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Hydrostatic Equilibrium between Soil Samples and Pressure Plates Used in Soil Water Retention Determination: Consequences of a Questionable Assumption

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ABSTRACT: Soil water retention is among the soil hydraulic properties most routinely measured in studies of soil physics and related areas. This property is used in dynamic simulations of vadose zone processes such as soil water availability, surface boundary processes of evaporation and infiltration, and the fate of soil pollutants. The most common measurement technique consists in establishing a hydrostatic equilibrium between an initially saturated soil sample and a porous medium at a certain tension on a tension table or pressure plate. However, there is reasonable doubt about the assumed hydrostatic equilibrium, especially in the dry range at low pressure heads. In this study we compared the traditional pressure plate apparatus protocol to an inverse parameter estimation protocol based on a transient evaporation experiment. Independent pressure head measurements using a dewpoint device were also performed. We sampled a variety of soil textures typical of the Brazilian subtropical humid zones, aiming to show differences between textures in their subjection to hydraulic nonequilibrium. The performed experiments allow to conclude that the two compared protocols showed real pressure heads in samples on a pressure plate to be less negative than the assumed ones, leading to an overestimation of the soil water content in the dry range at low pressure heads, especially in fine-textured soil samples. This affects the reliability of most soil hydraulic databases, derived PTFs in the dry range, as well as the wilting point estimation. Water availability predictions based on total and readily available water are more sensitive to the water retention measurement method when the chosen lower limits of available water are closer to the wilting point. In this sense, irrigation timing criteria based on readily available water should be preferred over total available water, especially for fine-textured soils. Finally, given the low reliability of the pressure plate apparatus for low pressure heads, possibly biasing hydrological simulations and their interpretation, alternative measurement methods for the drier part of the soil water retention curve should be preferred, e.g., the proposed inverse modeling of evaporation experiments.

Keywords: inverse parameter optimization, soil available water, wilting point.

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INTRODUCTION

Water retention, the matric potential or pressure head (*h*) of soil water at a given water content (θ), is the most routinely measured soil property in soil physics laboratories worldwide. To the obtained data pairs θ (*h*), typically 6 to 10 values usually in the range from near saturation (*h* = 0) to permanent wilting point (*h* around - 150 m), an analytical function is fitted to describe the soil water retention over this range. The resulting graphical representation of the θ (*h*) function is called the soil water retention curve (SWRC), and some frequently used equations to describe the SWRC are those proposed by Brooks and Corey (1966), Campbell (1974), van Genuchten (1980), Durner (1994), and Groenevelt and Grant (2004).

To obtain the data pairs θ (*h*), the most common measurement technique is based on establishing a hydrostatic equilibrium between an initially saturated soil sample and a porous medium device, such as a filter paper, fine sand, or a porous ceramic, at a certain tension (Dane and Hopmans, 2002; Cresswell et al., 2008). These measurements allow direct estimations of the static status of soil water availability, represented by the total soil available water, defined by specific pressure head values adopted as proxies of upper (field capacity) and lower (wilting point) limits of soil available water (Minasny and McBratney, 2018; Scarpare et al., 2019). On the other hand, the SWRC allows the dynamic simulation of soil water and nutrient balances by implementing Richards equation-based models such as Hydrus-1D (Šimůnek et al., 2016) or SWAP (Kroes et al., 2017). This allows predicting key processes in the vadose zone like the partitioning of water into soil water balance components and soil water availability to crops (Pinheiro et al., 2019b), the fate of soil pollutants (e.g., nutrients and pesticides) (Šimůnek et al., 2018), among others.

The pressure plate apparatus stands strong as the standard technique to determine θ (*h*) by hydrostatic equilibrium since its introduction by Richards and Fireman (1943) and Richards (1948). It can be used to determine the water content at pressure heads from -0.1 m down to -150 m, being the latter value commonly considered to correspond to the permanent wilting point (lower limit of crop water availability). Pressure plate apparatus equipment in soil physics laboratories is therefore designed to allow operation down to the corresponding pressure head of -150 m. The cost of the SWRC determination is largely determined by this lowest pressure head, requiring a powerful compressor, highly resistant pressure chambers and manifold, and specific ceramic plates. Besides, the high-pressure determinations are likely to require weeks (or sometimes months) to reach a supposed equilibrium. To shorten the equilibrium time, the -150 m pressure head determination is usually performed on disturbed samples spread directly over the pressure plate (Madsen et al., 1986; Cresswell et al., 2008).

Pressure plate apparatus determinations require the static equilibrium to be established, and in practice this is verified by outflow observation. After having been submitted for some time to the required pressure head (days for the higher pressure heads to weeks for the lower ones), the verification of equilibrium consists in the observation of water being expelled by the pressure plate apparatus. If the presence of water at the outlet is observed, equilibrium is considered not to be established and more time is allowed; if no outflowing water is observed for some days, equilibrium is supposed to be established and the samples are weighed to determine their water content. This protocol is well known and largely adopted by the soil physics community, but the absence of equilibrium at low pressure heads has been reported in literature (Madsen et al., 1986; Gee et al., 2002; Cresswell et al., 2008; Bittelli and Flury, 2009; Solone et al., 2012; Hunt et al., 2013; Roy et al., 2018). The assumption of hydrostatic equilibrium when it may not really have been reached leads to erroneous interpretation of soil hydraulic functioning in Richards equation-based models, as well as to misestimating of soil available water for crop growth, decreasing the efficiency of water use by irrigated agricultural systems with timing based on total available water depletion (e.g. Kisekka et al., 2016; Kothari et al., 2019).

Erroneous data caused by the absence of equilibrium when determining retention data on a pressure plate apparatus may subsequently propagate in pedotransfer functions (PTFs), frequently used to retrieve soil hydraulic properties from more easily accessible information, such as particle-size distribution, bulk density, and organic matter, and they are developed for field or regional applications (Tomasella et al., 2000; Schaap et al., 2001; Vereecken et al., 2010). Spatially-distributed simulations of regional soil water balance performed by hydrological models are usually dependent on PTFs. However, the baseline data used for validating those PTFs are based on available SWRC data, most probably determined using a pressure plate apparatus, and consequently, model outputs may be seriously biased (Solone et al., 2012). The recently launched Brazilian hydraulic property soil database Hybras (Ottoni et al., 2018) is an example, as it relies mainly on pressure plate apparatus data.

The importance of a correct determination of the SWRC, and a reasonable doubt about the most commonly adopted method to determine it, justifies a thorough determination of its reliability. This study aimed to compare two methods of soil water retention parameterization, the traditional method using the pressure plate apparatus with the assumption of hydrostatic equilibrium and, alternatively, an inverse parameter estimation based on a transient water flow experiment, thus independent of an equilibrium (Šimůnek et al., 1998; Peters et al., 2015; Pinheiro et al., 2019a). We hypothesize that the assumption of hydrostatic equilibrium in a pressure plate apparatus may not be true, especially at lower pressure heads, and that water retention curves determined by inverse modeling of a transient (nonequilibrium) condition are more reliable and able to show the shortcomings of the pressure plate apparatus. We used a variety of soil textures typical of the Brazilian subtropical humid zones, to verify possible differences between textures in their susceptibility to hydraulic nonequilibrium. We also show how the erroneous values obtained from the pressure plate apparatus affect subsequent estimates of soil water availability.

MATERIALS AND METHODS

Soil sampling

Soil samples were collected from nine sites in the subtropical humid climate zones of southeast Brazil. The sampling sites were within typical field conditions covering a broad range of textures (Table 1). A few days after rainfall, undisturbed soil samples were taken at two layers (between 0 and 0.15 m and between 0.30 and 0.45 m) at each site, using two different ring dimensions (a smaller ring of 46.8 mm inside diameter and 30 mm height, volume 51.6 cm^3; and a larger ring of 74 mm inside diameter and 70 mm height, 301 cm^3). Sample rings had a cutting edge and were gently pushed or hammered into the soil. Five replicates were taken for each type of ring and soil layers.

Traditional equilibrium water retention measurement

Soil samples collected in the smaller rings (51.6 cm^3) were used for the traditional method of measuring water retention based on the hydrostatic equilibrium between the soil sample and a porous medium at subsequently decreasing pressure head values. Samples were saturated by capillarity with a solution of $CaSO_4$ 0.005 mol L^{-1} to avoid clay dispersion and placed on a tension or pressure equipment. For soil water contents near saturation (pressure heads of -0.1, -0.2, and -0.6 m), a tension table equipped with filter paper was used. For more negative pressure heads (-1, -3.3, -10, -30, and -150 m), pressurized air was applied to a pressure plate apparatus consisting of a manifold, pressure chambers and porous ceramic plates (details described in Dane and Hopmans, 2002), manufactured by Soil Moisture Equipment Corp. A 1-bar ceramic plate was used for the heads of -1, -3.3, and -10 m; a 3-bar ceramic plate for -30 m; and a 15-bar ceramic plate for -150 m. Five replicates were used for each pressure head, and for -150 m an extra measurement was performed for some soils using disturbed samples (passed through a 2 mm sieve) spread over the pressure plate and contained in 10 mm high plastic rings. The van Genuchten (1980) equation was fitted to the obtained data-pairs minimizing the sum of squared errors using the RETC software (van Genuchten et al., 1991). This protocol to obtain retention parameters, using tension table and pressure plate apparatus will be referred to as PPA.

In order to independently verify the sample pressure head after supposedly attaining hydrostatic equilibrium when subjected to -150 m pressure head in the pressure plate apparatus for 15, 30, and 100 days, five soils of different texture (coarse-, medium-, and fine-textured) were randomly selected to be submitted to a measurement by a dewpoint meter equipment (WP4C manufactured by Decagon Devices). To do so, disturbed soil samples were spread directly over the pressure plate, the layer of soil not being thicker than 10 mm. An independent pressure plate apparatus was used for each equilibration time in order to keep the system with uninterrupted pressure for the entire period. After the respective time, the pressure was released and samples were immediately placed in the dewpoint meter sample holders and covered with caps to prevent any evaporation, and then instantly transferred to the dewpoint meter reading chamber one by one to determine the water potential. Subsequently, samples were transferred to an oven (105 °C for 24 h) for soil water content determination.

Evaporation experiment protocol

The soil samples collected in the larger rings (301 cm^3) were used for determining the soil water retention property using the evaporation experiment protocol. Samples were

Table 1. Particle size distribution, soil texture class, and current land use at the 9 sampling sites

Great soil group[1]	Site	Layer	Particle size fraction[2]			Texture class	Land use	Coordinates	
			Sand	Silt	Clay			South	West
		m	g kg^{-1}						
Arenosol/*Neossolo Quartzarênico*	1	0.00-0.15	885	27	88	Loamy fine sand	Pasture	22° 34.87′	47° 53.38′
		0.30-0.45	856	31	113				
Arenosol/*Neossolo Quartzarênico*	2	0.00-0.15	835	27	138	Sandy Loam	Sugarcane	22° 34.89′	47° 53.37′
		0.30-0.45	835	15	150				
Arenosol/*Neossolo Quartzarênico*	3	0.00-0.15	856	31	113	Loamy fine sand	Sugarcane	22° 14.67′	47° 43.31′
		0.30-0.45	845	29	126				
Arenosol/*Neossolo Quartzarênico*	4	0.00-0.15	204	167	629	Clay	Fallow	22° 43.52′	47° 35.15′
		0.30-0.45	221	125	654				
Ferralsol/*Latossolo*	5	0.00-0.15	181	127	692	Clay	Sugarcane	22° 43.71′	47° 33.29′
		0.30-0.45	139	106	755				
Ferralsol/*Latossolo*	6	0.00-0.15	481	113	406	Sandy clay	Native Forest	22° 42.93′	47° 36.66′
		0.30-0.45	509	61	430				
Ferralsol/*Latossolo*	7	0.00-0.15	427	92	481	Clay	Pasture	22° 42.87′	47° 36.68′
		0.30-0.45	388	81	531				
Acrisol/*Argissolo*	8	0.00-0.15	233	76	691	Clay	Native Forest	22°14.66′	47° 43.25′
		0.30-0.45	278	55	667				
Acrisol/*Argissolo*	9	0.00-0.15	202	45	753	Clay	Annual crops	22° 14.69′	47° 43.40′
		0.30-0.45	168	38	794				

[1] IUSS Working Group WRB (2015) and Santos et al. (2013). [2] Determined by sieving (sand) and hydrometer method (silt and clay).

quasi-saturated by capillarity with a solution of $CaSO_4$ 0.005 mol L^{-1} to avoid clay dispersion. Subsequently, the lower sample surface was sealed with a cap and water at the upper side could evaporate into the laboratory air. Once per day for two weeks, samples were weighed and soil water contents were measured at five vertical positions, 10, 15, 20, 35, and 50 mm below the soil sample surface by determining the attenuation of a collimated gamma-ray beam. This experiment design was described by Pinheiro et al. (2019a), which consisted in using a gamma-ray source of ^{137}C with radioactivity of 11.1 GBq and an energy peak of 661.6 keV. The source was coupled with a NaI(Tl) scintillation detector (7.62 × 7.62 cm), which was attached to a photomultiplier tube. A photon counter was interfaced with a computer, which stores data automatically. Circular collimators were adjusted and aligned between a source (diameter 3 mm) and a detector (diameter 4.5 mm). More details about the used gamma-ray attenuation device can be found in Pires et al. (2005).

This is a well-stablished technique for measuring the soil water content based on the Beer-Lambert attenuation law (Wang et al., 1975), equation 1, allowing θ measurements over the entire range of plant available water with a high accuracy (Pires et al., 2005), using the same undisturbed soil sample throughout the entire process:

$$\theta = \frac{ln\left(\frac{I_0}{I}\right)}{\mu_w \rho_w x} \qquad \text{Eq. 1}$$

in which I_0 (m^{-2} s^{-1}) is the photon beam intensity crossing the experimental unit with oven-dry soil (corresponding to the same soil cores used during the evaporation phase); I (m^{-2} s^{-1}) is the photon beam intensity crossing the experimental unit during the evaporation process; μ_w (m^2 kg^{-1}) is the mass attenuation coefficient of the water fraction for the corresponding γ radiation energy, ρ_w (kg m^{-3}) is the water density, and x (m) is the thickness of the soil sample.

To estimate retention parameters from inverse modeling, soil water contents measured at five positions versus time were included in the objective function Φ to be minimized using Hydrus-1D (Šimůnek et al., 2016) by simulating the one-dimensional variably-saturated water flow in the soil samples by numerically solving the Richards equation. The upper and lower water flow boundary conditions were set as atmospheric and constant (zero) flux boundary conditions, respectively. The surface evaporation flux was calculated for each time interval from the observed mass difference over a time interval (determined by weighing on a 0.01 g resolution balance) and used as a time-variable boundary condition. The soil water retention curve was assumed to be described by the analytical θ-*h* function defined by van Genuchten (1980) with the Mualem restriction:

$$\Theta = \left[1 + |\alpha h|^n\right]^{(1/n)-1} \qquad \text{Eq. 2}$$

with $\Theta = (\theta_s - \theta_r) / (\theta_s - \theta_r)$ is the effective saturation, θ (m^3 m^{-3}) is the water content, h (m) is the pressure head, θ_r (residual water content), θ_s (saturated water content), α (m^{-1}), and n are shape parameters. The protocol to obtain retention parameters from the evaporation experiment combined with this inverse modeling protocol will be hereafter referred to as IME.

Soil available water

In order to evaluate the effect of the two soil water retention measurements on static soil available water estimations, we calculated the total and readily available water (TAW and RAW, mm) for a root depth profile of 0.60 m, representing the most active soil depth in the vadose zone regarding the root water uptake fluxes for the majority of crops. The soil profile was subdivided into two layers with thickness Z_1 and Z_2, in which the specific hydraulic properties of both layers were considered according to the surface (L_1) and subsoil layers (L_2) of table 2:

$$TAW = (\theta^{L1}_{fc} - \theta^{L1}_{wp})\, Z_1 + (\theta^{L2}_{fc} - \theta^{L2}_{wp})\, Z_2 \qquad \text{Eq. 3}$$

$$RAW = (\theta^{L1}_{fc} - \theta^{L1}_{lim})\, Z_1 + (\theta^{L2}_{fc} - \theta^{L2}_{lim})\, Z_2 \qquad \text{Eq. 4}$$

in which θ_{fc}, θ_{lim}, and θ_{wp} stand for soil water contents at field capacity, onset of drought stress and wilting point, respectively; Z_1 and Z_2 represent layer thickness, here adopted as Z_1 = 0.25 m and Z_2 = 0.35 m.

For the field capacity, we used the pressure head value of -1 m, as recommended by De Jong van Lier and Wendroth (2016) and Pinheiro et al. (2019a) for tropical soils. Regarding θ_{lim}, values reported by Taylor and Ashcroft (1972) were adopted. For the wilting point, the standard pressure head value of -150 m was used (Savage et al., 1996).

Table 2. Optimized van Genuchten parameters for water retention obtained by inverse solution using the evaporation experiment data and by fitting the pressure plate apparatus data. The values between parentheses are the standard errors representative of the five replicas

Site	Layer	Evaporation experiment (IME)				Pressure plate apparatus (PPA)			
		θ_r	θ_s	α	n	θ_r	θ_s	α	n
	m	$m^3\ m^{-3}$		m^{-1}		$m^3\ m^{-3}$		m^{-1}	
1	0.00-0.15	0.025 (0.0021)	0.324 (0.0024)	2.221 (0.0930)	1.622 (0.0201)	0.000 –	0.434 (0.0211)	3.204 (0.0101)	1.423 (0.0498)
1	0.30-0.45	0.025 (0.0019)	0.320 (0.0024)	2.816 (0.1230)	1.565 (0.0168)	0.066 (0.0102)	0.428 (0.0211)	4.105 (0.0211)	1.688 (0.1293)
2	0.00-0.15	0.042 (0.0010)	0.344 (0.0016)	2.031 (0.0420)	1.788 (0.0091)	0.050 (0.0050)	0.366 (0.0096)	2.816 (0.004)	2.019 (0.1375)
2	0.30-0.45	0.034 (0.0010)	0.344 (0.0017)	2.693 (0.0480)	2.160 (0.2045)	0.044 (0.0028)	0.365 (0.005)	2.495 (0.0017)	2.163 (0.0915)
3	0.00-0.15	0.034 (0.0022)	0.290 (0.0015)	2.211 (0.0850)	1.471 (0.0141)	0.069 (0.0312)	0.376 (0.0138)	2.523 (0.0096)	1.446 (0.1481)
3	0.30-0.45	0.031 (0.0041)	0.306 (0.0023)	2.361 (0.1410)	1.397 (0.0180)	0.094 (0.0242)	0.382 (0.0311)	5.142 (0.0329)	1.499 (0.1867)
4	0.00-0.15	0.046 (0.0140)	0.395 (0.0011)	0.950 (0.0340)	1.206 (0.0133)	0.185 (0.0739)	0.488 (0.0857)	16.17 (0.3821)	1.204 (0.1344)
4	0.30-0.45	0.069 (0.0072)	0.415 (0.0013)	1.783 (0.0840)	1.180 (0.0066)	0.186 (0.0453)	0.459 (0.0377)	11.12 (0.1400)	1.219 (0.0976)
5	0.00-0.15	0.049 (0.0104)	0.378 (0.0010)	1.379 (0.0480)	1.202 (0.0107)	0.154 (0.0336)	0.460 (0.0195)	5.013 (0.0297)	1.292 (0.0951)
5	0.30-0.45	0.060 (0.0046)	0.372 (0.0010)	1.747 (0.0560)	1.173 (0.0044)	0.166 (0.0387)	0.491 (0.0966)	18.18 (0.3358)	1.261 (0.1100)
6	0.00-0.15	0.042 (0.0060)	0.350 (0.0013)	1.080 (0.0050)	1.242 (0.0094)	0.151 (0.0238)	0.426 (0.0109)	3.581 (0.0140)	1.310 (0.0788)
6	0.30-0.45	0.046 (0.0053)	0.344 (0.0010)	1.400 (0.0290)	1.217 (0.0066)	0.121 (0.0206)	0.406 (0.0119)	5.124 (0.0200)	1.288 (0.0614)
7	0.00-0.15	0.030 (0.0068)	0.362 (0.0010)	0.888 (0.0330)	1.208 (0.0076)	0.085 (0.1036)	0.384 (0.0122)	4.287 (0.0335)	1.146 (0.0907)
7	0.30-0.45	0.028 (0.0095)	0.350 (0.0010)	1.608 (0.0610)	1.197 (0.0100)	0.153 (0.0654)	0.363 (0.0123)	2.896 (0.0249)	1.218 (0.1477)
8	0.00-0.15	0.048 (0.0066)	0.410 (0.0011)	1.482 (0.0600)	1.183 (0.0060)	0.180 (0.0510)	0.468 (0.0225)	5.711 (0.0478)	1.238 (0.1082)
8	0.30-0.45	0.054 (0.0107)	0.415 (0.0020)	1.129 (0.0670)	1.201 (0.0107)	0.182 (0.0301)	0.466 (0.0139)	5.093 (0.0258)	1.259 (0.0739)
9	0.00-0.15	0.053 (0.0154)	0.427 (0.0012)	1.205 (0.0440)	1.192 (0.0126)	0.118 (0.2210)	0.461 (0.0210)	4.450 (0.0537)	1.147 (0.1608)
9	0.30-0.45	0.063 (0.0147)	0.419 (0.0010)	0.783 (0.0210)	1.180 (0.0109)	0.000 –	0.483 (0.0130)	8.677 (0.0481)	1.078 (0.0044)

RESULTS

Effects on soil water retention fitting parameters

The soil water retention parameters according to the van Genuchten (1980) analytical function were successfully determined by the two implemented protocols, IME and PPA (Table 2); the low standard errors indicate small variability among replicates for both measurement protocols. Comparing the parameters one by one, large differences between methods can be noticed, for instance, the θ_s values estimated by the PPA were on average 28 % (±10 %) larger than those estimated by IME. Parameter θ_r was also consistently higher for the PPA method, especially for some fine-textured soils. Parameter α, related to the average pore size distribution, was constantly larger for the PPA, ranging between 2.8-5.1 m^{-1} for coarse-textured soils (sites 1-3) and between 2.9-18.2 m^{-1} for fine-textured soils (sites 4-9), while for the IME, it ranged from 2.0 to 2.7 m^{-1} and from 0.8 to 1.8 m^{-1} for coarse and fine-textured soils, respectively. The *n* parameter, which responds for the curve slope, showed less pronounced differences, with PPA producing higher fitted values for almost all soil layers, regardless of texture.

According to independent dewpoint measurements from the five selected soils, only samples from the coarse-textured soil reached equilibrium at pressure head -150 m, with little deviations between equilibration times. On the other hand, all other soil samples remained far above the applied -150 m pressure head for the three equilibration times, ranging from -32 to -68 m for the fine- and medium-textured soils, respectively (Figure 1).

The water retention curves of soils 2, 4, 6, and 9 obtained by PPA and by IME fitted to the van Genuchten (1980) analytical equation are shown in figure 2 together with independent tension measurements (Figure 1) performed by the dewpoint device. Regarding the curve shape differences, in general, the results for the other soils/layers produced by the two measurement protocols (PPA and IME) were similar to those presented in figure 2.

The curves obtained by the two protocols agreed well for intermediate tensions, with some remarkable differences near saturation and at the dry branch, except for the coarse-textured soil (soil 2) that showed good agreement for the entire range of pressure heads. For the fine- and medium-textured soils, the discrepancy between the methods

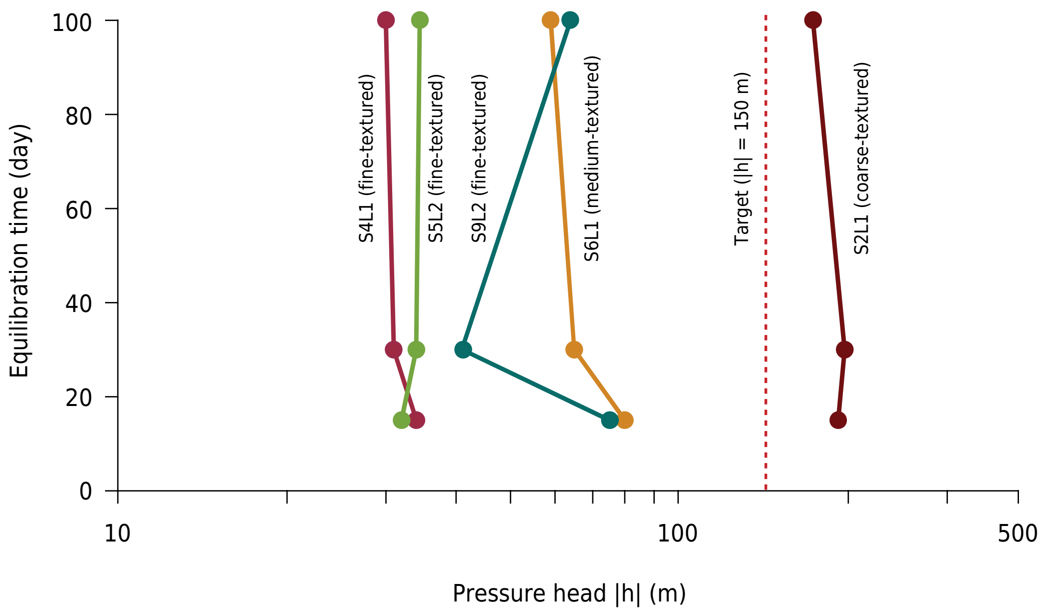

Figure 1. Pressure head measurements performed by the dewpoint device on soil samples allowing 15, 30, and 100 days of equilibration (open circles) in the pressure plate apparatus at pressure head -150 m.

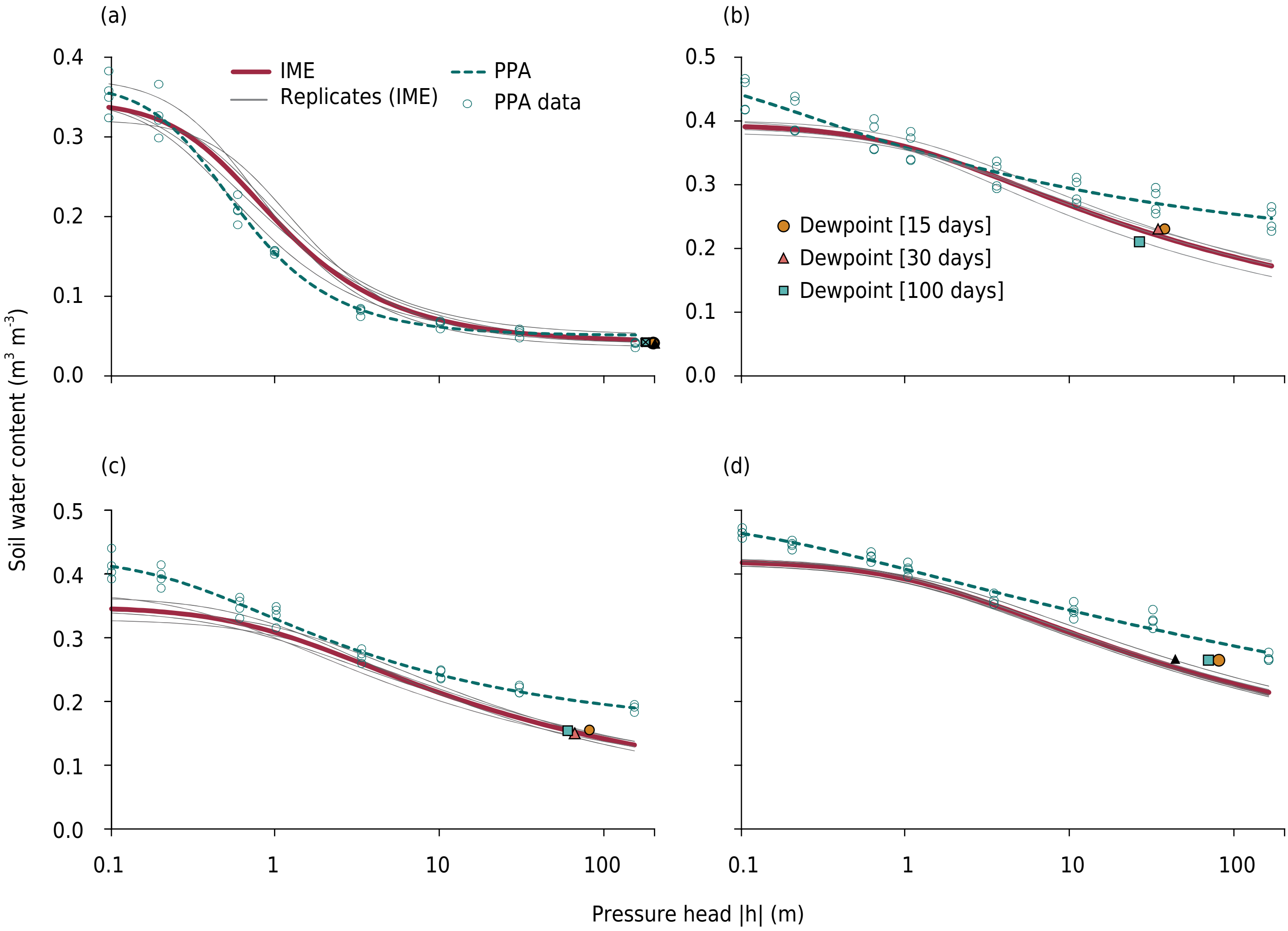

Figure 2. Water retention curves obtained by inverse modeling of a laboratory evaporation experiment (IME) and by tension table/pressure plate apparatus (PPA); together with dewpoint measurement data for different equilibration times. (a): site#4/layer#1); (b): site#6/layer#1; (c): site#2/layer#1); and (d): site#9/layer#2.

increased for pressure head below -10 m. The dewpoint measurements agreed well with the IME protocol, suggesting the previously reported lack of hydrostatic equilibrium of soil samples at pressure head -150 m for the PPA method (e.g., Cresswell et al., 2008; Bittelli and Flury, 2009; Solone et al., 2012).

Analogously to the results reported by Madsen et al. (1986) and Cresswell et al. (2008), the observed soil water contents for undisturbed (30 mm high) and disturbed (10 mm high) samples after equilibrating on a pressure plate apparatus at -150 m pressure head (Table 3), the differences in the final water content are small, indicating that given the facility of sampling, and the shorter time required for equilibrium (approximately one week), disturbed soil samples should be preferred for hydrostatic equilibrium attempts at -150 m pressure head in the pressure plate apparatus.

Effect on total and readily available water estimations

As the above results indicate, soil water contents determined in a pressure plate apparatus at low-pressure heads are plausibly overestimated, and in fact refer to higher (less negative) pressure heads than is supposed. This leads to a considerable underestimation of TAW (up to 33 %) for the fine- and medium-textured soils 4 to 9 (Figure 3).

When θ_{lim}, the lower limit of readily available water (RAW) is chosen closer to saturation, the difference between methods becomes smaller. This occurs because the lack of hydrostatic equilibrium affects mainly the dry range of the water retention curve. Figure 4 exemplifies this behavior in terms of readily available water based on two limiting pressure head values (-3 and -10 m) reported by Taylor and Ashcroft (1972). Accordingly,

Table 3. Average soil water content (from 5 replicates) with its standard deviation (SD) attained at pressure head -150 m for undisturbed samples equilibrated in the PPA, together with individual measurement using disturbed samples

Soil texture	Undisturbed samples		Disturbed samples
	$\bar{\theta}$	SD	θ
	$m^3 m^{-3}$		
Sandy loam	0.048	0.0052	0.039
Loamy fine sand	0.040	0.0027	0.043
Clay	0.246	0.018	0.226
Clay	0.240	0.015	0.228
Sand clay	0.188	0.0061	0.146
Sand clay	0.163	0.0079	0.158

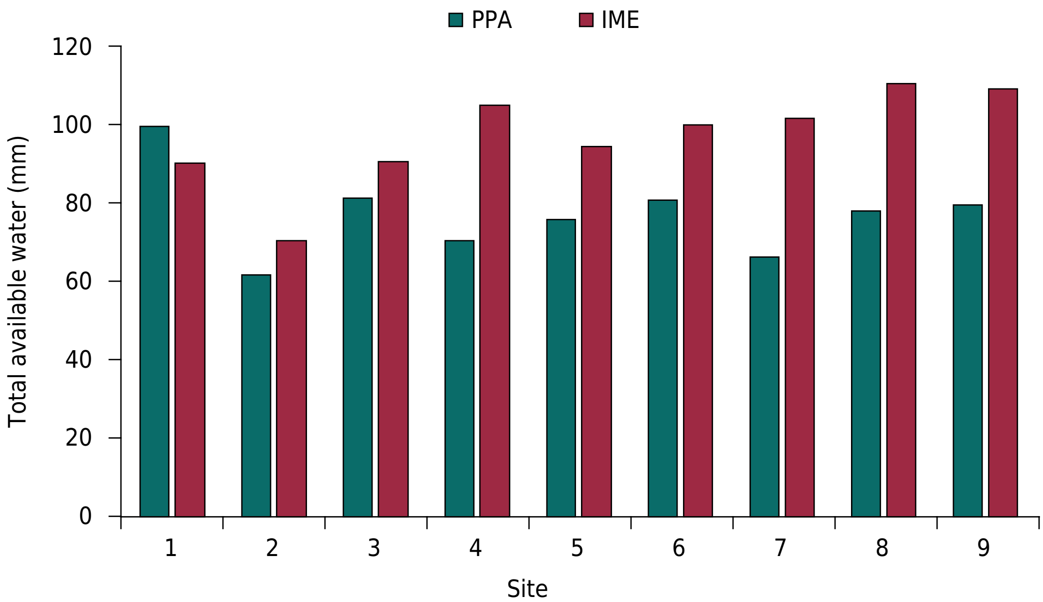

Figure 3. Total available water estimated for nine soils using the θ-*h* relations obtained by inverse modeling of a laboratory evaporation experiment (IME) and by the tension table/pressure plate apparatus (PPA).

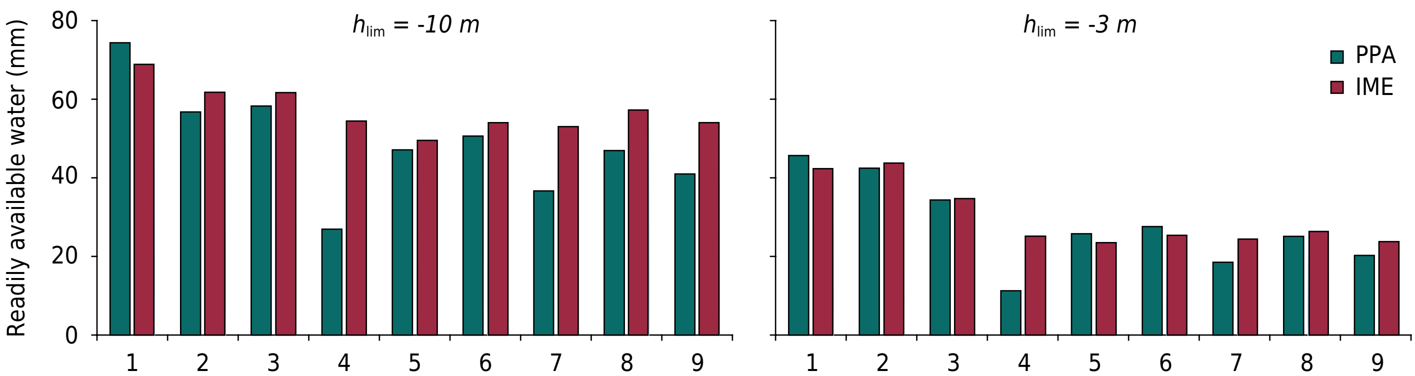

Figure 4. Readily available water estimated for the nine soils using the θ-*h* relations obtained by inverse modeling of a laboratory evaporation experiment (IME) and by the tension table/pressure plate apparatus (PPA) considering two pressure heads for the onset of drought stress (h_{lim}).

the adoption of RAW for irrigation timing criterion, instead of TAW, would reduce the negative effect of hydrostatic nonequilibrium of soil water retention parameterizations based on the PPA method; and the higher (less negative) the pressure head that defines the onset of drought stress, less important the difference between methods (PPA and IME) becomes.

DISCUSSION

Although a clear individual parameter difference between the two methods (PPA and IME) could be observed, it is important to highlight that soil water retention parameters can be highly correlated (Šimůnek et al., 1998), and as a result, individual comparisons between parameters may not identify their combined effect on dynamic simulations of soil water flow processes (Siltecho et al., 2015).

Many of the studies that dealt with the lack of hydrostatic equilibrium of the pressure plate apparatus method verified the hydrostatic nonequilibrium in the dry range of the retention curve with an additional method (usually a dewpoint device), while the wet range measurement protocol was always based on table tensions or sand boxes combined with pressure plates at low tensions (Madsen et al., 1986; Bittelli and Flury, 2009; Solone et al., 2012). Therefore, only deviations regarding nonequilibrium in the dry range are usually reported. However, the accurate description of retention curves in the wet range remains a challenge as well, partially due to regular failures in determining the soil water content close to saturation. In our study, the IME protocol allowed to obtain the complete retention curve from near saturation to wilting point, and for this reason, differences near saturation (θ_s) were reported between SWRC determination methods. As discussed in Pinheiro et al. (2019a), one plausible explanation for these results may be related to different sample size, for instance, saturation attained by soil cores (51.6 cm^3) used in the PPA was up to 10-15 % higher than of those (301 cm^3) used in evaporation experiments. As the samples used in the evaporation experiments are about 6 times larger in volume than PPA samples, they are more representative of field conditions, i.e., more prone to water repellency and dissolved or entrapped air (Pachepsky et al., 2001; Vereecken et al., 2010), thus reaching a saturation degree closer to the field conditions.

Regarding the dry range of SWRC, the dewpoint measurements agreed well with the IME protocol, suggesting the previously reported lack of hydrostatic equilibrium of soil samples equilibrated at pressure head -150 m for the PPA method (e.g., Cresswell et al., 2008; Bittelli and Flury, 2009; Solone et al., 2012). This lack of hydrostatic equilibrium, especially for fine-textured soils, has been related to drainage impediment, which is enhanced by low plate and soil conductance, poor soil-plate contact, sample height, and soil dispersion (Madsen et al., 1986; Bittelli and Flury, 2009; Solone et al., 2012; Silva et al., 2018). Besides these plausible explanations, the verification of equilibrium consisting of the empirical observation of water being expelled by the pressure plate apparatus is questionable. In the first place, even if water expelling is not observed, water may still be coming out at a rate lower than the evaporation rate. Furthermore, even if water expelling is observed, it may be due to a (small) temperature reduction in the laboratory, e.g., during the night, causing some water to condense in the vapor-saturated pressure chamber. Our results show a small influence of a larger equilibration time, in which the tension measurements performed by the dewpoint device for the 15-day interval were very similar to the measurements on samples allowed 100-day interval in the PPA. For some soils, the variation in measurements for distinct equilibration intervals was within the equipment accuracy of ±5 m for the tension measurement range of this study. In fact, Gee et al. (2002) demonstrated that for a low-pressure head (-150 m) complete hydrostatic equilibrium may take months or even years, mainly due to the decreasing soil hydraulic conductivity combined with low plate conductance.

The main reason that justifies the measurement of a SWRC is its ability, together with soil hydraulic conductivity functions, to predict key processes in the vadose zone when embedded in hydrological models. Accordingly, the errors related to the hydrostatic nonequilibrium of PPA data are likely transmitted to hydrological simulations and results interpretation. As numerically demonstrated by Solone et al. (2012), common pedotransfer functions based on SWRC obtained by the PPA method may provide flawed soil hydraulic properties, seriously biasing simulations of transient processes in the soil. Moreover, according to our results of total available water estimations, PPA errors can also add another source of variations to simulations of soil water balance components of large scales, usually performed by bucket-type models, in which soil water storage is bound between field capacity and wilting point.

Regarding crop available water, this quantity depends on soil hydraulic properties (both retention and hydraulic conductivity), crop specific properties, and climate variables. Therefore, quantities estimated by fixed limiting values, like those represented by total and readily available water, only represent a static status of soil water availability. However, these two proxies of soil water availability are of particular interest for irrigation management, in which the irrigation timing criterion is based on the depletion of total or readily available water. When this criterion is adopted, a minimum fraction of TAW or RAW is used to decide the time to irrigate, and when the proxies of soil available water are underestimated, the number of triggered irrigation events will be higher, increasing the unproductive water loss by runoff, deep drainage, and evaporation, with an overall negative effect on crop water use efficiency of the irrigation water.

For the purpose of this study, the concepts of TAW and RAW suffice as a straightforward example of how the lack of hydrostatic equilibrium of soil samples in the PPA may lead to erroneous estimation of these two largely used proxies of soil water availability (Kisekka et al., 2016; Minasny and McBratney, 2018; Kothari et al., 2019; Scarpare et al., 2019). Furthermore, for agro-hydrological simulations performed by process-based models, which are highly dependent on the soil hydraulic properties (K-θ-h), especially in the near-wilting range (De Jong van Lier et al., 2015), water retention curves of fine-textured soils fitted with PPA data may lead to faulty predictions of crop water demand due to poor simulations of crop drought stress, especially under dry conditions likely to occur in rainfed scenarios.

CONCLUSIONS

The two protocols for the determination of soil water retention properties compared in this study, the traditional method based on the assumption of hydrostatic equilibrium on a pressure plate apparatus, and the inverse modeling of transient conditions during a laboratory evaporation experiment, showed real pressure heads in samples on a pressure plate to be higher than assumed ones, leading to an overestimation of the soil water content at lower pressure heads, especially in fine-textured soil samples.

This result affects the reliability of most soil hydraulic databases, derived PTFs in the dry range, as well as the wilting point commonly used as lower bound of crop available water.

Attempts to estimate water availability based on static quantities, represented by total and readily available water, are more sensitive to the water retention measurement method when the chosen lower limits of available water are closer to the wilting point. In this sense, when pressure plates are used for the determination of soil water retention properties, irrigation timing criteria based on readily available water should be preferred over total available water, especially for fine-textured soils.

Consequently, given the low reliability of the pressure plate apparatus for high tensions, possibly biasing hydrological simulations and their interpretation, alternative measurement methods for the drier part of the soil water retention curve should be preferred, e.g. the proposed inverse modeling of evaporation experiments.

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