223
255	0.206
256	0.153
257	0.135
258	0.101