CORRECTION OF RESISTANCE TO PENETRATION BY PEDOFUNCTIONS AND A REFERENCE SOIL WATER CONTENT[1]

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SUMMARY

The soil penetration resistance is an important indicator of soil compaction and is strongly influenced by soil water content. The objective of this study was to develop mathematical models to normalize soil penetration resistance (SPR), using a reference value of gravimetric soil water content (U). For this purpose, SPR was determined with an impact penetrometer, in an experiment on a Dystroferric Red Latossol (Rhodic Eutrudox), at six levels of soil compaction, induced by mechanical chiseling and additional compaction by the traffic of a harvester (four, eight, 10, and 20 passes); in addition to a control treatment under no-tillage, without chiseling or additional compaction. To broaden the range of U values, SPR was evaluated in different periods. Undisturbed soil cores were sampled to quantify the soil bulk density (BD). Pedotransfer functions were generated correlating the values of U and BD to the SPR values. By these functions, the SPR was adequately corrected for all U and BD data ranges. The method requires only SPR and U as input variables in the models. However, different pedofunctions are needed according to the soil layer evaluated. After adjusting the pedotransfer functions, the differences in the soil compaction levels among the treatments, previously masked by variations of U, became detectable.

Index terms: pedotransfer functions, Oxisol, impact penetrometer, soil compaction.

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RESUMO: *CORREÇÃO DA RESISTÊNCIA À PENETRAÇÃO USANDO UMA UMIDADE DO SOLO DE REFERÊNCIA E PEDOFUNÇÕES*

A resistência do solo à penetração (SPR) é um dos principais indicadores do estado de compactação do solo; contudo, a SPR é altamente influenciada pelo conteúdo de água no solo. O objetivo deste trabalho foi desenvolver modelos matemáticos para a correção da SPR para um valor de umidade gravimétrica (U) de referência. Para isso, a SPR foi determinada, por meio de um penetrômetro de impacto, em um experimento instalado sobre um Latossolo Vermelho distroférrico, usando seis níveis de compactação do solo, obtidos por meio da escarificação mecânica e da compactação adicional, pelo tráfego de uma colhedora de grãos autopropelida (quatro, oito, 10 e 20 passadas), além de uma testemunha, a qual foi mantida sob sistema plantio direto sem escarificação ou compactação adicional. A fim de obter ampla variação nos valores de U, as avaliações da SPR foram realizadas em diferentes épocas. Amostras de solo com estrutura preservada foram coletadas para determinar a densidade do solo (BD). Foram geradas funções de pedotransferência relacionando os valores de SPR, de U e de BD. Usando essas funções, a correção da SPR foi satisfatória para todas as amplitudes de U e BD. O método requer apenas SPR e U como variáveis de entrada dos modelos. No entanto, são necessárias diferentes equações, em função da camada de solo avaliada. A aplicação das funções de pedotransferência, obtidas neste trabalho, permite observar diferenças no estado de compactação do solo entre os tratamentos, que antes não eram detectadas, em função de variações na U.

Termos de indexação: função de pedotransferência, Latossolo Vermelho, penetrômetro de impacto, compactação do solo.

INTRODUCTION

The soil compaction level can be assessed based on soil penetration resistance (SPR), which is determined by penetrometry. This method has some advantages, e.g., the easiness and speed in obtaining data; identification of compacted layers at different depths; and high correlation with plant root growth (Bengough et al., 2011).

Despite the advantages of using penetrometers, SPR varies directly in function of soil bulk density (BD) and inversely in function of soil water content (U) (Busscher, 1990; Bengough et al., 2001; Vaz et al., 2011). This fact limits comparisons of soils of the same type with different water contents, once a small reduction or increase in U results in a large increment or reduction of SPR (Vaz et al., 2011), leading to an under- or overestimation of the soil compaction level. Correlation between SPR and soil water content have already been exhaustively studied; nevertheless SPR depends on factors such as: soil management (Busscher et al., 1997); compaction level (Torres & Saraiva, 1999; Bengough et al., 2001; To & Kay, 2005; Almeida et al., 2008); organic matter content (To & Kay, 2005); and soil texture (Almeida et al., 2008; Vaz et al., 2011).

The most commonly used functions to express correlations between SPR and gravimetric soil water content (U) were the negative exponential (Almeida et al., 2008; Silveira et al., 2010) or negative power function (Busscher et al., 1997; Almeida et al., 2008; Silveira et al., 2010; Vaz et al., 2011) equations. Vaz et al. (2002) indicated that the ideal procedure would be to measure U together with SPR, and apply some type of correction or normalization for a reference value of soil water content afterwards. This procedure may reduce interpretation problems of results obtained under different field conditions and soil management systems (Busscher et al., 1997).

One of the earliest attempts to correct the values of SPR to a reference value of soil water content was performed by Busscher (1990), who adjusted regression equations using SPR, BD and U data. Busscher et al. (1997) developed a method to correct SPR as a function of U, based on the first term of a Taylor series. These authors, however, adjusted regression equations correlating SPR exclusively with U, without considering other variables, such as the soil compaction level. Thus, normalization of SPR to a reference value of U, through that method, implies in the use of different regression equations, in function of the soil management system. According to Almeida et al. (2008), the correction of SPR data needs several equations, based on different conditions of soil texture and BD.

A correction method, based on volumetric soil water content (θ), associated to the matric potential of -10 kPa, together with the procedure proposed by Busscher et al. (1997), was proposed by Vaz et al. (2011). These authors described the need to measure the BD together with the SPR to determine the θ values as a great disadvantage of the method. In this sense, Vaz et al. (2011) concluded that U-based models could be a less complex and laborious procedure of SPR correction.

The objective of this study was to develop a method from the procedure proposed by Busscher et al. (1997)

for a Rhodic Eutrudox, to correct SPR values to a reference value of U through pedotransfer equations that correlate SPR to BD and U.

MATERIAL AND METHODS

This study was carried out at the Experimental Station of Embrapa Soybean, in Londrina, State of Paraná, Southern Brazil (lat. 23º 11' S, long. 51º 11' W; 620 m asl). The experiment was carried out on a Dystroferric Red Latossol (Brazilian soil classification) (Santos et al., 2006), or Rhodic Eutrudox (American soil classification) (Soil Survey Staff, 2010), under no-tillage (NT) since 1996, with 731 g kg^{-1} clay, 146 g kg^{-1} silt, 123 g kg^{-1} sand, 18.50 g kg^{-1} organic carbon, and particle density of 2.96 Mg m^{-3} in the 0-20 cm layer. The average slope of the experimental area is 0.03 m m^{-1}.

To obtain the SPR correction equations as function of U, the variation range of the parameters used for their adjustment (SPR, BD, and U) must be wide enough. For this purpose, an experiment was established in rows in August 2010, using a completely randomized design, with two replications. The treatments were arranged in plots (2.5 x 20 m), consisting of six soil compaction levels: NT with recent chiseling (NTCh); NT without chiseling and no additional compaction (NT); and NT with additional compaction by harvester traffic at four intensities, induced by four (NTH4), eight (NTH8), 10 (NTH10), and 20 (NTH20) passes over the same track. The harvester used had a mass of 10.28 Mg and a tire-soil contact pressure of 0,23 MPa in the front axle. The soil chiseling was performed by using a 5-shank chisel plow, reaching a depth of 0.3 m.

Prior to the earliest SPR assessment and after treatment application, the whole experiment was irrigated (irrigation level 100 mm), in order to uniformize and raise U values to over 32.3 %, corresponding to the soil field capacity of the experimental area, determined at a matric potential of 0.01 MPa in a pressure plate apparatus (Embrapa, 1997). The SPR was measured in nine evaluations (two, three, four, seven, nine, 11, 14, 23, and 31days after irrigation) which, together with the lack of rainfall in the experimental period, widened the variation range of U values. The SPR was determined in the soil layers 5.5-10.5 and 13.5-18.5 cm, with an impact penetrometer (model IAAPlanalsucar-Stolf) (Stolf, 1991), using a 130 mm^2 base area and 30º circular stainless steel cone (Asabe, 2010). The SPR readings were performed at eight points, 15 cm away from each other, along a line (transect) transversal to the harvester track and chisel plow passes. In each assessment, two replications (transects) were used per compaction level. Next to each transect, two soil samples were collected (layers 5.5-10.5 and 13.5-18.5 cm), to determine U, according to Embrapa (1997).

Undisturbed soil samples were collected in stainless steel cores (height 5 cm x internal diameter 5 cm), horizontally inserted by means of a hydraulic jack, in the center of the layers 5.5-10.5 and 13.5-18.5 cm, on the wall of trenches opened in each plot. For each treatment and soil layer, 24 soil cores were sampled, totaling 288 samples. In the laboratory, these cores were analyzed for BD, and U equivalent to the soil field capacity (0.01 MPa) by means of a pressure plate apparatus (Embrapa, 1997). The permanent wilting point was determined in disturbed soil samples, according to the method described by Klein et al. (2006), using a thermocouple psychrometer (Decagon, model WP4-T).

The SPR values were adjusted to U values by an equation of the potential type used by Busscher et al. (1997). To facilitate later computations, the equation was linearized (Equation 1):

$$\text{RP} = b + a\ \text{Ln(U)} \qquad (1)$$

where *b* and *a*, are empirically adjusted parameters of the models; and Ln(U) = natural logarithm of gravimetric soil water content.

Functions expressing the correlation between SPR and U were estimated for each treatment (compaction levels) and soil layer. This means that, corresponding to each mean BD of the different treatments and layers, there is a value for parameter *a*, which is the angular coefficient of equation 1 (i.e., the first derivative) and therefore represents the variation rate of SPR with LnU. In this sense, the extent of SPR variation in function of U increases with increasing BD (Bengough et al., 2001; To & Kay, 2005; Almeida et al., 2008). Therefore, the next step of the method, which represents a major advance in relation to the correction procedure proposed by Busscher et al. (1997), was to relate the module of the angular coefficient of the functions that represent the relationship between SPR and LnU (|a|) with the mean BD measured per treatment, according to equation (2):

$$|a| = c\ \text{BD}^{d} \qquad (2)$$

where *c* and *d* are empirically adjusted parameters of the models.

The SPR was corrected by the first term of a Taylor series (Equation 3) (Busscher et al., 1997). The U value of 27 % was used as reference to correct SPR, corresponding to the center of the friability range, as determined by Torres & Saraiva (1999) for the same soil type, with a soil management similar to that used in the experiment of this study.

$$\text{SPR}_{corr.} = \text{SPR}_{read} - [\,|a|\ (\text{LnU}_{ref.} - \text{LnU}_{read})] \qquad (3)$$

where $SPR_{corr.}$ = soil resistance to penetration corrected in function of the reference value of the gravimetric soil water content ($U_{ref.}$); SPR_{read} = soil resistance to penetration read in the field; $LnU_{ref.}$ = natural logarithm of $U_{ref.}$ (27 %); LnU_{read} = natural logarithm of U, of the same site and soil layer as the SPR assessment.

So far, the method proposed to correct the SPR in function of U, required BD data to determine |a|. However, when SPR is used as indicator of soil compaction in the field, the assessment of BD is usually infeasible, once the quantification method is laborious and time-consuming. To eliminate the need of determining BD, pedotransfer functions were adjusted to estimate this property in function of SPR_{read}, specific for six intervals of U values in the 5.5-10.5 cm layer and four intervals in 13.5-18.5 cm (Table 1). The U intervals were determined so as to meet the following criteria, in both soil layers: i) a minimum number of five points per soil water content interval; ii) in each interval, all treatments should be present for a sufficient variation range of BD and SPR; and iii) determination coefficient (r^2) of pedofunctions > 0.70.

To validate the proposed method, the pedotransfer functions were applied to SPR data measured in another experiment by Torres & Saraiva (1999), in the layers 5.5-10.5 and 13.5-18.5 cm of a very clayey Rhodic Eutrudox under no-tillage at four soil compaction levels evaluated over time, totaling 13 U values. It is worth remembering that this data set was not used for the pedofunctions adjustment, but only to validate the method. For this purpose, the SPR data at U of 27 %, determined at different soil compaction levels using equations relating SPR to U adjusted with the data obtained by Torres & Saraiva (1999), were compared to SPR data corrected for the same U value, by the method proposed here, by means of linear regression analysis.

Table 1. Equations to estimate the soil bulk density (BD) using the soil resistance to penetration (SPR) as independent variable, for different soil layers and intervals of gravimetric soil water content (U), on a Rhodic Eutrudox

Interval of U (%)	Equation(1)	No. of equation
	5.5 - 10.5 cm	
If, 21.1 < U ≤ 23.1	BD = e RP ^{f}	4
If, 23,1 < U ≤ 25.1	BD = g + h RP	5
If, 25.1 < U ≤ 27.1	BD = i + j RP	6
If, 27.1 < U ≤ 29.1	BD = k RP ^{l}	7
If, 29.1 < U ≤ 31.5	BD = m RP ^{n}	8
If, 31.5 < U ≤ 34.5	BD = o RP ^{p}	9
	13.5 - 18.5 cm	
If, 23.1 < U ≤ 26.3	BD = q RP ^{r}	10
If, 26.3 < U ≤ 29.1	BD = s RP ^{t}	11
If, 29.1 < U ≤ 32.1	BD = u RP ^{v}	12
If, 32.1 < U ≤ 35.1	BD = x RP ^{z}	13

(1) *e, f, g, h, i, j, k, l, m, n, o, p, q, r, s, t, u, v, x,* and *z* are empiric parameters to adjust the models.

Results were subjected to ANOVA and treatment means compared by the Tukey test, at 5 % probability, using the Statistical Analysis System (SAS, 2002). The same software was used for regression analysis to adjust the pedotransfer functions.

RESULTS AND DISCUSSION

In both soil layers, BD was significantly higher in the treatments with additional soil compaction after harvester traffic than in the NT (Table 2). In contrast, soil tilling by chiseling resulted in lower BD than in the other treatments. In the 5.5-10.5 cm layer, BD varied from 1.10 Mg m^{-3} (NTCh) to 1.50 Mg m^{-3} (NTH20), which is near the maximum BD estimated by the Normal Proctor Test for this Oxisol, corresponding to 1.53 Mg m^{-3} (Torres & Saraiva, 1999). Similarly, in the layer 13.5-18.5 cm, BD varied from 1.10 Mg m^{-3} (NTCh) to 1.42 Mg m^{-3} (NTH20). Therefore, the BD variation range was large in both soil layers, which is a basic requirement for adequate pedofunction adjustments to correct SPR to a reference U value.

In the 5.5-10.5 cm layer of treatment NTH20, the introduction of the penetrometer into the soil led to the formation of vertical cracks below the cone, resulting in low SPR values (data not presented), incoherent with the high BD measured in this layer and treatment (Table 2). At high BD and low U values, To & Kay (2005) also observed that the penetrometer movement in the soil forms small vertical craks right below the cone, reducing the SPR values. Therefore, the SPR data obtained in NTH20, layer 5.5-10.5 cm, were not considered for the establishment of the pedotransfer functions. This problem was not observed in the 13.5-18.5 cm layer, possibly as a consequence of lower BD than in the 5.5-10.5 cm layer. Thus, results obtained in treatment NTH20, layer 13.5-18.5 cm, were used in the adjustment of pedotransfer functions.

The assessments of SPR in different periods resulted in a wide variation range of U, which is also a requirement for the adjustment of pedotransfer functions. Values of U varied between 34.1 and 21.1 % (5.5-10.5 cm), and between 34.8 and 23.6 % (13.5-18.5 cm). Within these variation ranges, minimum and maximum values were similar to the U values associated with the permanent wilting point (1.5 MPa) and the field capacity (0.01 MPa), corresponding, in the mean among treatments, to 24.8 and 32.3 %, respectively. The large variation amplitude for BD and U (Table 2) resulted in a wide range of SPR values (0.57 - 21.66 MPa in the 5.5-10.5 cm, and 0.74 - 14.31 MPa in the 13.5-18.5 cm).

Table 2. Descriptive statistics for the soil bulk density of a Rhodic Eutrudox, assessed at different compaction levels and in two soil layers

Treatment	No.	Minimum	Mean	Maximum	Median	Modal	Standard deviation	CV (%)
				5.5-10.5 cm				
NTCh[(1)]	24	0.95	1.10 Ea**	1.28	1.11	1.04	0.073	6.67
NT	24	1.16	1.25 Da	1.32	1.25	1.25	0.044	3.50
NTH4	24	1.28	1.36 Ca	1.46	1.36	1.36	0.038	2.84
NTH8	23	1.38	1.43 Ba	1.47	1.44	1.47	0.030	2.11
NTH10	24	1.36	1.45 Ba	1.52	1.46	1.46	0.040	2.86
NTH20	23	1.43	1.50 Aa	1.53	1.50	1.52	0.030	2.01
				13.5-18.5 cm				
NTCh	24	0.98	1.10 Da	1.23	1.11	1.15	0.069	6.32
NT	24	1.16	1.25 Ca	1.32	1.26	1.27	0.043	3.42
NTH4	24	1.28	1.34 Bb	1.43	1.33	1.33	0.036	2.69
NTH8	24	1.29	1.36 Bb	1.42	1.36	1.35	0.026	1.93
NTH10	24	1.26	1.38 Bb	1.47	1.38	1.44	0.580	4.18
NTH20	24	1.34	1.42 Ab	1.49	1.42	1.43	0.048	3.42

[(1)] No-tillage with soil chiseling (NTCh), No-tillage without chiseling or additional compaction (NT), NT with additional compaction by 4 (NTH4), 8 (NTH8), 10 (NTH10) and 20 (NTH20) harvester passes. **Treatments followed by the same upper case letter in the same soil layer, or lower case letter in soil layers of the same treatment, do not differ from each other statistically by the Tukey test at 5 %.

The correlation between SPR and U was expressed satisfactorily by equation (1), since the adjustment was statistically significant ($p<0.01$) and r^2 values were > 0.90, for all treatments and soil layers (Figure 1). When U increased, the SPR differences among treatments decreased (Figure 1), in agreement with results of Torres & Saraiva (1999). The differences among treatments for SPR practically disappeared when U approached field capacity (32.3 %; LnU 3.47) (Figure 1). Thus, determining SPR at field capacity, as recommended by the standard ASABE EP542 (ASABE, 2006), is inappropriate when the objective is to use the SPR as an indicator of the effects of traffic and soil management on the compaction level.

The parameter $|a|$ of the regression equations relating SPR to LnU increased with the increasing compaction level in each treatment (Figure 1), i.e., the higher the compaction level, the higher the increase in SPR with decrease in U, as already described by Torres & Saraiva (1999) and Bengough et al. (2001). From this observation, a power function was fit expressing the variation of $|a|$ with the mean BD of each treatment (Figure 2). The use of this equation allowed estimating $|a|$ at different BD values, which were then used in equation (3). The values of $|a|$ were higher in the 13.5-18.5 cm than the 5.5-10.5 cm layer for the entire BD variation range (Figure 1), indicating that SPR is more sensitive to U variation in deeper soil layers. This result also shows that the correction of SPR to a reference U value, through this method, requires specific pedotransfer functions for each soil layer.

The correction of SPR by equation (3) and using $|a|$, estimated for each treatment using the BD values obtained in the field, was efficient for the soil layers 5.5-10.5 cm (Figure 3a,b,c,d,e) and 13.5-18.5 cm (Figure 3f,g,h,i,j,l). In all cases, the relationship between SPR_{read} and U was a negative-exponent power function. After correction, SPR_{corr} did not vary in function of U ($p>0.05$). Likewise, the relationship between SPR_{corr} and U gave rise to a horizontal straight line, parallel to the abscissa axis, which crosses the SPR_{read} approximately at the reference value of U (U_{ref}), equivalent to 27 %. Thus, within the entire variation interval of U, the SPR_{corr} value was similar to the SPR_{read} value, obtained in the field, at 27 % of U.

To eliminate the need for determining BD in the field to estimate $|a|$, which would limit the extensive use of the method proposed here, pedotransfer functions were adjusted to estimate BD in relation to SPR_{read}. These functions were specific for six U intervals in the 5.5-10.5 cm layer (Figure 4a), and for four U intervals in the 13.5-18.5 cm layer (Figure 4b). The model relating SPR to BD and θ, proposed by Busscher (1990), was not used, once the BD could not be reliably estimated at extreme SPR and U values. The use of U instead of θ most likely reduced the model precision in situations of high variations in SPR and U.

In both soil layers and for most U intervals, the relationship SPR x BD was better expressed by exponential-type models (Figure 4), agreeing with results obtained by Busscher (1990). Nevertheless, in the 5.5-10.5 cm layer and for U ranges between 23.1 and 25.1 % as well as between 25.1 and 27.1 %, the best fitting was obtained by the linear model (Figure 4a). Excepting the U interval between 32.1 and 35.1 %

(plastic soil consistency) in the 13.5-18.5 cm layer (Figure 4b), the r^2 values of the other fitted functions were > 0.93 (Figure 4), indicating a high precision in estimating BD, using SPR as independent variable.

Independently of the soil layer, the SPR_{corr} values using the BD estimated by the pedotransfer functions (Figure 4) were similar to those obtained using the BD observed at each soil compaction level (Figure 3). The relationship between LnU and SPR_{corr} using |a|, determined from the estimated BD (Figure 3), was also represented by a straight line, parallel to the abscissas axis, cutting the SPR_{read} x LnU approximately at the values of U_{ref} (27 %); demonstrating that the method was efficient in eliminating the effect of U on SPR. In this way, the correction of SPR by U can be performed without determining BD in the field.

To validate the proposed method, the pedotransfer functions were applied to SPR data obtained at different soil compaction levels and U values by Torres & Saraiva (1999), in previous research of the same soil type and layers used in this study (Figure 5). In all situations, SPR was corrected for the values of U_{ref} (27 %), where |a| was determined by means of BD predicted using SPR_{read} as independent variable in the pedotransfer functions (Figure 4).

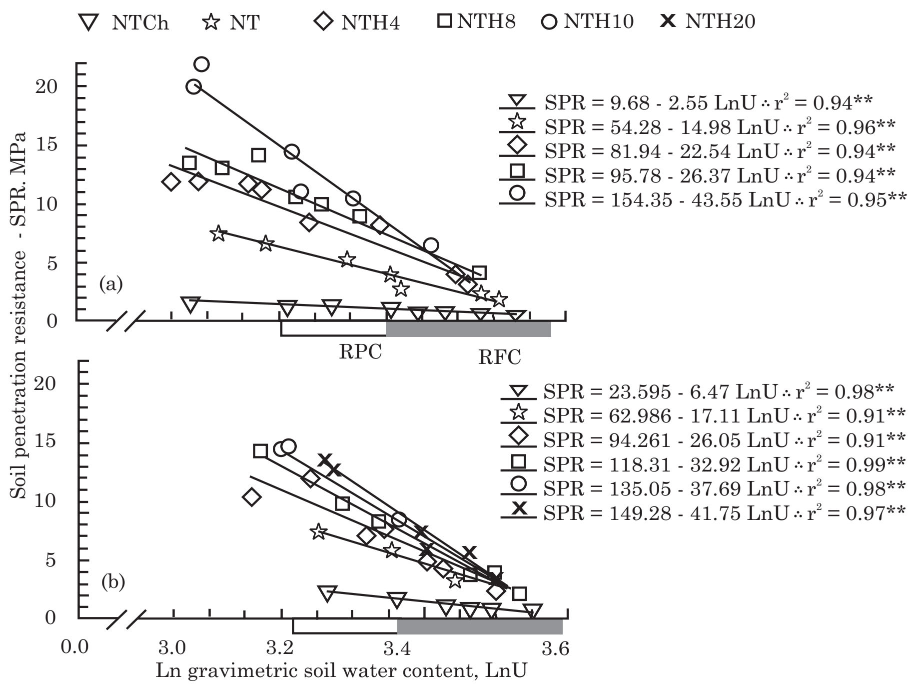

Figure 1. Variation of soil penetration resistance with gravimetric soil water content at each soil compaction level (NTCh = no-tillage with chiseling; NT = no-tillage without chiseling or additional compaction; NTH4, NTH8, NTH10 and NTH20 = NT with additional compaction by four, eight, 10, and 20 harvester passes, respectively), in the layer 5.5-10.5 cm (a) and 13.5-18.5 cm (b), in a Rhodic Eutrudox. **Statistically significant equations (F test, p<0.01). RPC = range of plastic consistency; RFC = range of friable consistency of soil.

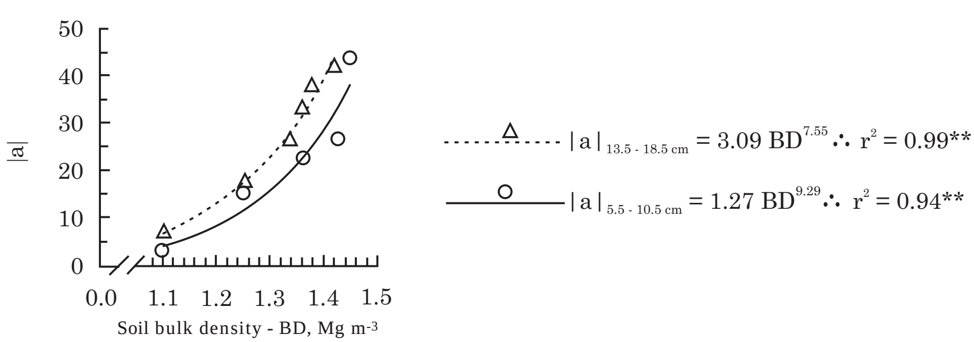

Figure 2. Variation of |a| with the soil bulk density assessed in the field in the 5.5-10.5 and 13.5-18.5 cm layer, in a Rhodic Eutrudox. **Statistically significant equations (F test, p<0.01).

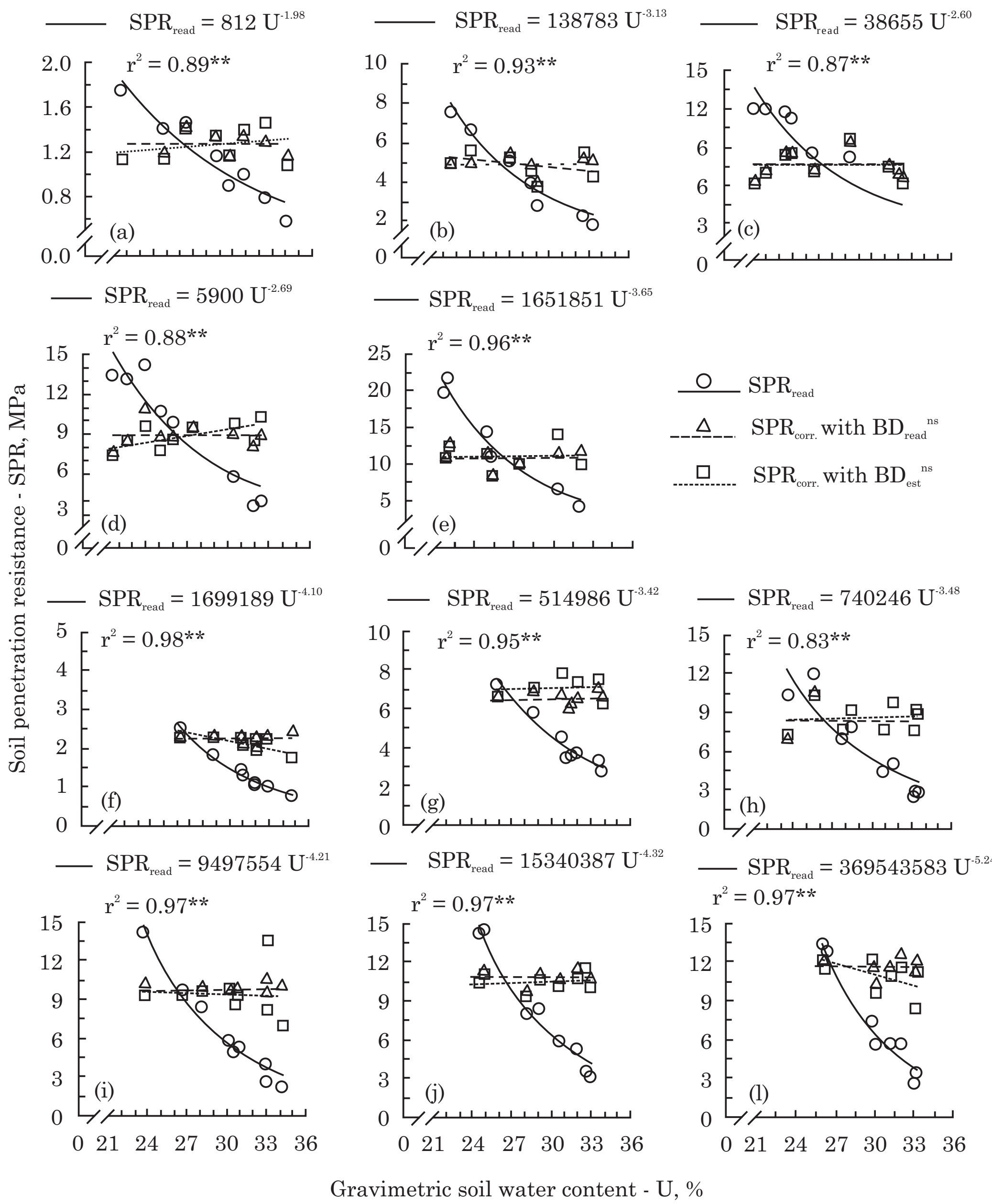

Figure 3. Correction of soil penetration resistance, in function of gravimetric soil water content in a Rhodic Eutrudox, in the 5.5-10.5 cm layer: a) NTCh = no-tillage with chiseling; b) NT = no-tillage without chiseling or additional compaction; c) NTH4 = NT with additional compaction by four harvester passes; d) NTH8 = NT with additional compaction by eight harvester passes; e) NTH10 = NT with additional compaction by 10 harvester passes; and in the 13.5-18.5 cm layer: f) NTCh; g) NT; h) NTH4; i) NTH8; j) NTH10; l) NTH20 = NT with additional compaction by 20 harvester passes. **Significant equations (F test, p<0.01); ns non-significant. SPR_{corr} with BD_{obs} = SPR corrected in function of U by using the soil bulk density observed in the field; SPR_{corr} with BD_{est} = SPR corrected in function of U based on soil bulk density estimated by the pedotransfer functions shown in figure 4.

Prior to correction, the SPR_{read} in the 5.5-10.5 cm and 13.5-18.5 cm layer decreased with the increase of U, following a negative-exponent power function (Figure 5). However, variation of SPR_{corr} with U was not statistically significant in both soil layers, resulting in a straight line, approximately parallel to the abscissa axis. The dispersion of some SPR_{corr} values, observed along the straight line of the regression SPR_{corr} x U, mainly in the 5.5-10.5 cm layer (Figure 5a,b,c,d), may be explained by variations in the soil compaction level at each point where SPR was measured. The existence of this dispersion is important, showing that the

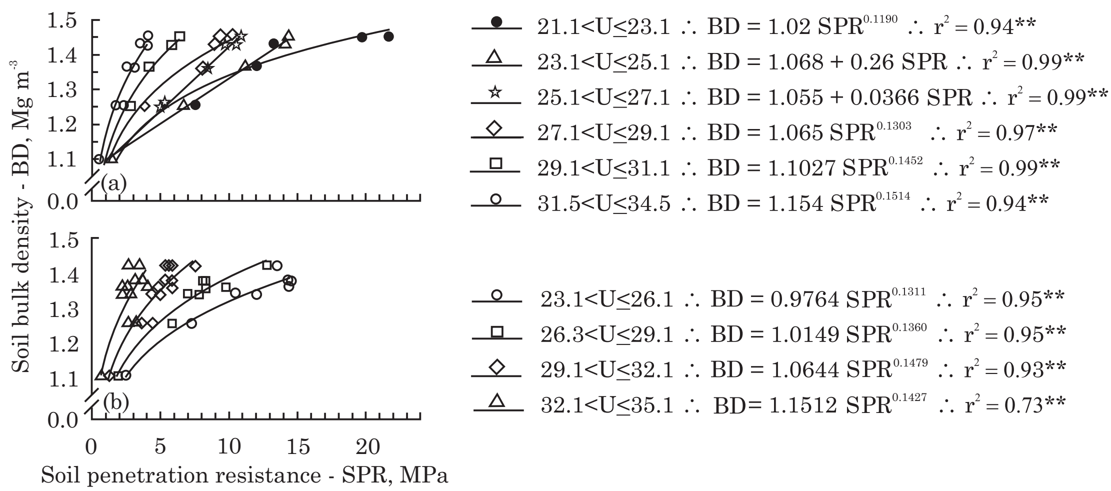

Figure 4. Pedotransfer functions to estimate soil bulk density in function of soil penetration resistance, for different ranges of gravimetric soil water content in the 5.5-10.5 cm layer (a) and 13.5-18.5 cm layer (b), in a Rhodic Eutrudox soil. **Statistically significant equations (F test, p<0.01).

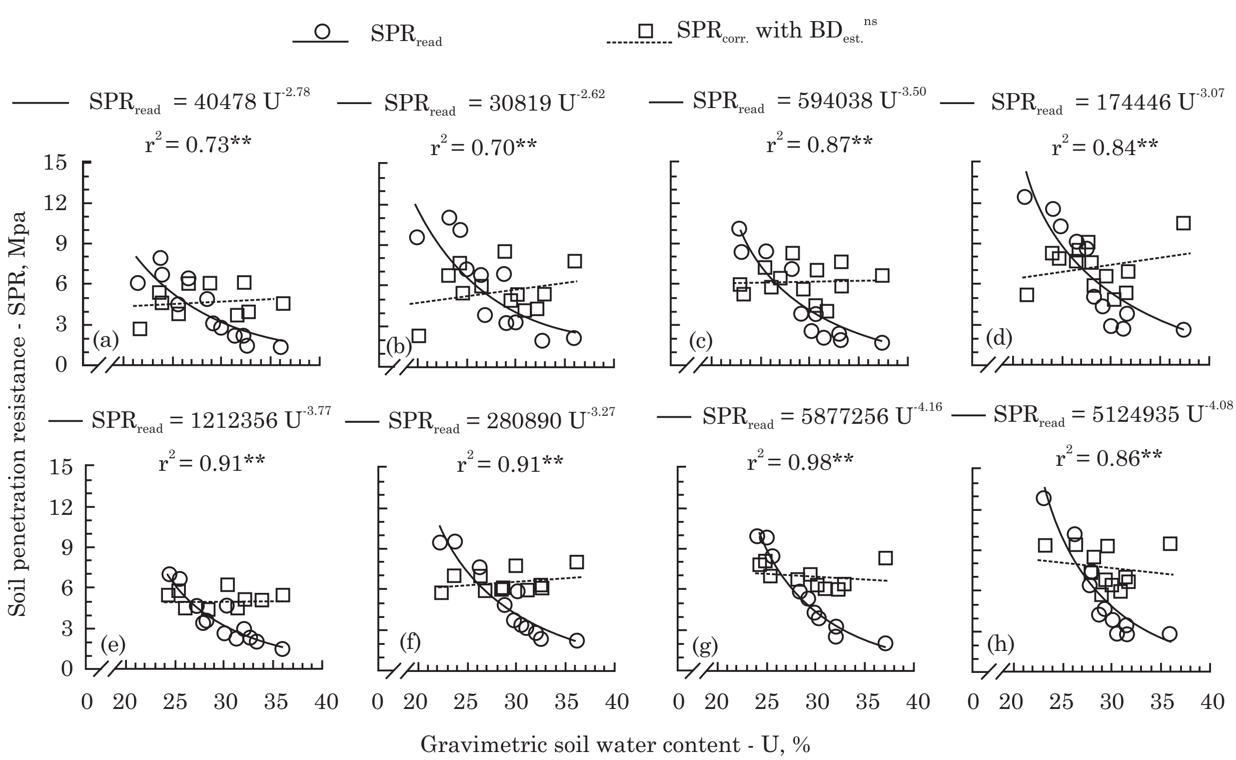

Figure 5. Variation of soil penetration resistance read in the field (SPR_{read}) and corrected (SPR_{corr}) with the gravimetric soil water content, in a Rhodic Eutrudox at different compaction levels, in the 5.5-10.5 cm layer: a) 1.13 Mg m^{-3}; b) 1.30 Mg m^{-3}; c) 1.30 Mg m^{-3}; d) 1.33 Mg m^{-3}; and in the 13.5-18.5 cm layer: e) 1.22 Mg m^{-3}; f) 1.28 Mg m^{-3}; g) 1.29 Mg m^{-3}; h) 1.31 Mg m^{-3}. Original data obtained by Torres & Saraiva (1999). **Statistically significant equations (F test, p<0.01); ^{ns} non-significant.

method proposed here minimizes the effect of U on SPR, but without changing the sensitivity of that variable to the soil compaction level.

The mean SPR_{corr} of each soil compaction level and layer was linearly related with the SPR at U of 27 %, estimated by the equations fitted to the data measured in the field by Torres & Saraiva (1999) (Figure 6). In both soil layers (5.5-10.5 and 13.5-18.5 cm), the determination coefficient of the linear equations representing the relationship between SPR_{corr} and

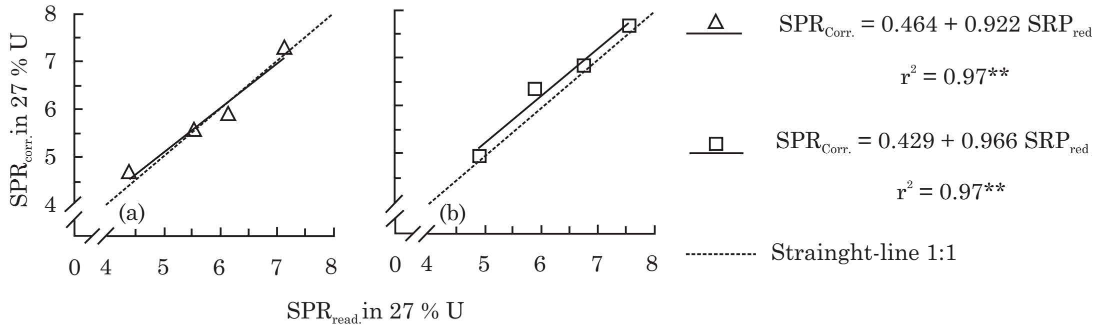

Figure 6. Relationship between the corrected value of soil penetration resistance (SPR_{corr}) and soil penetration resistance observed at the gravimetric soil water content (U) of 27 % (SPR_{read}), for the soil layers 5.5-10.5 cm (a), and 13.5-18.5 cm (b), of a Rhodic Eutrudox. Original data obtained by Torres & Saraiva (1999). **Statistically significant equations (F test, p<0.01).

SPR observed at 27 % of U was high (0.97), very close to the 1:1 line. These results proved that the method of correction, exempting from field determination of BD, was efficient in minimizing the effect of U variation on the SPR values when applied to a data set which, although obtained for the same soil type and layer, differs from the data used to fit the pedotransfer functions.

The purpose of correcting SPR data is to diminish the effect of U on the interpretation of results. Vaz et al. (2002) stated that, despite the SPR readings taken between field capacity and permanent wilting point, some type of correction is necessary. According to these authors, the variation of U within this range causes a large variation in SPR, in the order of 5 MPa. This variation is sufficient to cause significant distortions in diagnoses of the soil compaction level based on SPR data.

In this study, the SPR_{read} in the 5.5-10.5 cm layer varied from 2 to 8 MPa for the NT (BD=1.25 Mg m^{-3}) (Figure 3b), and from 4 to 22 MPa for the NTH10 (BD=1.42 Mg m^{-3}) (Figure 3e). Thus there was an overlapping between the SPR values obtained for the treatments NT and NTH10, in a way that variations in U may lead to a misinterpretation of results, as for example, that SPR in the NT is equal or higher than in the NTH10 treatment. After the correction, the SPR values varied from 4 to 5.5 MPa in NT and from 9 to 13 MPa in NTH10. A similar behavior was observed in the 13.5-18.5 cm layer, where SPR_{read} varied from 2.5 to 7.5 MPa in the NT (Figure 3g), and from 3.2 to 11.5 MPa in the NTH10 treatment (Figure 3j). The overlapping of SPR values in the 13.5-18.5 cm was higher than in the 5.5-10.5 cm layer, increasing the probability of erroneous interpretations, due to eventual variations of U between treatments. However, after correction, the SPR varied between 6.1 to 7.1 MPa in the treatment NT and from 9.5 to 11.5 MPa in the treatment NTH10, thus eliminating overlapping of the variation ranges and minimizing the risk of inadequate interpretations. It is important to emphasize that the variations in SPR_{corr}, within the same treatment and soil layer, occur mainly due to spatial variability of soil compaction levels, once the correction was based on the mean BD for each treatment.

In relation to other methods of correcting SPR by the soil water content, the procedure proposed here has some important advantages. For example, the proposed method can be used at different soil compaction levels due to the adjustment of regression equations to estimate |a|, using BD as independent variable, which was not considered in the original method of Busscher et al. (1997). Additionally, the use of pedotransfer functions to estimate BD from the SPR_{read} allows a satisfactory correction of SPR to a reference U value without the need of quantifying BD in the field, which would hamper the use of this method. This represents an important advantage over the method of SPR correction based on the θ value at a matric potential of -0,01 MPa, as proposed by Vaz et al. (2011), which requires the field estimation of BD. In this context, the use of U instead of θ is another characteristic of the method proposed here, which allows the correction of SPR without the need to determine BD.

Still, it is important to consider that the pedotransfer functions, which represent the relationship between SPR and BD in different U ranges; SPR and U; and |a| and BD, are specific for the layers and the soil conditions inherent to this experiment. In other situations, the fitting coefficients or even the models are expected to be different. Therefore, these adjustments are a condition for the application of this method to soils and layers different from those used in this study.

CONCLUSIONS

1. The proposed method allows correcting SPR to a reference value of U, without affecting the sensitivity of the indicator to the soil compaction level.

2. With the correction of SPR to a reference value of U, differences among treatments, previously masked by variations of U, became detectable.

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