A variation of the Field Capacity (FC) definition and a FC database for Brazilian soils

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Abstract
Field capacity (FC) is a widely applied parameter in Soil Science. It is related to frequent sequential infiltration and drainage in soils. This paper proposes a variation of the FC definition, based on 48-h drainage time, aiming not only at minimizing the inadequacies of its concept and determination, but also at maintaining its original, practical meaning. Data of 22 Brazilian soils showed that FC determined from standardized field procedures can primarily depend on basic soil data, especially volumetric water content data, such as $\theta(6\ kPa)$ or $\theta(33\ kPa)$.

Key Words
Drainage, pedotransfer function, Brazilian soils

Introduction

Field capacity (FC) is a soil parameter that is widely used in soil and water engineering. The original definition of FC by Veihmeyer and Hendrickson (1949) was slightly modified in the Glossary of Soil Science Terms (SSSA 1984) as: "FC is the amount of water remaining in soil two or three days after having been wetted and after free drainage is negligible". Despite the broad application of FC, its concept bears substantial uncertainty (Cassel and Nielsen 1986; Hillel 1998, chap. 16; Nachabe *et al*., 2003). Indeed, what a negligible free drainage rate is must be better stated. In addition, evapotranspiration is not specifically mentioned, profile wetting and initial soil moisture before water application are not precisely described, which may be relevant, particularly when hysteresis in soil water redistribution after infiltration (Hillel 1998, chap. 6) is significant. The presence of impeding or highly permeable layers and phreatic levels, as well as the influence of lateral flow in sloping landscapes, are also overlooked, especially if it is considered that the 'free drainage' in the above definition implies absence of these conditions. Indeed, all of these factors must be clarified before FC can be considered a reproducible, consistent, and intrinsic soil water variable.

The best standardized procedure to evaluate FC is by flooding a square or rectangular plot on a bare field (Cassel and Nielsen 1986); after irrigation, it is covered with a plastic sheet to avoid evaporation. The distribution of moisture in the upper part of the soil profile, which was fully moistened at the end of infiltration (quasi-saturated), measured 2 or 3 days after water application, defines the FC profile. This FC profile usually depends on the texture and structure of the individual soil layers (Salter and Williams 1965). Based on this dependence and on the operational difficulties of a field test, FC is commonly evaluated in a laboratory setting as the moisture of undisturbed soil samples at a specific matric potential. Cassel and Nielsen (1986) reported that a wide range of matric potentials (from -2.5 kPa to -50 kPa) has been used for this purpose, although suctions of 5 kPa, 6 kPa, 10 kPa, and 33 kPa are more common choices; however, there is no satisfactory general criterion for selection of the suction values for the determination of FC (Hillel 1998, chap. 16). Taking into account the dynamic nature of drainage, some authors (Nachabe *et al*., 2003) argue that the definition of FC must be based on an arbitrary choice for the "negligible" downward flux, instead of the drainage time of 2 or 3 days, or the suction at FC. Meyer and Gee (1999) considered that such selected small fluxes could be between 0.01 mm/d and 1.0 mm/d depending on the type of application. When FC is evaluated by the flux-based method, the drainage times may vary by an enormous range, even for an individual soil, from tens of hours to tens of days, depending on the flow rate chosen, as clearly demonstrated in Hillel (1998, chap. 16). Overall, despite being a widely applied soil parameter, the understanding of FC is neither unique nor exact.

In this paper, a variation of the definition of FC is proposed and empirically tested by the development and analysis of a FC database. The goal is to minimize the problems associated with the FC concept by creating a theoretical and practical framework for the proper and reproducible evaluation of the sequenced processes of

infiltration (ponding) and internal drainage in the top soil layer. This will enable the standardization of experimental procedures, as well as the use of current mathematical tools, such as analytical and numerical modeling, and pedotransfer functions (Pachepsky and Rawls 2005) to determine FC profiles as required by engineers and land planners.

Variation of the FC Definition
"Field Capacity (FC) is the volumetric water content distribution in the upper part of a soil profile that, in the course of ponded infiltration (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".

According to the above definition, measurement of FC is made only in the upper part of the profile, above the infiltration wetting front, which was monotonically drained from saturation or quasi-saturation so that the hysteresis effects were minimized (Hillel 1998, chap. 16). Rain and evapotranspiration effects were considered null during the 48 h of drainage. The duration of 48 h was chosen since it is a classical choice (Cassel and Nielsen 1986), and also because 2 days of drainage is a frequently used time period to infer crop damage by lack of soil aeration (Ochs *et al*., 1980; Hillel 1998, chap. 10). As a result, FC data can be utilized to evaluate soil profile aeration. Additionally, if a longer period were chosen, rain between irrigation and FC measurement would be more probable. We have not adopted a negligible constant downward flux due to difficulties in measuring small deep percolation flows in the field and due to the long test duration required for slow-draining profiles, sometimes over a week, which is particularly deleterious in wet climates because of the high frequency of rain.

FC Database
The FC database included soil data on FC, textural fractions (according to the USDA classification), bulk density (BD), organic matter content (OM), and volumetric water content at the suctions of 6, 33 and 1500kPa (respectively $\theta(6)$, $\theta(33)$, and $\theta(1500)$). It comprises 22 soils (n=165 samples), most from the state of Rio de Janeiro, Brazil. The climate of the region is humid and tropical with rainy summers. Field work was in late fall and winter, when soil was relatively dry. In the FC test, a metal frame dike (1.0 m × 1.0 m × height = 0.25 m) (Embrapa 1979) was driven about 5 cm into the soil. The landscape slopes at the experimental sites varied from zero to approximately 20%. About 250 L of water was applied to most soils. Determination of antecedent soil moisture profiles near the experimental plots indicated that the used water volumes were frequently sufficient to saturate each of the soil profiles up to the 70-cm depth. Therefore, most soils were sampled in this depth range. At the end of infiltration, the wetted areas were covered with a plastic sheet and 48 h later, two undisturbed core samples were taken near the plot center, generally from the middle of each identified soil horizon. The soil property value reported in the database, including FC, was the arithmetic mean of the measurements made for each pair of samples at the corresponding depth and site.

The samples were sealed to prevent water loss and sent to the laboratory, where they were weighed for FC calculation. For detailed information on soils, laboratory and field procedures, sampled depths, and soil data see Fabian and Ottoni Filho (2000), Thurler (2000), Macedo *et al*. (2002), and Ottoni (2005).
Ranges of values of in situ FC in the database, according to textural classes, are shown in Table 1. For most samples, the suctions corresponding to FC were in the range from 6 kPa to 33 kPa, according to the comparisons made between the measured value of FC and the corresponding $\theta(6)$ and $\theta(33)$. The Pearson correlation coefficients (r) between FC and the soil properties are given in Table 2. The data set presents significant correlations between FC and soil properties. The most significant correlations were between moisture retention data ($\theta(6)$, $\theta(33)$, and $\theta(1500)$), especially for $\theta(6)$, where r=0.93. This is an indication of the important influence of soil structure on FC, which was greater than the influence of texture. Silt was the least correlated textural content.

Table 1. Confidence intervals for FC (10^{-2} m^3.m^{-3}) in the database according to textural classes (n=165).

Subset 1		Subset 2			Subset 3		
Sand (s)	Loamy sand (ls)	Sandy loam (sl)	Loam (l)	Sandy clay loam (scl)	Clay loam (cl)	Sandy clay (sc)	Clay (c)
10.6±2.5 (n=8)	15.4±3.9 (n=10)	20.3±3.7 (n=38)	32.5±6.4 (n=4)	26.1±4.5 (n=56)	33.5±3.6 (n=8)	28.5±3.5 (n=15)	30.4±8.2 (n=26)

Table 2. Pearson correlation coefficients between field capacity and soil properties (n= 165).

Sand	Silt	Clay	θ(6)	θ(33)	θ(1500)	OM	BD
-0.720**	0.371**	0.628**	0.926**	0.795**[a]	0.825**[a]	0.223**	-0.213**

** Significative correlation at P= 5%, according to Pearson Test.
[a] Calculated for n= 149, since the work of Fabian and Ottoni Filho (2000) (n= 16) does not include information on θ(33) and θ(1500).

Based on the high correlations observed, we investigated how well FC could be calculated from basic soil properties; Table 3 presents 6 multilinear pedotransfer (PTF) models for FC (M1 to M6) and their root mean squared residues (RMSRs). The RMSRs are within the range commonly found in the literature for soil moisture PTFs (Nemes *et al*., 2003; Saxton and Rawls 2006). When θ(6) was added as an input variable (model M6), FC estimation improved significantly. However, for model M5, in which θ(6) was the sole predictor, RMSR (0.0281 $m^3 m^{-3}$) was only marginally larger than its correspondent, M6, a sophisticated model that had 6 predictors. This suggests that soil moisture is a useful input variable in the prediction of FC, which is generally the case with soil moisture evaluation by PTFs (Nemes *et al*., 2003; Schaap *et al*., 2004)

Table 3. Coefficients of multilinear PDFs for field capacity ($m^3 m^{-3}$). Models are enumerated in a decreasing order of RMSRs. Units of the input variables are: kg kg^{-1} (sand, silt, clay, OM); kg dm^{-3} (BD); $m^3 m^{-3}$ (θ(6), θ(33)).

Model	Sand	Silt	Clay	OM	BD	θ (6)	θ (33)	Constant	RMSR
									m^3m^{-3}
M1	0.08478	0.4048	0.3792					0.03533	0.0514
M2	-0.0231	0.3912	0.3010		0.1077			-0.04645	0.0497
M3							0.6561	0.1043	0.0463
M4	0.1678	0.5967	0.4977	2.241	0.1190			-0.2877	0.0458
M5						0.8476		0.01181	0.0281
M6	0.03160	0.09379	0.03302	-0.3359	0.05547	0.8638		-0.1156	0.0270

Conclusion
FC has been defined here as the water content distribution in the soil profile as a function of sequential ponded infiltration and drainage without evapotranspiration or rain at 48 h after the end of infiltration. Therefore, the distribution FC(z) can be determined by hydraulic or numerical experiments that reproduce the above processes. Hysteresis effects are minimal in the above context. From standardized field procedures it was seen that FC can be accurately determined from basic soil properties. Without such standardization alternative laboratory, statistical or numerical methods for determining FC will remain ambiguous.

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