Scaling the Dependency of Soil Penetration Resistance on Water Content and Bulk Density of Different Soils

Carlos M. P. Vaz*
Embrapa Agricultural Instrumentation
P.O. Box 741
São Carlos, SP, 13560-970, Brazil

Juliana M. Manieri
Centro Universitário Central Paulista
UNICEP
São Carlos, SP, 13570-300, Brazil

Isabella C. de Maria
Instituto Agronômico de Campinas (IAC)
Campinas, SP, 13020-902, Brazil

Martinus Th. van Genuchten
Dep. of Mechanical Engineering
COPPE/LTTC
Federal Univ. of Rio de Janeiro
RJ, 21945-970, Brazil

and
Dep. of Earth Sciences
Utrecht Univ.
Budapestlaan 4
3584CD Utrecht, Netherlands

Although soil cone penetrometers have been used for decades to assess soil mechanical strength and evaluate soil compaction, the strong dependency of the penetration resistance (PR) on soil water content and soil type makes it difficult to compare field data that vary in space and time because of soil spatial variability, variable weather conditions, and implementation of varying soil and crop management practices. In this study we introduce and evaluate a procedure to normalize and scale PR data measured with a dynamic soil cone penetrometer in six Brazilian soil profiles having different soil textures. Data covered a wide range of water contents taken during both dry and wet seasons. Correlations between PR and measured volumetric water content (θ_v) and bulk density (ρ_b) data often display exponential type relationships that are known to depend on such soil properties as texture, mineralogy, and organic matter (OM) content. However, expressing θ_v and ρ_b as a function of scaled water contents and bulk densities significant reduced the influence of soil type and allowed a parameterization independent of soil texture. The obtained regression equation produced much lower root mean square deviation (RMSD) values for our dataset as compared to previously published equations for PR using pedotransfer function approaches. The proposed scaling approach seems very promising and should be tested and expanded to other classes of soils and databases.

Abbreviations: LVAd, "*Latossolo Vermelho Amarelo distrófico*" (Oxisol–Typic Hapludox); LVd, *Latossolo Vermelho distrófico*" (Oxisol–Rhodic Hapludox); LVdf, "*Latossolo Vermelho distroférrico*" (Oxisol–Rhodic Hapludox); NVef, "*Nitossolo Vervelho eutroférrico*" (Oxisol–Rhodic Eutrodox); OM, organic matter; PR, penetration resistance; PTF, pedotransfer function; PVAd, "*Argissolo Vermelho Amarelo distrófico*" (Ultisol–Typic Hapladult); RQo, "Entisol–*Neossolo Quatzarênico órtico*" (Quartzpsamment).

Soil PR as measured with a cone penetrometer is an important parameter in many soil management and geotechnical studies (Schneider et al., 2001; Whalley et al., 2008). Unfortunately, its strong dependence on soil type and such soil properties as volumetric water content (θ_v), soil matric potential (ψ), bulk density (ρ_b), porosity (ϕ), and OM content makes it difficult to compare data acquired at different times at a particular field site due to temporal variability in the water content, and from different sites due to spatial variability in texture and other soil properties.

To reduce the effect of water content on PR readings, it has been suggested to acquire the PR data at soil water contents close to field capacity (Smith et al., 1997), or to post-correct the data measured at different water contents to a reference PR at field capacity (Busscher, 1990; Busscher et al., 1997; Vaz et al., 2011). In a previous study, Vaz et al. (2011) showed that correcting PR readings to a common water content requires one to measure and model the penetrometer response as a function of water content or matric potential and bulk density over a significant range in values of these two parameters. They derived exponential equations for

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*Corresponding author (carlos.vaz@embrapa.br).

four Brazilian oxisols to correct PR readings obtained for a wide range of water contents (from close to saturation to wilting point) to PR values at field capacity (assumed to be the water content at a matric potential of −10 kPa), thus allowing better comparison of the PR data. However, the obtained regression equations were still soil dependent and could not be generalized. Post-correcting PR readings to a common water content value would require additional time-consuming experiments and fitting efforts (Busscher, 1990; Vaz et al., 2011).

Differences in observed PR values with changes in the water content and bulk density of different soils have been attributed mainly to the effects of soil texture, OM, and the soil water retention curve (Elbanna and Witney, 1987; Canarache, 1990; Smith et al., 1997; To and Kay, 2005; Whalley et al., 2007; Dexter et al., 2007; Silva et al., 2008; Vaz et al., 2011). However, it is expected that much of this variation could be reduced if the water content and bulk density were expressed as relative values. Canarache (1990), Whalley et al. (2007), and Dexter et al. (2007) used the degree of saturation and degree of compaction as relative parameters to better express the dependence of PR on water content or matric potential and bulk density. The soil bulk density (ρ_b) is known to be influenced by soil mineralogy, the particle density of the mineral fraction (sand, silt, clay), and the amount of OM, as well as by soil structure, aggregation, and total pore space. Hence, ρ_b can exhibit considerable variation in the field, ranging from <1 g cm^{-3} for organic and very fine-textured soils to about 2 g cm^{-3} or more for some coarse-textured, compacted soils, or soils high in iron oxides (Tomasella et al., 2000). At the same time, soil water content measurements alone have little meaning in many soil physical and geotechnical process studies if not combined with soil water potential data or expressed in terms of a normalized degree of saturation.

Based on these considerations we hypothesize that expressing PR as a function of relative or normalized bulk density and water content values could reduce considerably the effects of soil type on soil cone PR readings. The objective is to test the validity of this hypothesis by expressing PR as a function of relative bulk density and water content values for soils having different textures, and to compare the performance of this approach with other methods described in the literature.

MATERIALS AND METHODS

Soils Studied and Measurements

The soils used in this study are six Brazilian soils taken from the Embrapa Southeast Cattle Experimental Farm, São Carlos, São Paulo, Brazil (latitude: 21°57′42″ S longitude: 47°50′28″ W, elevation: 860 m). Soil classes according to the Brazilian, FAO, and Soil taxonomy are NVef: "*Nitossolo Vervelho eutroférrico*" (Oxisol–Rhodic Eutrodox), LVdf: "*Latossolo Vermelho distroférrico*" (Oxisol–Rhodic Hapludox), LVAd: "*Latossolo Vermelho Amarelo distrófico*" (Oxisol–Typic Hapludox), RQo: "Entisol–*Neossolo Quatzarênico órtico*" (Quartzpsamment), PVAd: "*Argissolo Vermelho Amarelo distrófico*" (Ultisol–Typic Hapladult), and LVd: "*Latossolo Vermelho distrófico*" (Oxisol–Rhodic Hapludox).

Table 1. Soil physical properties of six Brazilian soils.

Soil†	*NVef*	*LVdf*	*LVAd*	*RQo*	*PVd*	*LVd*
Sand, g g^{-1}	0.18	0.43	0.62	0.86	0.70	0.43
Silt, g g^{-1}	0.16	0.08	0.06	0.06	0.06	0.10
Clay, g g^{-1}	0.66	0.49	0.32	0.08	0.24	0.47
OM, g dm^{-3}	39	54	31	11	23	37
ρ_b, g cm^{-3}	1.13	1.38	1.48	1.61	1.55	1.28
ρ_p , g cm^{-3}	3.05	3.02	2.73	2.64	2.68	2.90

†OM: organic matter content, ρ_b: bulk density, ρ_p: particle density.

The experiments were conducted over an 8-mo period (January to August 2007) to cover soil water conditions from very dry to very wet. Measurements included the PR, bulk density, and water content at each 5 cm in the soil profile (12 points from the 0- to 60-cm depth) at different times (ranging from three measurements for soils NVdf and LVd to six samplings for soils LVef and LVAd). Samples from each soil were taken from a relatively small plot (10 × 10 m) to avoid texture variability within the soil. Temporal variability due to sampling at different times of the year (wet and dry seasons) and the natural spatial variability of each soil profile (0 to 60 cm deep) provided the variability necessary to model PR as a function of ρ_b and θ_v. The data presented express these variabilities, which are necessary for the fitted equation to represent the large variations generally found for these parameters in the field.

The cone PR was measured with a dynamic hammer penetrometer (Kamaq, model IAA/Stolf, Araras, Brazil), and the bulk density and water content by sampling undisturbed soil samples (steel rings, 5 cm diam., 5 cm long). Accuracy of the soil penetrometer apparatus was about ± 0.1 MPa. More details about the experimental setup, the soil properties, and the PR, ρ_b and θ_v dataset in general are given by Vaz et al. (2011). Some physical properties of the soils are presented in Table 1. Soil textures ranged from very coarse (86% sand for soil RQo) to very fine (66% clay for the NVef soil), while the silt and OM contents were relatively low.

Bulk Density and Water Content Maximum and Minimum Values

Maximum bulk densities (ρ_{bmax}) were determined by means of a mini-proctor test (Cozzolino and Nogami, 1993) on samples having five different gravimetric water contents and submitted to compaction using a 2.27-kg steel cylinder falling from 30.5 cm (six drops). Minimum soil bulk densities (ρ_{bmin}) were set to the lowest value measured in the field for each soil type at the locations where the samples were taken. Values of the normalized soil bulk density (ρ_b*) were then calculated using the expression.

$$\rho_b^* = \frac{\rho_b - \rho_{b\min}}{\rho_{b\max} - \rho_{b\min}} \quad [1]$$

Undisturbed soil samples collected at depths of 5 to 10 cm, 20 to 25 cm, 35 to 40 cm, and 50 to 55 cm for each soil type were used to obtain the soil water retention curves by using tension table (−0.1, −2, −4, −8, and −10 kPa) and pressure chamber (−33,

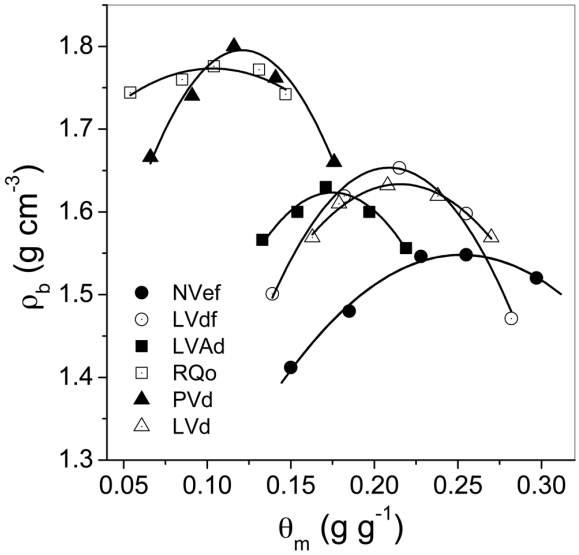

Fig. 1. Mini-Proctor tests (DER-M191/88) for estimating the maximum soil bulk density (ρ_{bmax}) of six Brazilian soils.

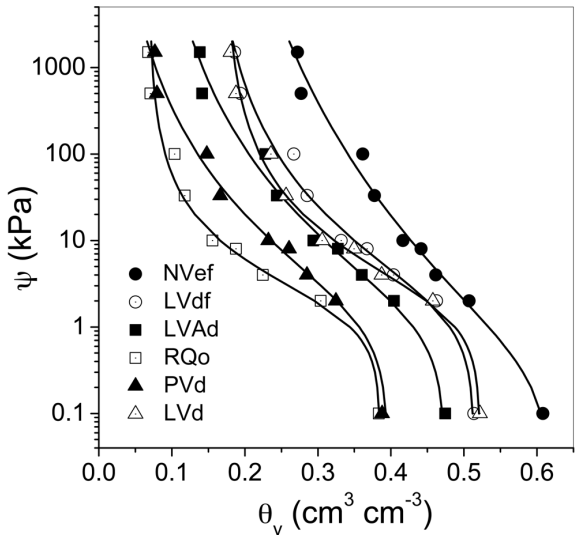

Fig. 2. Soil water retention data of the six Brazilian soils used in this study. Solid lines represent the fitted van Genuchten retention functions.

−100, −500, and −1500 kPa) methods. The acquired retention data (ψ versus θ_v) were averaged over each profile and fitted with the soil water retention function of van Genuchten (1980). For the normalized water content (S_p) we scaled measured values between the saturation (θ_s) and the permanent wilting point (θ_p) at −1500 kPa as follows:

$$S_p = \frac{\theta_v - \theta_p}{\theta_s - \theta_p} \qquad [2]$$

Normalization of Penetration Resistance Data

Vaz et al. (2011) showed that the PR of four of the soils (Oxisols) used in this study could be described better with an exponential function of ρ_b and θ_v, first proposed by Jakobsen and Dexter (1987), as compared to many other regression equations previously used for this purpose. Although good descriptions were obtained for each soil individually, the fitting parameters were soil dependent and no general equation could be obtained for all soils combined. Here we test a more general equation to describe the PR dependency on ρ_b and θ_v:

$$PR = \exp\left(a + b\rho_b^* + cS_p\right) \qquad [3]$$

where a, b and c are fitting parameters, and where ρ_b^* and S_p represent the normalized bulk density and water content as defined by Eq. [1] and [2], respectively.

Equation [3] was fitted to the experimental dataset (312 points of PR, ρ_b^* and S_p for the six soils) using the nonlinear least squares parameter optimization software of Wraith and Or (1998). Standard errors of the fitting Parameters a, b and c were obtained with the bootstrap method (Efron and Tibshirani, 1993) using 20 random samplings. The significance of the root mean square deviation (RMSD), used as the goodness-of fit for the proposed procedure based on Eq. [3] and the other equations and models proposed in the literature, was evaluated using paired t tests.

RESULTS AND DISCUSSION

Results from the mini-proctor tests used to obtain estimates of the maximum bulk density (ρ_{bmax}) are presented in Fig. 1. Final bulk density values after compaction are plotted as a function of the mass based water content (θ_m) of the soil samples. The data were fitted with a second-order polynomial equation (solid lines), which allowed us to estimate the ρ_{bmax} values directly from the fitted equations.

Measured and fitted soil water retention curves of the six soils are presented in Fig. 2. Good descriptions of the data were obtained over the range of measured retention data between saturation and the permanent wilting point at 1500 kPa. However, except for the very coarse RQo soil, no unambiguous estimates could be obtained for the residual water content (θ_r) because of a lack of data in the very dry range. For this reason we used the permanent wilting point (θ_p) in our scaled water content (S_p), rather than θ_r.

Values of ρ_{bmax} as estimated from the proctor tests, ρ_{bmin} as measured in the field, and the water contents at saturation (θ_s) and the permanent wilting point (θ_p) are presented in Table 2. Differences $\Delta\rho$ between ρ_{bmax} and ρ_{bmin} tended to increase as the clay and silt contents of the soils increased due to the higher compressibility of these soil fractions, while differences $\Delta\theta$ between θ_s and θ_p were very similar for our soils.

Table 2. Values of the maximum bulk density (ρ_{bmax}), minimum bulk density (ρ_{bmax}), the difference in bulk density ($\Delta\rho$), the water contents at saturation (θ_s) and the wilting point (θ_p), and the differences in water content ($\Delta\theta$) for each soil studied.

	NVef	*LVdf*	*LVAd*	*RQo*	*PVd*	*LVd*
ρ_{bmax}, g cm^{-3}	1.55	1.65	1.62	1.77	1.80	1.64
ρ_{bmin}, g cm^{-3}	0.97	1.20	1.34	1.46	1.40	1.16
$\Delta\rho$†	0.58	0.45	0.28	0.31	0.40	0.48
θ_s, cm^3 cm^{-3}	0.62	0.53	0.47	0.39	0.42	0.55
θ_p, cm^3 cm^{-3}	0.28	0.19	0.13	0.07	0.09	0.18
$\Delta\theta$†	0.34	0.34	0.34	0.32	0.33	0.37

†$\Delta\rho = (\rho_{bmax} - \rho_{bmin})$, $\Delta\theta = (\theta_s - \theta_p)$.

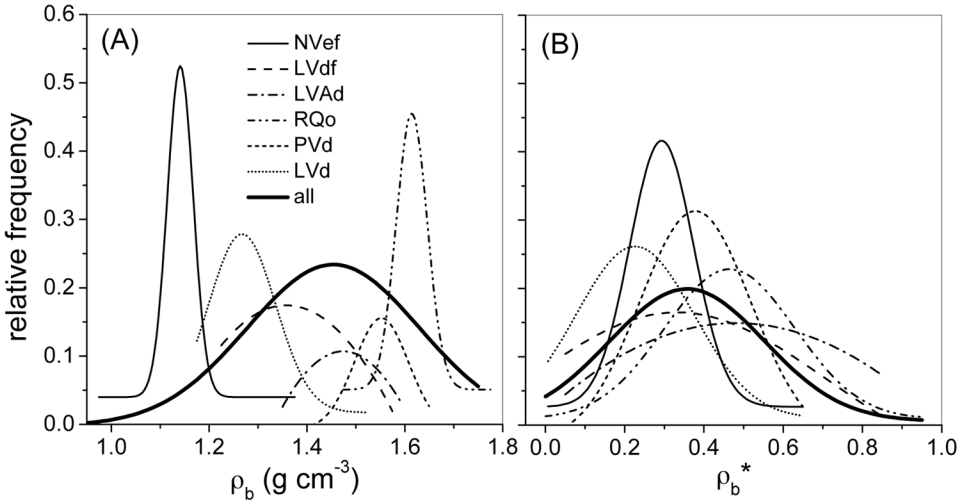

Fig. 3. Frequency distribution (Gaussian fit) of the measured bulk density (A) and their normalized values (B) according to Eq. [1], for each soil.

The frequency distributions of the measured ρ_b and θ_v values (Fig. 3A and 4A, respectively) displayed substantial variability among the six soils. This variability is a direct consequence of considerable differences in the particle density (caused by large variations in the iron oxide content) and its effect on ρ_b, and in soil texture and OM content, which affect especially θ_v. After converting ρ_b and θ_v to normalized values using Eq. [1] and [2], respectively, the variability in the frequency distributions among the soils reduced substantially as expected (Fig. 3B and 4B). The bi-modal distributions of the water contents in Fig. 4A and 4B are due to the data being collected in different periods of the year (wet and dry).

Soil PR values measured during the experiments for all soils are plotted against the volumetric water content and bulk density in Fig. 5A and 6A, respectively. The plots show similar behavior of PR with ρ_b and θ_v for all soils, notably an exponential decay of PR with θ_v and an increase in PR with ρ_b. However, the changes occur in different parts of the water content and bulk density axes due to the effects of particle density and mineralogy on ρ_b, and texture and OM on θ_v, as mentioned earlier. The continuous and segmented lines in Fig. 5A were obtained by fitting an exponential equation similar to Eq. [3] to the data, but using ρ_b and θ_v instead ρ_b* and S_p. The plots in Fig. 5A were obtained using the average ρ_b values of each soil as listed in Table 1. A good example illustrating the considerable variability in relationships between PR with θ_v or ρ_b among the different soils is the water content at a PR of 2.5 MPa. These water contents were 0.16, 0.27, 0.31, and 0.43 cm^3 cm^{-3} for soils RQo, LVAd, LVdf and NVef, respectively, which suggests that no unique relationship should be expected between PR and θ_v. We further note that the observed bi-modal distributions of the water content in Fig. 4A and 4B explain the two clusters delimitated in Fig. 6A.

Converting ρ_b and θ_v to their relative values (ρ_b* and S_p) did group the data and reduced the variability among soils as can be observed in Fig. 5B and 6B. Equation [3] fitted to the experimental data by least square optimization (Wraith and Or, 1998) provided the coefficients *a*, *b* and *c* shown in Table 3. Fitting the data from all soils combined produced the following general equation:

$$PR=\exp\left[1.50(\pm0.06)+2.18(\pm0.09)\rho_b^*-4.00(\pm0.16)S_p\right] \quad [4]$$

The lines in Fig. 5B and 6B were obtained with Eq. [4] using different values (0, 0.25, 0.5, and 1) for ρ_b* and S_p, respectively. The lines for the scaled ρ_b* and S_p values of 0 and 1 provide clearly defined envelopes for the experimental PR data. This suggests that the normalization expressions given by Eq. [1] and [2] are effective in providing a general relationship between PR, ρ_b and θ_v, by reducing the effects of soil type (especially texture, OM content, and mineralogy) on PR response. Other, more simple normalization expressions such as ρ_b/ρ_{bmax}, ρ_b/ρ_{pmin} and θ/θ_s were also tested, but their RMSD values as obtained for all soils combined were always much higher than those based on the normalizations given by Eq. [1] and [2]. Still, we note that one obvious disadvantage of Eq. [1] and [2], as compared to the simpler scaling expressions, is the need to determine the four parameters ρ_{bmax}, ρ_{bmin}, θ_s, and θ_p for each soil.

Other studies have also proposed soil-independent or general equations to express the dependence of PR on θ_v, θ_m, ψ, and/or ρ_b. As summarized by Vaz

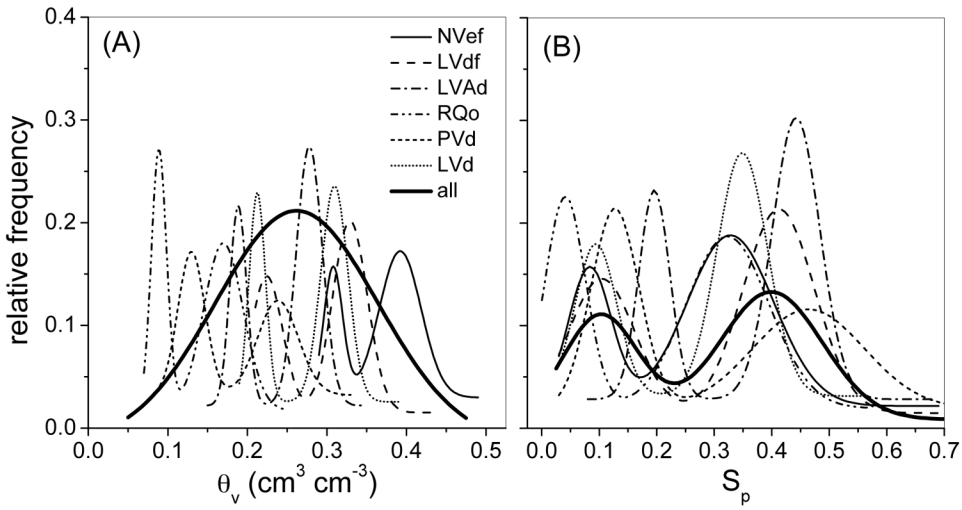

Fig. 4. Frequency distribution (Gaussian fit) of the measured volumetric water content (A) and of their normalized values (B) according to Eq. [2], for each soil.

et al. (2011), most of these studies used the soil clay and OM contents in attempts to reduce the variability in PR response among soils. Elbanna and Witney (1987) suggested using the clay ratio [clay/(1− clay)] to reduce the effect of soil type on the PR, θ_v, ρ_b relationships. Using classical bearing capacity theory, they proposed a general cone PR equation to represent the variability in cohesion and friction angle by means of the clay ratio and θ_m. Canarache (1990) proposed the use of relative mass water content and degree of compaction, and fitted coefficients related to the soil bulk density and clay content. Specific relationships were obtained for a relatively large database consisting of soils from different countries in Europe and the United States. Pedotransfer functions (PTFs) were generated by Whalley et al. (2007) for PR as a function of θ_v, ρ_b, and σ_w, where σ_w is a component of soil strength (or total stress) associated with soil water stress (i.e., $\sigma_w = S\psi$, for $S > 0.5$, where $S = \theta_v/\theta_s$), while Silva et al. (2008) obtained PTFs for PR as a function of θ_v, ρ_b, and clay fraction.

We evaluated the performance of the generalized equations proposed by Elbanna and Witney (1987), Whalley et al. (2007), and Silva et al. (2008) using our current dataset, thus providing another measure for judging the accuracy of Eq. [4]. We did not use the equations proposed by Canarache (1990) because of a possible inconsistency in one of their equations (i.e., the coefficient "*m*" as a function of ρ_b and clay content). Table 4 compares RMSD values obtained for the various models. The best performance (lowest RMSD) for our dataset was obtained with the scaling procedure inherent in Eq. [4]. The lowest RMSD value (1.82 MPa) of the PR obtained using the normalized parameters S_p and ρ_b* was about half of the RMSD (3.55 MPa) obtained with the original (non-normalized) parameters θ_v and ρ_b.

It is interesting to note that the expression suggested by Whalley et al. (2007), which uses the soil strength component σ_w instead of the water content, produced the lowest RMSD (2.37 MPa) when fitted with the non-normalized parameters, and the second lowest RMSD (2.22 MPa) when fitted with the normalized ρ_b* parameter. This was possible since σ_w, as used by Whalley et al. (2007), is essentially already a normalized parameter. A significance test performed using the paired *t* test showed that the RMSD produced with Eq. [4] was statistically different from Elbanna and Witney (1987) and Silva et al. (2008),

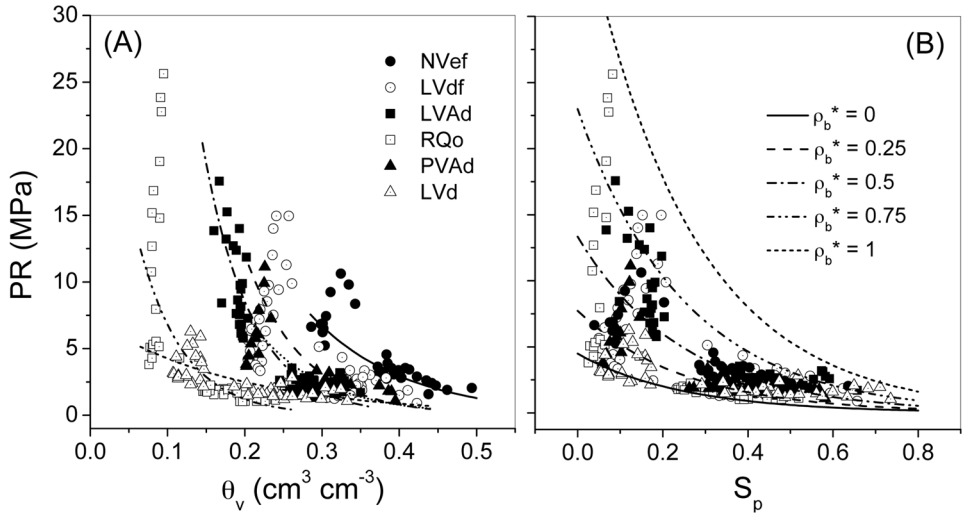

Fig. 5. Plots of field-measured PR values as a function of the volumetric water content, θ_v (A) and the normalized water content or degree of saturation, S_p (B) for each soil. Lines in both graphs were obtained with Eq. [4] assuming specific values for ρ_b in A and ρ_b* in B.

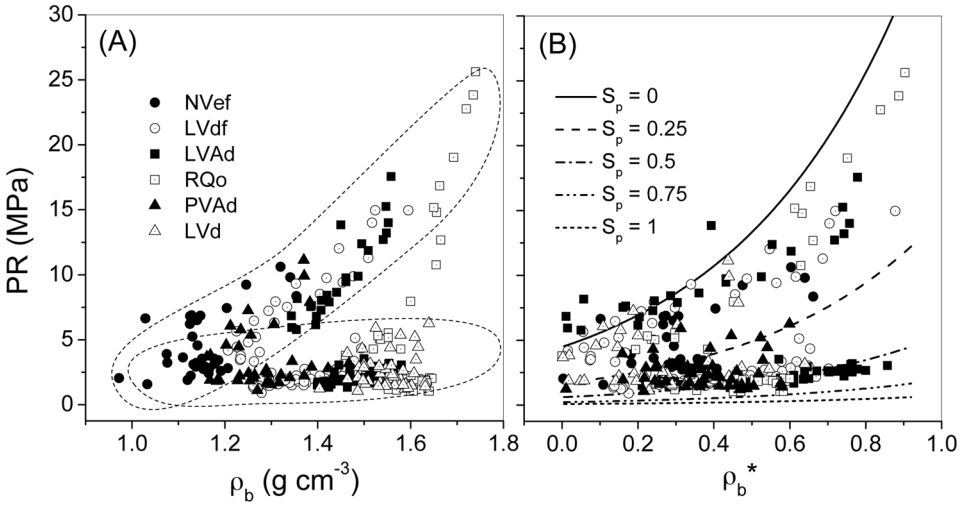

Fig. 6. Plots of field-measured PR values as a function of bulk density, ρ_b (A) and the normalized bulk density, ρ_b* (B) for each soil. Lines were obtained with Eq. [4] assuming specific values of the degree of saturation, S_p.

Table 3. Fitting coefficients (*a*,*b*,*c*) and root mean square deviation (RMSD) and determination coefficient (r^2) values obtained by least squares optimization for each soil separately and all soils combined.

Soil	PR = exp(*a* + *b* ρ_b* + *c* S_p)					
	a	b	c	RMSD	r^2	N†
NVdf	1.59	1.72	−2.79	0.59	0.94	36
LVef	1.71	2.28	−4.61	0.79	0.95	72
LVAd	2.83	0.84	−5.43	1.01	0.94	72
RQo	1.05	2.87	−5.52	1.06	0.97	48
PVd	1.24	0.63	−1.88	0.89	0.50	48
LVd	1.76	2.02	−4.23	0.99	0.82	36
all	1.50	2.18	−4.00	1.82	0.79	312

† N: number of points measured (12 points in the soil profile from 0 to 60 cm multiplied by the number measurement at different days) and used for the least squares analyses.

Table 4. RMSD values of the estimated PR for the scaling procedure given by Eq. [4] and the PTFs of Elbanna and Witney (1987), Whalley et al. (2007) and Silva et al. (2008) for the original (θ_v, θ_m, σ_w, ρ_b, and γ) and normalized (S_p and ρ_b*) parameters.

Model	Parameters†	RMSD (MPa)	
		Non-normalized	Normalized
Equation [4]	θ_v, ρ_b	3.55	1.82[a]
Elbanna & Witney (1987)	θ_m, γ, C_r	3.35	3.05[c]
Whalley et al. (2007)	σ_w, ρ_b	2.37	2.22[ab]
Silva et al. (2008)	θ_v, ρ_b, clay	3.11	2.34[b]

† γ: soil specific weight (kN m^{-3}); C_r: clay ratio; σ_w: effective stress ($\sigma_w = S\psi$, where $S = \theta_v/\theta_s$), significance level of 0.05 using the paired *t* test

but not statistically different from Whalley et al., 2007 (Table 4). A disadvantage of the PTF by Whalley et al. (2007) is the need to measure the matric potential, which is generally more difficult and time consuming to obtain in the field than the volumetric or mass water content. The expression suggested by Silva et al. (2008) provided similar RMSD values as the equation of Whalley et al. (2007) for the normalized S_p and ρ_b* parameters, while the equation proposed by Elbanna and Witney (1987) did not work well for our particular dataset using either the non-normalized or normalized parameters. Figure 7 compares measured PR values with estimated values using Eq. [4] and the models of Whalley et al. (2007), Silva et al. (2008) and Elbanna and Witney (1987).

The fact that the RMSDs decreased when the clay content or clay ratio was included in the calibration for the non-normalized parameters (Table 4) in the models of Elbanna and Witney (1987) and Silva et al. (2008) shows that clay content has an effect on PR readings. However, in terms of importance, the water content (or matric potential) seemed to be the most sensitive parameter affecting PR as reflected by the fitted values of the coefficients *a*, *b*, and *c* in Eq. [3] listed in Table 3. The value of *c* was about two times larger than *b*. Such a comparison of the coefficients is possible only because the parameters θ_v and ρ_b, were both normalized (in S_p and ρ_b*) to values between 0 and 1. Figure 8A shows the measured PR data for all soils plotted against S_p, with the data separated into two groups: data for ρ_b* < 0.36 and data for ρ_b* > 0.36. Figure 8B shows similar plots of the PR data versus ρ_b*, with the experimental data grouped in S_p < 0.23 and S_p > 0.23. The continuous and segmented lines were obtained with Eq. [4] fitted using the average values of ρ_b* and S_p of the two groups depicted in Fig. 8A and 8B, respectively. The two graphs encapsulate very well the relatively good fits obtained with Eq. [4] for our dataset.

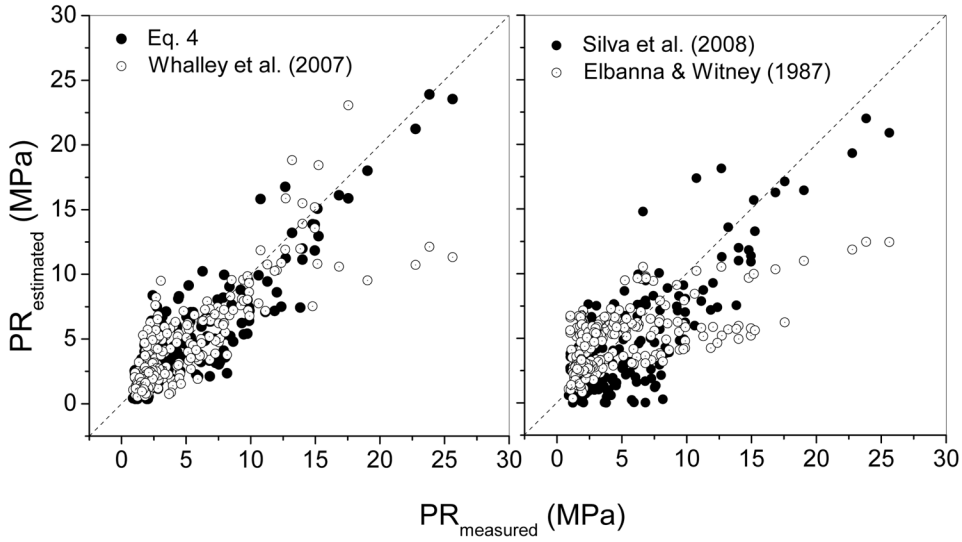

Fig. 7. Comparison of penetration resistances estimated with Eq. [4], those estimated by Whalley et al. (2007), Silva et al. (2008), and Elbanna and Witney (1987), with measured values.

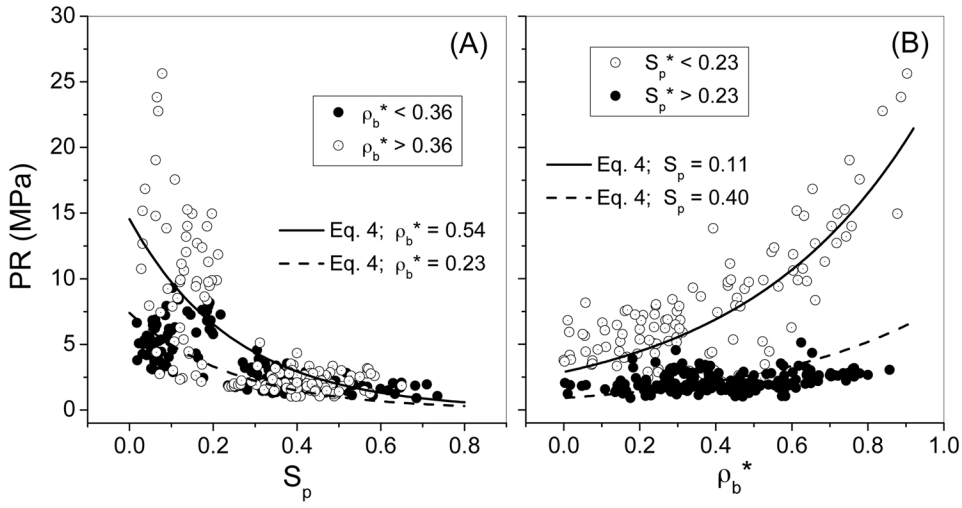

Fig. 8. Plots of PR as a function of the normalized water content, S_p (A) and normalized bulk density, ρ_b* (B) for all soils. The data are divided in two groups of ρ_b* (A) and S_p (B) according to the distributions shown in Fig. 3B and 4B, respectively. Continuous and segmented lines were obtained with Eq. [4] using specific values of ρ_b* and S_p, representing the average of the two groups.

The lowest RMSD value (1.8 MPa) of the PR in Table 4 was obtained using the normalized Eq. [4]. This value of 1.8 MPa seems high considering, for instance, that a PR value of 2.5 MPa is already known to restrict root elongation (Whalley et al., 2007). However, it is important to note that the field-measured PR values ranged from about 1 to 25 MPa, with a mean value of 4.2 MPa. Hence if the RMSD is used as a goodness of fit criterion, its value also reflects the difficulty of estimating very high PR values accurately. When Eq. [4] was fitted to each soil individually, the average RMSD was only about 0.9 MPa, half the value obtained when grouping all soils together. This suggests that other soil

properties (such as clay type) should have been included in the scaling procedure, or perhaps that the normalized Eq. [1] and [2] could be refined further, for example by finding better ways of defining and estimating the reference parameters (ρ_{bmax}, ρ_{bmin}, θ_s, and θ_p) in these equations. The parameters ρ_{bmax}, θ_s, and θ_p were determined using standard tests or procedures, but ρ_{bmin} was simply equated to the lowest field measurement for each individual soil. Developing a standard test for ρ_{bmin} may well improve the proposed scaling or normalization procedure.

Once a general equation relating PR with ρ_b^* and S_p is established, such as our Eq. [4], it is possible to normalize PR measurements performed at different water contents to the PR at a certain reference water content. This will permit a much more effective comparison of the PR measurements versus depth or over a season with variable moisture conditions. Since the water content at field capacity seems to be a very convenient reference value for such normalization (Vaz et al., 2011), the problem reduces to finding the reference S_p value equivalent to θ_v at field capacity (i.e., $S_{p\text{-}fc}$). That reference water content value can be found immediately from the retention functions shown in Fig. 2, after which Eq. [4] is used for the normalization to that reference value. Table 5 presents values of S_p when the field capacity (the water content at −10 kPa) is used as the reference point, as well as average S_p values and values of the two peaks in Fig. 4B representing data obtained during the dry and wet seasons. Substituting the average value of $S_{p\text{-}fc}$ = 0.434 in Eq. [4] and using measured ρ_b^* values thus allows determining the normalized PR values for each point.

As an example, PR values measured in the six soil profiles (0–60 cm) at three different times, one time in the dry season and two times in the wet season, and their normalized values are presented in Fig. 9. After normalization, the very high values of PR measured during the dry season (up to 25.6 MPa) were reduced, as expected, to very similar, relatively small values typical of wet seasons. The results in Fig. 9 show that normalization leads to a very

Table 5. Average and peak values of the frequency distribution of saturation S_p (as obtained from Fig. 4B) and their values at −10 kPa (assumed to be field capacity) $S_{p\text{-}fc}$.

Soil	S_p			
	peaks		average	$S_{p\text{-}fc}$
NVdf	0.085	0.328	0.277	0.432
LVef	0.104	0.414	0.311	0.465
LVad	0.196	0.443	0.360	0.521
RQo	0.041	0.324	0.232	0.297
PVd	0.127	0.460	0.338	0.436
LVd	0.094	0.348	0.286	0.454
all	0.104	0.399	0.307	0.434

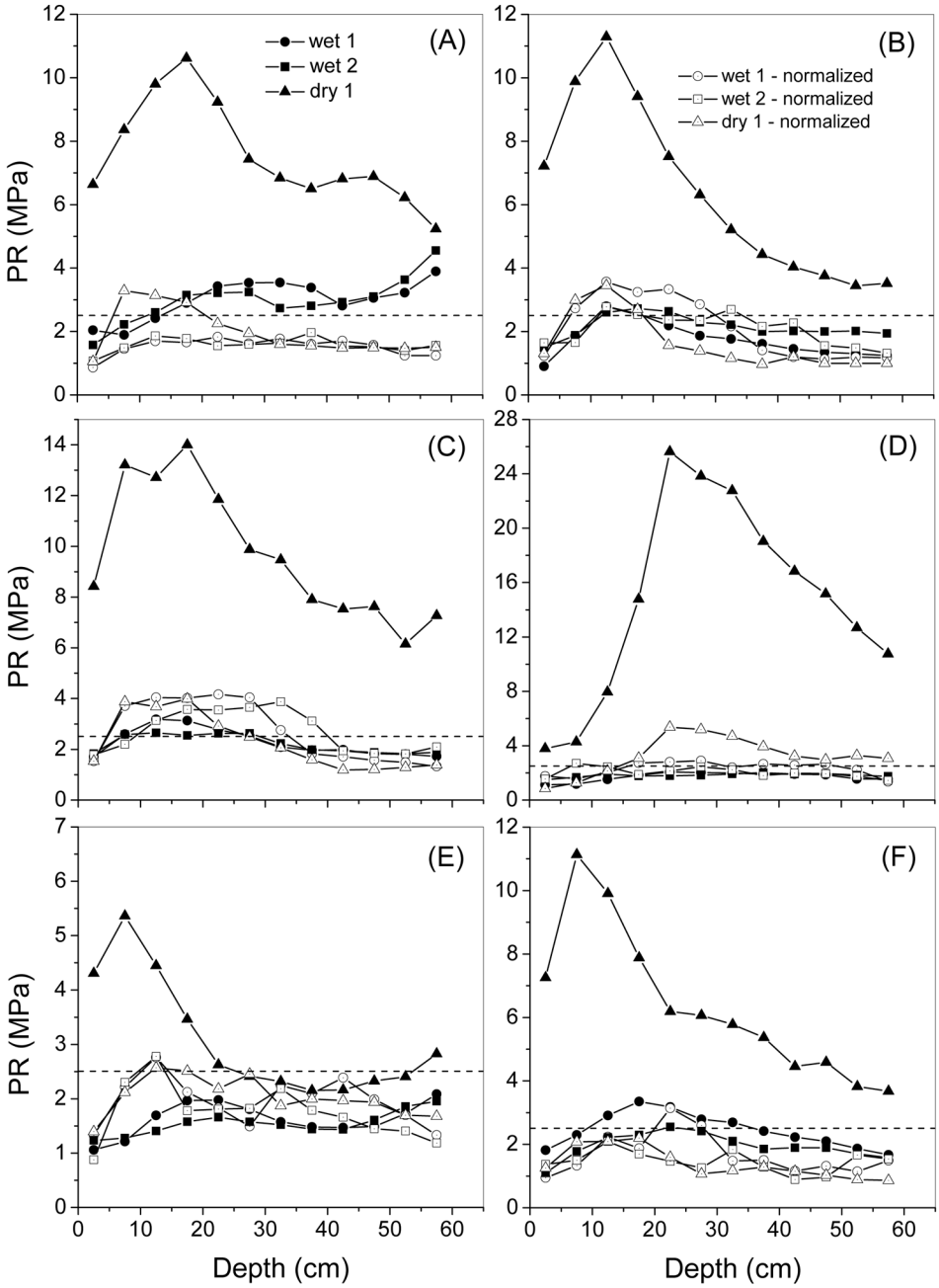

Fig. 9. Values of the penetration resistance (PR) measured in different periods of the year (dry 1, wet 1, wet 2) along vertical profiles of soils NVef (A), LVdf (B), LVAd (C), RQo (D), PVAd (E), and LVd (F), and their values normalized to field capacity. Solid symbols represent the original data and open symbols the normalized data.

Table 6. Statistics of the original field measured PR data and their values after normalization using Eq. [4].

	PR (MPa)	
	Original	Normalized†
Minimum	0.9	0.9
Maximum	25.6	5.4
Mean	4.2	2.1
SD	3.9	0.9
CV (%)	94	42
% > 2.5 MPa	53	25

† Normalized to PR at field capacity (-10 kPa); SD: standard deviation; CV: coefficient of variation.

effective comparison of data acquired in different periods of the year. Table 6 shows some statistics of the PR distributions before and after normalization. Normalization to field capacity caused the mean PR value to be reduced from 4.2 to 2.1 MPa, which is now lower than the critical PR value of 2.5 MPa for healthy root development. The standard deviation, the coefficient of variation and the percentage of measured points with PR values above 2.5 MPa (the critical value) are also reduced considerably using our normalization procedure.

SUMMARY AND CONCLUSIONS

Soil cone PR field measurements were performed on six different Brazilian soil profiles showing considerable variations in the water content (θ_v) and bulk density (ρ_b). The data were fitted with an exponential function containing normalized water content (S_p) and bulk density (ρ_b*) parameters. The normalized equation proved to be very effective in reducing the effects of θ_v and ρ_b on PR resulting from large variations in the soil texture, OM content, particle density and transient soil moisture conditions.

The use of relative values of bulk density (ρ_b*) and water content (S_p) seems to be a very promising approach for deriving soil-independent expressions for PR. The expressions may be used also to correct PR measurements taken at different times or conditions to a reference value. The approach helps to better understand the influence and importance of bulk density and water content on PR response, and should be an attractive alternative to existing PTFs that relates PR to bulk density, water content, clay content, OM, cation-exchange capacity, and/or other parameters. The general equation, given by Eq. [4] in this study, and the one proposed by Whalley et al. (2007), performed better than previously published equations by Elbanna and Witney (1987) and Silva et al. (2008).

While the proposed normalization equations worked very well for our database, further improvements may be possible by developing a standard test for estimating the lower limit of the bulk density (ρ_{bmin}) for each soil. Also needed is extension of the approach to other soils with a greater variation in texture, mineralogy and OM to evaluate its more general validity. Unfortunately, most PR data currently available in the literature do not provide all parameters necessary for the scaling approach, such as PR, ρ_b, θ_v, ρ_{bmax}, ρ_{bmin}, θ_s, and θ_p. This suggests that additional experiments may need to be performed for other soils. Alternatively, to facilitate application of the proposed approach, relationships between ρ_{bmax}, θ_s, θ_p, and the clay or sand contents perhaps could be derived using published data for a large variety of soils.

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