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An Algebraic Pedotransfer Function to Calculate Standardized *in situ* Determined Field Capacity

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Abstract

Despite the large applicability of the field capacity (FC) concept in hydrology and engineering, it presents various ambiguities and inconsistencies due to a lack of methodological procedure standardization. Experimental field and laboratory protocols taken from the literature were used in this study to determine the value of FC for different depths in 29 soil profiles, totaling 209 soil samples. The volumetric water content (θ) values were also determined at three suction values (6 kPa, 10 kPa, 33 kPa), along with bulk density (BD), texture (T) and organic matter content (OM). The protocols were devised based on the water processes involved in the FC concept aiming at minimizing hydraulic inconsistencies and procedural difficulty while maintaining the practical meaning of the concept. A high correlation between FC and θ(6 kPa) allowed the development of a pedotransfer function (Equation 3) quadratic for θ(6 kPa), resulting in an accurate and nearly bias-free calculation of FC for the four database geographic areas, with a global root mean squared residue (RMSR) of 0.026 $m^3 \cdot m^{-3}$. At the individual soil profile scale, the maximum RMSR was only 0.040 $m^3 \cdot m^{-3}$. The BD, T and OM data were generally of a low predicting quality regarding FC when not accompanied by the moisture variables. As all the FC values were obtained by the same experimental protocol and as the predicting quality of Equation 3 was clearly better than that of the classical method, which considers FC equal to θ(6), θ(10) or θ(33), we recommend using Equation 3 rather than the classical method, as well as the protocol presented here, to determine in-situ FC.

Keywords: field capacity, internal drainage, pedotransfer functions

1. Introduction

Taking into account the acknowledged imprecision of the FC concept, it is surprising that it is extensively used in hydrological and engineering studies. The Glossary of Soil Science Terms (Soil Science Society of America, 2008) defines FC as “the volumetric water content remaining in a uniform soil profile two or three days after having been completely wetted with water and after free drainage beyond the root zone has become negligible”. The literature also states that this definition depends on wetting hydraulic processes and the subsequent redistribution of water in a natural soil profile (although the definition is restricted to uniform soils). Additionally, the concept of “free drainage” is accepted to be vague, “negligible drainage” to be undefined and that two-to-three-day drainage time might not be compatible with negligible drainage (Cassel & Nielsen, 1986; Hillel, 1998; Romano & Santini, 2002; Twarakavi, Sakai, & Simunek, 2009; Assouline & Or, 2014). Due to operating field experiment difficulties, FC is commonly estimated in laboratory from soil samples, such as the water content at a specific suction value, typically 10 kPa or 33 kPa, which is generally considered incompatible with the definition of FC (Hillel, 1998; Twarakavi et al., 2009; Nemes, Pachepsky, & Timlin, 2011; Romano, Palladino, & Chirico, 2011; Ottoni Filho, Ottoni, Oliveira, Macedo, & Reichardt, 2014a). Thus, it is not only the FC concept that is questionable (Cassel & Nielsen, 1986; Assouline & Or, 2014), but also its most usual determination methodology.

To overcome such major inconveniences, revision of the definition of FC first is obviously necessary, at the same time keeping its meaning of a specific soil moisture “after drainage has stopped” and that represents the water storage upper limit “available” for plant use. These are the meanings that lead to a great practical demand for FC. Ottoni Filho et al. (2014a) redefined FC 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 text considers that FC is a moisture profile, FC(z), and is consistent with the fact the FC concept must be based on hydraulic processes that occur in actual soil profiles in the field, where the variable z represents the depth in the top profile fully wetted by ponded infiltration. As proposed, FC(z) is the moisture profile 48 h after the end of the infiltration process for bare soil conditions and without evaporation or rain. Instead of drainage time, there is the option of choice of a low and arbitrary drainage rate at the base of the profile for which the characterization of FC(z) is wanted (Romano & Santini, 2002; Twarakavi et al., 2009). A drainage time of 48 h was chosen mainly due to the experimental difficulty to measure small deep percolation rates, which would make the validation of field work rather difficult. Therefore, the definition above focuses on the standardization and field experimental easiness of validation of the FC concept, at the same time keeping its practical meaning and minimizing the cited inconveniences. For simplicity, the moisture profile FC(z) is frequently referred to as FC here. A broader discussion on the proposed FC definition can be found in Ottoni Filho et al. (2014a). To evaluate the reproducibility and consistency of the FC(z) moisture profiles obtained with their definition experiment, Ottoni Filho et al. (2014a) experimentally demonstrated that in 22 actual soil profiles studied in Brazil FC(z) was little sensitive to the amount of water applied and to the initial moisture values of the profile, in agreement with that reported in an analytical study by Warrick, Lomen and Islas (1990), who demonstrated a lack of variation in vertical moisture profiles for fixed drainage times in relation to irrigation depth changes. This result is similar to that reported by Twarakavi et al. (2009) for homogeneous soils and using numerical simulation for the FC experiment with fixed drainage rates rather than fixed drainage times. The field methodology in Salter and Williams (1965), similar to that standardized by Ottoni Filho et al. (2014a) and applied to 11 actual soil profiles, indicated little FC sensitivity to initial moisture values. Another result indicative of the reproducibility and consistency of the FC values according to the proposed definition is that linear algebraic pedotransfer functions (PTFs) based on textural percentages, both isolated and together with a combination of values of bulk density, organic matter content and soil moisture at a pre-defined suction level successfully reproduced in-situ FC measurements for 22 soils at different depths (165 samples) with root mean squared residues (RMSRs) from 0.027 $m^3 \cdot m^{-3}$ to 0.051 $m^3 \cdot m^{-3}$, depending on the PTF adopted (Ottoni Filho et al., 2014a). Majou, Bruand and Duval (2008) found relevant correlations involving FC, soil texture and water retention at a specific matrix potential level. They used 433 soil samples from France with a FC determination methodology similar to that of Ottoni Filho et al. (2014a), although wetting was by non-specified rain rather than ponded irrigation; it is not clear whether there was either evapotranspiration or rain during their drainage time of 2 to 3 days. Nemes et al. (2011) also successfully calculated the in-situ FC for 243 soil samples from different depths from the USA using the volumetric water content for a suction value of 33 kPa and the percent clay content, with an RMSR of 0.044 $m^3 \cdot m^{-3}$; in this study soil wetting was by either rain or irrigation and a deep drainage rate of 0.1 to 0.2% (volumetric soil moisture) per day was chosen for all depths. All this indicates that a standardized field experiment may give FC(z) values that are dependent mainly only on basic soil variables at z, regardless of the soil morphology and nature, which must be better assessed using larger FC(z) databases.

The aim of this study was to emphasize the experimental demonstration from Ottoni Filho et al. (2014a) that their FC definition is able to reproduce FC(z) profiles that are strongly dependent only on basic soil variables at z depth, thus confirming the possibility that these moisture profiles, considered as a standard representation of actual soil drainage, can be calculated from PTFs. In this context the paper presents a simple PTF algebraic model for the calculation of FC.

2. FC Database

2.1 Experimental Procedure

The experimental field is located in the municipality of Silva Jardim, Rio de Janeiro state, Brazil (22°28′51″S and 42°12′14″W), in a predominantly flat fluvial valley (15 km^2) used mainly for pasture. The weather is hot and humid, with a dry season from April to September. At higher grounds, the soil is a clayey Haplic Cambisol. In lower parts with a high water table, the soils are either Gleysols or Histosols derived from fluviomarine sediments and contain a high clay content as well. Further details on the study area and its pedology can be found in Leal (2011). The FC experiment followed the guidelines in Ottoni Filho et al. (2014a) and is described in the next paragraph.

Seven soils (PP02 to PP07 and PP09) were investigated during the 2008 dry season. Two metal frame dikes (1.0 m × 1.0 m × height = 0.25 m) were set close to the soil survey trench 5 cm deep and 10 m distant, as duplicates, in each soil. The ponding area of 1.00 m^2 follows Embrapa's (1979) recommendation, which is similar to the area of 1.2 m × 1.2 m used by Paige and Hillel (1993). Ottoni Filho, Ottoni, Oliveira, and Macedo (2014b) discuss the ponding area size. The grass within dikes was mowed, but the roots were kept in the soil. A water depth of 200 mm (200 L) was applied to each site up to field saturation of a 70 cm deep profile, the depth usually adopted in our study. The study by Ottoni Filho et al. (2014a) indicated that the FC determined in soil profile lengths 70 cm deep is generally invariant with respect to water application depths of around 200 mm. The ponding water depth was kept smaller than 10 cm during tests. When infiltration was over, the ponded area was covered with a plastic sheet and after approximate 48 h undisturbed and disturbed soil samples were taken at various depths, close to the center of each identified soil horizon. From these samples, in addition to FC ($m^3 \cdot m^{-3}$), the following properties were determined for all depths: sand, silt and clay contents, organic matter content (OM), bulk density (BD), particle density (PD), total porosity (TP), θ(6), θ(10) and θ(33). The last three are the volumetric water contents ($m^3 \cdot m^{-3}$) for the respective suction values of 6 kPa, 10 kPa and 33 kPa. The undisturbed core samples were used in the determination of FC and BD by the gravimetric method, as well as in the determination of θ(6), θ(10) and θ(33) according to the pressure plate extractor method (Dane & Hopmans, 2002). The other variables were obtained from the disturbed samples: the three textural contents (according to the USDA classification) by the densimeter method (Embrapa, 2011); PD by the volumetric flask method (Embrapa, 2011); and OM by the Walkey-Black method (Nelson & Sommers, 1982). Total porosity was determined from BD and PD [TP = 1 - (BD/PD)]. Further details on the soil sampling and experimental methods are given in Ottoni Filho et al. (2014a).

2.2 Silva Jardim Data Analysis

The estimated field capacity (FC') was evaluated for a data set of n samples with respect to measured field capacity (FC) by RMSR (root mean squared residue) statistics:

$$RMSR=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(FCi-FC'i)^2} \tag{1}$$

FC estimation bias was determined by the non-parametric Wilcoxon test (Bradley, 1968; Zar, 1999). These tools have been used for both the Silva Jardim database and the extended database presented later in the text.

For the seven studied Silva Jardim soils, Table 1 gives the mean textural classes of soil horizons and the mean OM, TP, FC and drainable porosity values in the soil profile of depth D. Profiles PP02, PP07 and PP09 presented unusual FC and TP values, with mean values over 0.55 $m^3 \cdot m^{-3}$ and 0.69 $m^3 \cdot m^{-3}$, respectively, which can be attributed to the fact that they are clayey soils with a very high organic matter content. The OM, FC and TP values for the other soils were more common. As shown in Table 1, the water table in profiles PP02 and PP09 was shallow, above the 70 cm depth, which indicates that the 200 mm water application may have been excessive and influenced the measured FC value. To settle this issue, all the measured FC values were plotted against the corresponding θ(10) values (Figure 1). The results in Figure 1 (including the Wilcoxon test application) indicate that the FC data for PP02 and PP09 (n = 8) follow the same trend of being well estimated with the use of the θ(10) values as the FC data from the other soils (n = 34). Taking into account all the data (n = 42), the RMSR was only 0.0110 $m^3 \cdot m^{-3}$. Therefore, as θ(10) is a basic soil variable, everything indicates that the water application depth used in the test had no relevant influence on the measured FC values, such as reported by Ottoni Filho et al. (2014a).

Table 1. Mean properties of Silva Jardim soils in the length D profile where field capacity was determined

Soil identification	Depth D (m)	Texture	Organic matter (kg/kg)	Total porosity ($m^3 \cdot m^{-3}$)	Field capacity ($m^3 \cdot m^{-3}$)	Drainable porosity(3) ($m^3 \cdot m^{-3}$)
PP02	0.63(1)	clay	0.180	0.708	0.553	0.155
PP03	0.70	sandy clay loam	0.020	0.440	0.345	0.095
PP04	0.70	clay	0.011	0.546	0.306	0.240
PP05	0.70	sandy clay	0.006	0.475	0.290	0.185
PP06	0.70	clay loam	0.035	0.534	0.337	0.197
PP07	0.70	clay loam	0.130	0.743	0.558	0.185
PP09	0.35(2)	clay	0.057	0.694	0.608	0.086

Note. (1) A transition for a phreatic level was found at the 0.63-m depth; (2) A transition for a phreatic level was found at the 0.35-m depth; (3) Difference between total porosity and field capacity.

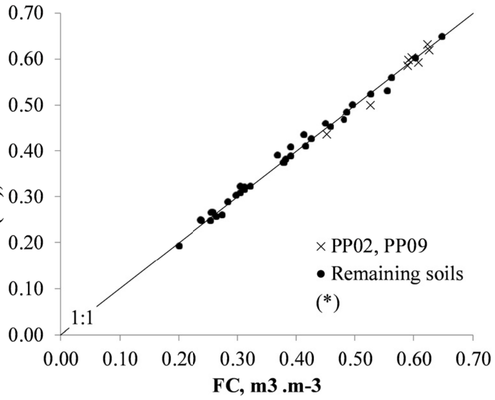


Figure 1. Relationship between measured field capacity (FC) and field capacity estimated by θ(10) for Silva Jardim soils

Note. * means that θ(10) is statistically indistinguishable from FC (at $p < 0.05$) by the Wilcoxon test.

2.3 Extended FC Database

The soil variables determined in Silva Jardim practically coincided with those presented by Ottoni Filho et al. (2014a) by basically the same field and laboratory procedures. An exception is variable θ(10), which was not presented in the abovementioned work, but determined for Seropédica soils (Macedo, Meneguelli, Ottoni Filho, & Lima, 2002), except profile P-AD (Table 2), and Campos soils (Thurler, 2000). θ(10) was not obtained for the S. J. Ubá area either (Ottoni Filho et al., 2014a). Thus, our database ($n = 42$) was added to that of Ottoni Filho et al. (2014a) ($n = 165$) to make an extended database ($n = 207$) of in-situ determined FC and other soil variables. The 29 soils in this database are identified in Table 2, together with length D of the depth range where FC was determined. The soil profiles are from four different geographical areas of Rio de Janeiro state: Seropédica, S. J. Ubá, Campos and Silva Jardim; they contain four pedological orders of the U. S. Classification System (Alfisols, Entisols, Inceptisols and Ultisols) or 7 orders of the Brazilian Classification System (Argissolos, Cambissolos, Gleissolos, Luvissolos, Neossolos, Organossolos and Planossolos), including profiles with potential restriction to drainage due to the presence of an R layer or water table. The database includes all USDA textural classes (Figure 2), with the exception of the silty clay and silt classes, but generally the silty classes were underrepresented. The OM data range ($0.001\ kg \cdot kg^{-1}$-$0.234\ kg \cdot kg^{-1}$) is widespread and so are the FC data ($0.09\ m^3 \cdot m^{-3}$-$0.65\ m^3 \cdot m^{-3}$). Detailed information about the soils and locations of the extended database can be found in the abovementioned literature.

3. Pedotransfer Function (PTF) Development

The six linear PTFs for FC that were adjusted for the 22 soils in Ottoni Filho et al. (2014a), represented in their Table 3, were applied to the Silva Jardim soils. The RMSRs of this validation are presented in Table 3. All the predictions based on the soil texture, including or not BD, or including BD and OM were unsatisfactory (RMSR $> 0.12\ m^3 \cdot m^{-3}$), which indicates the inefficacy of this set of variables regarding the prediction of FC in Silva

Jardim soils, unless a moisture value at a preset suction level is included as a predictor variable (model M6, for which the RMSR decreased to 0.089 $m^3 \cdot m^{-3}$). This inclusion is seen as beneficial in the prediction of the soil moisture using PTFs (Wösten, Pachepsky, & Rawls, 2001; Nemes, Schaap, & Wösten, 2003), as well as in the prediction of in-situ FC (Majou et al., 2008; Nemes et al., 2011). The most satisfactory validations were those based only on the moisture values (models M3 and M5), especially the latter, based only on $\theta(6)$, the RMSR of which was 0.047 $m^3 \cdot m^{-3}$, a good accuracy regarding the prediction of soil moisture with PTFs (Cornelis, Ronsyn, Meirvenne, & Hartmann, 2001; Nemes et al., 2003; Tóth et al., 2015). The importance of the soil moisture as an input variable in PTFs for the determination of in-situ FC was also observed by Majou et al. (2008), Nemes et al. (2011) and Ottoni Filho et al. (2014a), which justifies the frequent use of the soil moisture itself as a direct estimate of FC. The accuracy of the prediction of M3 based only on $\theta(33)$, with an RMSR of 0.077 $m^3 \cdot m^{-3}$, is low according to the criterion proposed by Cornelis et al. (2001). This indicates a greater predicting capacity of $\theta(6)$ for FC in Silva Jardim soils in comparison to $\theta(33)$, as also reported by Ottoni Filho et al. (2014a).They also observed that $\theta(6)$ was the variable that better correlated to FC. The reason for this great FC predicting potential of $\theta(6)$ can be due to the fact that the soil air content associated with $\theta(6)$, as a soil structural variable, might describe the more conductive macroporous space in general better than the air content associated with $\theta(33)$, also taking into account that soil drainability must maintain a close relationship with the unit volume of the soil pore space of larger sizes (“macroporosity”). Coincidentally, some researchers (Uhland, 1949; van Doren & Klingeriel, 1949; Brewer, 1964; Embrapa, 2011) refer to a suction value of 6kPa as a limit value for the distinction between macropore (or mesopore) and micropore sizes.

Table 2. Soil units in the extended database, which comprises four different geographical areas (Seropédica, S. J. Ubá, Campos and Silva Jardim). D is the soil profile length in which the field capacity was determined

Soil identification	No. of samples (n)	Soil Classification		Depth D (m)
		U.S. System(6)	Brazilian System (3° level)(6)	
Seropédica (n = 60)				
PVd5	11	Typic Kandiustult	ARGISSOLO VERMELHO-AMARELO Distrófico	0.50
PVe1	12	Typic Kandiustalf	ARGISSOLO VERMELHO-AMARELO Eutrófico	0.50
PVe3	11	Typic Kandiustalf	ARGISSOLO AMARELO Eutrófico	0.50
PVe6	10	Typic Kandiustalf	ARGISSOLO VERMELHO-AMARELO Eutrófico	0.50
P-AD	16	Typic Kandiustult	ARGISSOLO AMARELO Distrófico	1.00
S. J. Ubá (n = 92)				
P4	8	Typic Kandiustult	ARGILOSSOLO VERMELHO-AMARELO Distrófico	0.70
P5	6	Lithic Haplustept	CAMBISSOLO HÁPLICO Ta Eutrófico	0.50(1)
P6	8	Typic Fluvaquent	GLEISSOLO HÁPLICO Tb Eutrófico	0.70
P15	8	Aquic Hapludult	PLANOSSOLO HÁPLICO Distrófico arênico	0.70
P20	6	Lithic Quartzipsamment	NEOSSOLO LITÓLICO Eutrófico	0.30(2)
P21	8	Mollic Fluvaquent	GLEISSOLO HÁPLICO Ta Eutrófico	0.70
P22	6	Typic Haplustept	CAMBISSOLO HÁPLICO Ta Eutrófico	0.60(3)
P24	8	Typic Kandiustalf	ARGISSOLO VERMELHO-AMARELO Eutrófico	0.70
P27	4	Typic Hapludalf	LUVISSOLO HÁPLICO Órtico típico	0.70
P32	8	Typic Kandiustalf	ARGISSOLO VERMELHO-AMARELO Eutrófico	0.70
P34	6	Typic Haplustept	CAMBISSOLO HÁPLICO Ta Eutrófico	0.70
P36	8	Aquic Hapludult	PLANOSSOLO HÁPLICO Eutrófico gleissólico	0.70
PE	8	Non-classified	Non-classified	0.70
Campos (n = 13)				
P(1-5)	5	Typic Kandiustult	ARGISSOLO VERMELHO-AMARELO Distrófico	0.60
P(6-10)	5	Typic Kandiustult	ARGISSOLO AMARELO Distrófico	0.60
P(11)	1	Oxic Kandiudult	ARGISSOLO AMARELO latossólico	0.60
P(12-13)	2	Typic Kandiustult	ARGISSOLO AMARELO Distrófico	0.60
Silva Jardim (n = 42)				
PP02	4	Haplic Sulfaquent	GLEISSOLO TIOMÓRFICO Órtico típico	0.63(4)
PP03	8	Typic Fluvaquent	GLEISSOLO HÁPLICO Tb Distrófico	0.70
PP04	6	Oxic Haplustept	CAMBISSOLO HÁPLICO Tb distrófico	0.70
PP05	8	Typic Fluvaquent	GLEISSOLO HÁPLICO Tb Distrófico	0.70
PP06	6	Haplic Sulfaquent	ORGANOSSOLO TIOMÓRFICO Sáprico típico	0.70
PP07	6	Haplic Sulfaquent	GLEISSOLO TIOMÓRFICO Órtico típico	0.70
PP09	4	Mollic Sulfaquent	GLEISSOLO TIOMÓRFICO Húmico típico	0.35(5)
Total **29**	207			

Note. (1) A transition for a R-layer was found at the 0.50-m depth; (2) A R-layer was found at the 0.30-m depth; (3) A transition for a R-layer was found at the 0.60-m depth; (4) A transition for a phreatic level was found at the 0.63-m depth; (5) A transition for a phreatic level was found at the 0.35-m depth; (6) Soil profiles were originally surveyed and classified according to the Brazilian Classification System; for the sake of pedological precision, both Soil Classification Systems are presented.

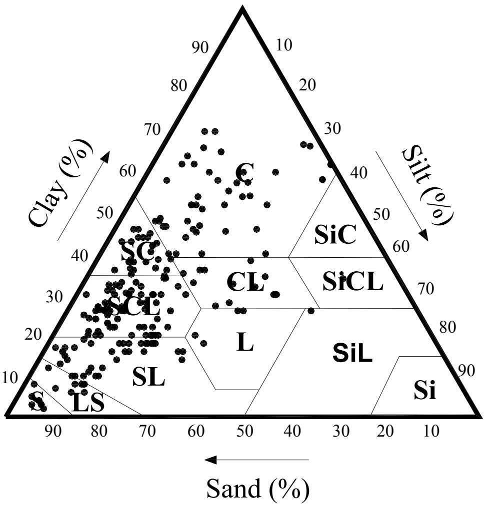


Figure 2. Extended database soils plotted in the textural triangle

Note. S: sand; LS: loamy sand; SL: sandy loam; L: loam; SCL: sandy clay loam; SiL: silty loam; Si: silt; SiCL: silty clay loam; SiC: silty clay; CL: clay loam; C: Clay; SC: sandy clay.

Table 3. Validation of six linear pedotransfer models (M1 to M6) for Silva Jardim soils (n = 42)

PTF	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
Input data	Sand, Silt, Clay	Sand, Silt Clay, BD	θ(33)	Sand, Silt, Clay, BD, OM	θ(6)	Sand, Silt, Clay, BD, OM, θ(6)
RMSR ($m^3 \cdot m^{-3}$)	0.137	0.187	0.077	0.125	0.047	0.089

Taking into account the 22 soils (n = 165) in Ottoni Filho et al. (2014a) and square fitting the FC data in relation to the θ(6) data:

$$FCc = 0.531\theta^2(6) + 0.557\theta(6) + 0.0480 \quad (R^2 = 0.861) \quad (2)$$

Validating the model above for the Silva Jardim soil data, the RMSR fell sharply to 0.0277 $m^3 \cdot m^{-3}$ in relation to M5 (RMSR = 0.047 $m^3 \cdot m^{-3}$). This reduction is explained by the fact that several of Silva Jardim samples had very large FC values, far greater than the maximum value of 0.43 $m^3 \cdot m^{-3}$ observed by Ottoni Filho et al. (2014a) (Figure 3). Linear model M5 in general was incapable of estimating these atypically high values as well as it estimated the other values. Adjusting the quadratic model to the extended database (n = 207, Figure 3):

$$FCc = 0.560\theta^2(6) + 0.576\theta(6) + 0.0436 \quad (R^2=0.944) \quad (3)$$

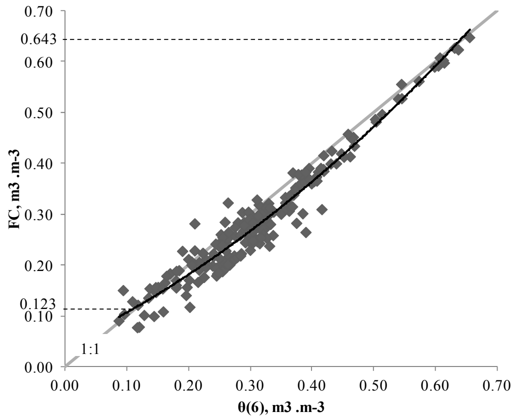
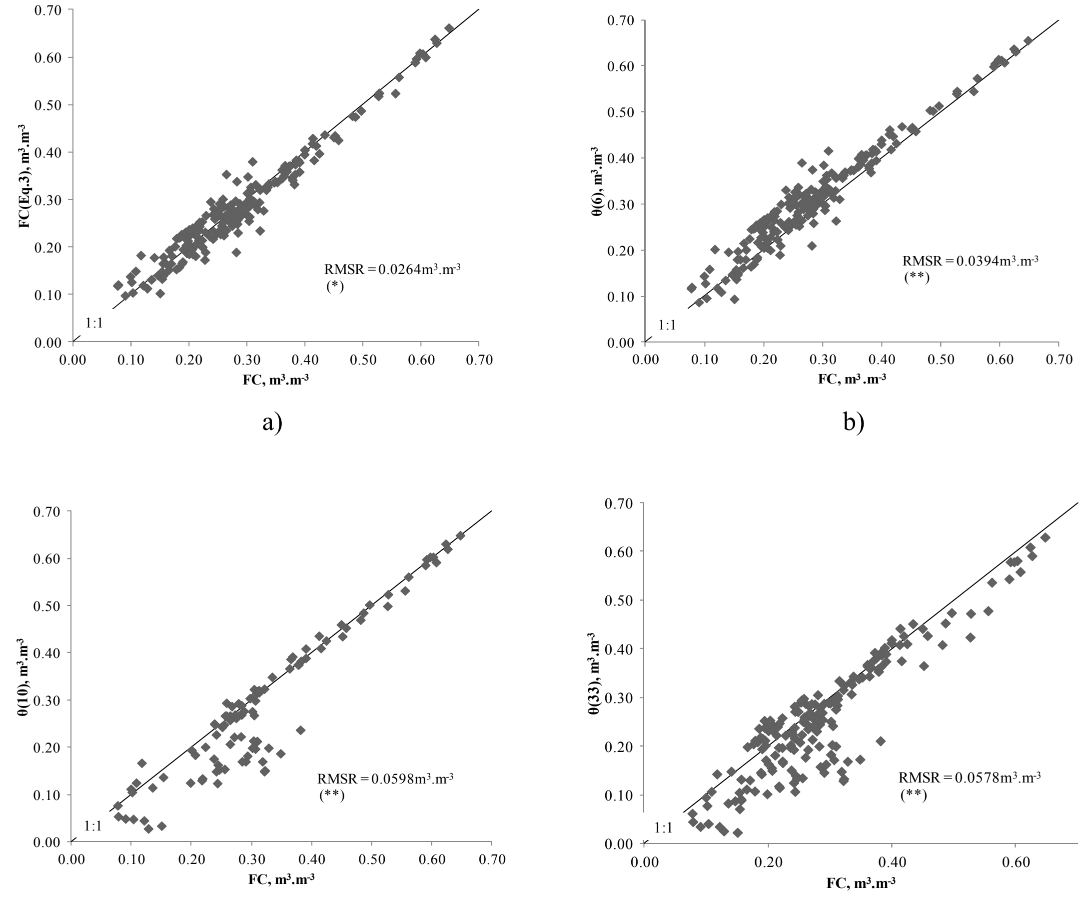


Figure 3. Measured in-situ field capacity (FC) vs. θ(6) for the extended database (n = 207) and graphic representation of the corresponding FC quadratic model (Equation 3)

Taking into account the fitting of Equation 3 (Figure 3), the FC data tend to be smaller than the θ(6) data if the former were in their more usual variation interval from 0.123 $m^3 \cdot m^{-3}$ to 0.634 $m^3 \cdot m^{-3}$. This may explain the tendency of traditionally measuring FC with values θ(10) or θ(33). In contrast, with either lower FC values (lower than 0.123 $m^3 \cdot m^{-3}$) or higher values (over 0.634 $m^3 \cdot m^{-3}$), FC tends to be greater than the corresponding value for θ(6).

4. Pedotransfer Function (PTF) Evaluation

Figure 4a shows a comparison of the measured and the predicted FC values using the extended database (n = 207) and the quadratic model of Equation 3. We can see that Equation 3 predicted in-situ FC with great accuracy (RMSR = 0.0264 $m^3 \cdot m^{-3}$) and without bias, according to the Wilcoxon test. This error was far lower than the RMSR of 0.0438 $m^3 \cdot m^{-3}$ determined by Nemes et al. (2011) and slightly lower than the lowest RMSR (0.027 $m^3 \cdot m^{-3}$) calculated by Ottoni Filho et al. (2014a). Figure 4 also compares the classical FC predictions based on the moisture values themselves θ(6), θ(10) and θ(33): these predictions (Figures 4b, 4c and 4d) were poorer than that of Equation 3 and always had a bias, but not too great RMSRs (0.0394 $m^3 \cdot m^{-3}$, 0.0598 $m^3 \cdot m^{-3}$ and 0.0578 $m^3 \cdot m^{-3}$) [it stands out that the number of measurements for θ(10) (n = 99) is much smaller than those for θ(6) (n = 207) and θ(33) (n = 191)]. There is a global tendency of θ(6) to overestimate FC, as previously observed, and for θ(10) and of θ(33) to underestimate it. Additionally, FC is better correlated to θ(6) (Pearson R = 0.97) than to θ(10) and θ(33) (R = 0.94 and 0.91, respectively), even though the θ(6) prediction is more biased than the θ(10) and θ(33) predictions, as confirmed by the Wilcoxon test. Thus, globally, we can say that θ(6) estimated FC more accurately for the extended database than θ(10) and θ(33), but with a greater bias; in fact, a major number of samples had the θ(6) value greater than FC, as shown in Figure 4b.



a) b)

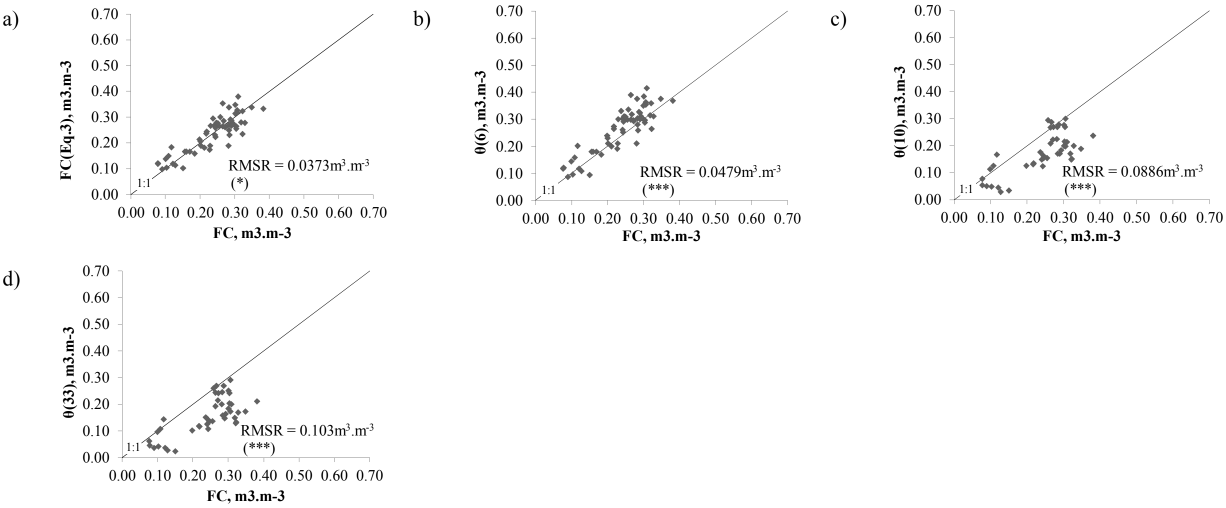
c) d)

Figure 4. Global scale evaluation of field capacity (FC) taking into account the entire extended dataset and the predictions of Equation 3, θ(6), θ(10) and θ(33) (a, b, c, d)

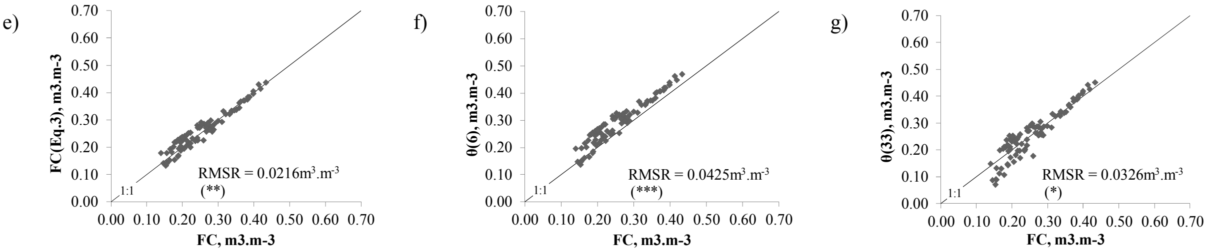
Note. * and ** mean that the variable on the vertical axis is statistically indistinguishable (at $p < 0.05$) or statistically distinguishable (at $p < 0.01$) from FC, respectively, by the Wilcoxon test.

To evaluate the consistency of the FC predictions by the four models mentioned in the previous paragraph, the analysis shown in Figure 4 was repeated in Figure 5 separately for the four study areas (Seropédica, S. J. Ubá, Campos and Silva Jardim). The soils from each of these areas are distinct (Table 2), but have the same parent material in general. The high predicting potential of Equation 3 is confirmed at regional level: this model calculated FC accurately in all four areas (Figures 5a, 5e, 5h and 5l) with a maximum error for Seropédica (RMSR = 0.0326 $m^3 \cdot m^{-3}$), and a small bias occurred only in Silva Jardim, according to the Wilcoxon test, despite the high accuracy of this estimate (RMSR = 0.0188 $m^3 \cdot m^{-3}$). The bias of Equation 3 in the underestimation of FC for Silva Jardim samples (Figure 5l) may have been due to the preponderant presence of a high water table in this area, which may have restricted profile drainage during the two-day drainage protocol time, even if not markedly. The FC predictions by all four models were the worst for Seropédica. As the field and laboratory methodologies were basically the same for the four areas, the greater RMSRs in Seropédica must have been related to the pedology of its Ultisols and Alfisols and/or the parent material.

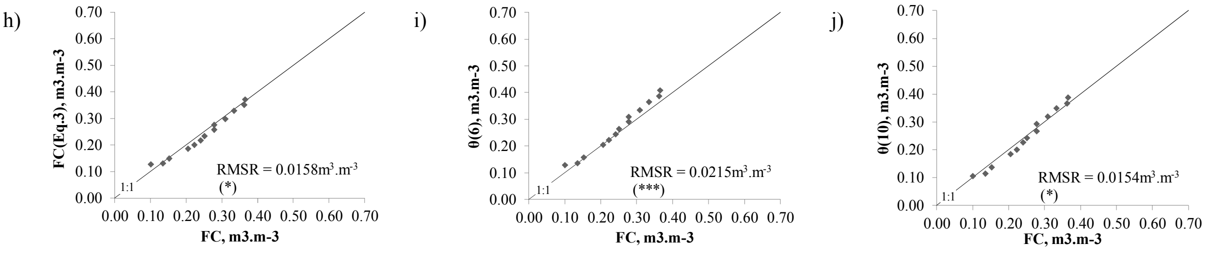
SEROPÉDICA

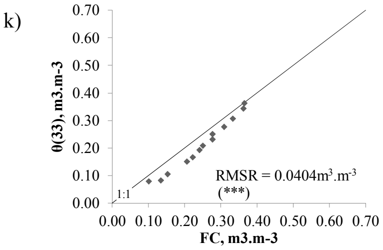


S. J. UBÁ



CAMPOS





SILVA JARDIM

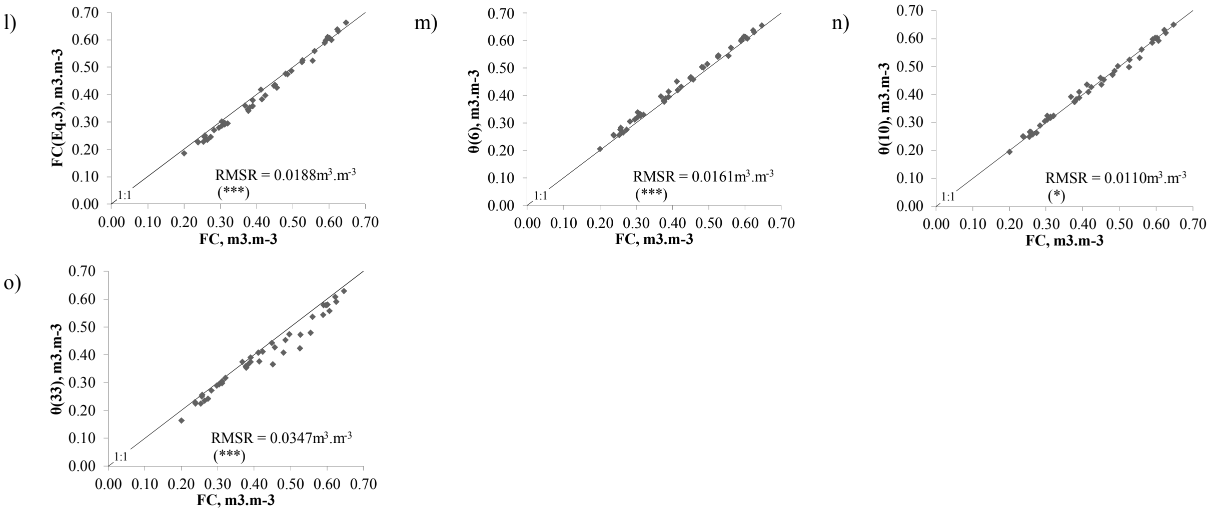


Figure 5. Regional scale evaluation of field capacity (FC) taking into account data from Seropédica (a, b, c, d), S. J. Ubá (e, f, g), Campos (h, i, j, k) and Silva Jardim (l, m, n, o), as well as the predictions from Equation 3, θ(6), θ(10) and θ(33)

Note. *, ** and*** mean that the variable on the vertical axis is statistically indistinguishable (at $p < 0.05$), statistically indistinguishable (at $p < 0.01$) or statistically distinguishable (at $p < 0.01$) from FC, respectively, by the Wilcoxon test.

Figures 5b, 5f, 5i, and 5m indicate that the four regional predictions of θ(6) had suitable accuracy (RMSR < 0.0479 $m^3 \cdot m^{-3}$), but also a bias, according to the Wilcoxon test, indicating that one of the qualities of Equation 3 is to correct the bias introduced by the θ(6) prediction. The classical predictions of FC given by θ(33) and θ(10) were bias free and rather accurate only for S. J. Ubá [θ(33)] and Campos and Silva Jardim [θ(10)], for which the maximum RMSR was only 0.0326 $m^3 \cdot m^{-3}$ (Figure 5g). Despite the lack of θ(10) measurements for S. J. Ubá, everything suggests that they would be biased FC predictions due to fact that the θ(33) value [smaller than θ(10)] was not a biased FC estimate in that area. However, in Seropédica, θ(33) and θ(10) were clearly poor and biased FC predictions, with RMSR values of 0.1031 $m^3 \cdot m^{-3}$ and 0.0886 $m^3 \cdot m^{-3}$, respectively [Figures 5d and 5c]. This all confirms a result that is consistent with indications from literature that a moisture value for a single pre-established suction level is generally not a reliable estimate of FC. The predictions for Silva Jardim using the four models were always adequate (Figures 5l, 5m, 5n, and 5o), with RMSR values smaller than 0.0347 $m^3 \cdot m^{-3}$, even though only those for θ(10) were bias free. In the other areas, the best prediction was that of Equation 3 [taking into account that in Campos it was practically equal to that of θ(10)].

Figure 6 affords another comparison of quality of the FC prediction of Equation 3, in relation to the classical predictions of the values of θ(6) and θ(33), from the calculation of the respective three RMSR values made separately for each soil profile. Figure 6 shows the probability distribution function of these "local RMSRs" values from the three models taking into account the 29 soil units in the database. Variable θ(10) was not considered because it was not measured for the 13 soils from S. J. Ubá. At a local soil profile scale we clearly notice in Figure 6 the superior prediction potential of Equation 3 in relation to the values of θ(6) and especially of θ(33). The 95-percentile for the local prediction from Equation 3 was only about 0.040 $m^3 \cdot m^{-3}$, while for θ(6) and θ(33) they were about 0.065 $m^3 \cdot m^{-3}$ and 0.13 $m^3 \cdot m^{-3}$, respectively. The corresponding 75-percentiles for the three models were 0.032 $m^3 \cdot m^{-3}$, 0.046 $m^3 \cdot m^{-3}$ and 0.047 $m^3 \cdot m^{-3}$, respectively, and this same order of increasing RMSR sequence is maintained for all the other probability values. This result points to a high predicting quality of Equation 3 also when FC is estimated for a given specific soil, with errors hardly greater than 0.040 $m^3 \cdot m^{-3}$.

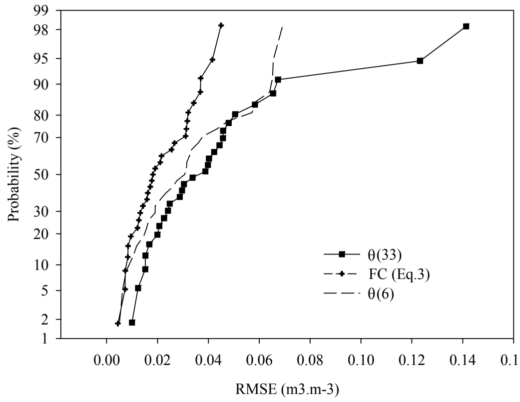


Figure 6. Local scale evaluation of field capacity (FC) taking into account the RMSR cumulative probability distributions for the predictions of Equation 3, θ(6) and θ(33) made for each of the 29 soils in the extended database

Thus, in relation to the FC definition proposed by Ottoni Filho et al. (2014a), we have shown that for the 29 soils in the extended database the standardized measurements and field hydrological methodology resulted in soil moisture profiles, FC(z)s, systematically and strongly dependent only on basic soil variables at depth z. This minimizes the criticisms found in the literature (Cassel & Nielsen, 1986; Assouline & Or, 2014) of ambiguities and difficulties with the FC concept. Among such FC predictor variables in our database, the most relevant were the soil water contents at pre-established suction values. This result is consistent with the in-situ FC prediction by Majou et al. (2008) and Nemes et al. (2011) using distinct databases. However, it has to be said that their field experiment and experimental methodologies for obtaining FC were not strictly similar to ours. Therefore, due to methodological differences (different wetting methods and areas, distinct drainage times, soil profiles nearly saturated, or not, at the end of wetting, occurrence, or not, of rain and/or evapotranspiration after wetting, different soil moisture determination methods), the three FC databases may not be consistent with each other, that is, they may describe different FC(z) profiles. Thus, the standardization of the methodology for the FC field experiment is essential, as acknowledged by Nemes et al. (2011) and Ottoni Filho et al. (2014a).

The quadratic model of Equation 3 calculates the in-situ FC properly in the extended database, at regional (four study regions) and local (each of the 29 soils studied) scales, which did not occur with the FC predictions based on the use of the θ(6), θ(10) or θ(33) values in general. Thus, taking into account the large range of variation of FC in the database (from 0.09 $m^3 \cdot m^{-3}$ to 0.65 $m^3 \cdot m^{-3}$), as well as the significant pedological diversity involved, we propose using Equation 3 instead of the classical procedure of considering FC equal to the soil water content at a single specific value of suction, unless additional hydraulic information is available. In the absence of such information, our study indicates that it is more reasonable to employ Equation 3. However, this does not minimize the need for continued testing of the experimental protocol proposed by Ottoni Filho et al. (2014a) in other pedological environments. As this protocol successfully generated an accurate practical formula (Equation 3) that in a sense described the internal drainage capacity of actual soil profiles in a standard way, we propose conducting field experiments for the determination of FC using the proposed methodology.

5. Conclusion

In applied soil science, field capacity (FC) is valued as an "optimal" moisture content that "remains" in the soil after wetting and "cessation" of drainage in an actual soil profile, thus being the upper limit of stored water content that is "available" for plant use. Despite the great practicality of FC, due to such subjectivity, the literature acknowledges the difficulty in the consistence and validation of this concept when the dynamics of the actual hydraulic processes involved (infiltration, internal drainage, moisture redistribution, evapotranspiration and rain) are considered. As these hydraulic processes are inherent to FC, field tests are required for the validation and rigor of the concept. In acknowledgement of these facts, this study evaluated a FC database which included other soil variables; the FC values were obtained based on the definition proposed by Ottoni Filho et al. (2014a) in an attempt to standardize the hydraulic processes and measurements involved in the conception and in in-situ testing of FC, at the same time that it basically maintains the subjective principles that lend practicality to the concept. The result for the 29 soil profiles studied was that, independently from the depth value in the profile, the corresponding FC value was strongly dependent on moisture values at any of the suction levels studied (6 kPa, 10 kPa and 33 kPa), but weakly dependent on the sand, silt and clay fractions, organic matter content and bulk density. The best correlations were with moisture at 6 kPa [θ(6)], which allowed the accurate determination of FC by a pedotransfer function (PTF) quadratic for θ(6) (Equation 3). This PTF had a high global (RMSR = 0.026 $m^3 \cdot m^{-3}$) and regional (RMSR maximum = 0.033 $m^3 \cdot m^{-3}$, for the four studied geographic areas) accuracy. At the individual soil profile scale, the maximum RMSR (95-percentile) was only 0.040 $m^3 \cdot m^{-3}$. In the absence of field tests, we recommend that FC be determined by the proposed PTF instead of the classic use of the θ(6), θ(10) or θ(33) values themselves, which does not dismiss the need to repeat and validate the methodological procedure from this work to other pedological environments.

The FC value obtained through the methodological standardization of the definition proposed by Ottoni Filho et al. (2014a) had a high potential of being predicted using PTFs. For this reason and to reduce possible inconsistencies between in-situ FC values resulting from different field test methodological procedures, we propose adopting the methodology from Ottoni Filho et al. (2014a) as a reference. Given the importance of the FC concept, we recommend that variable θ(6) be determined in soil surveys as a routine.

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