Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Scientific Paper
Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v42n3e20210229/2022

SIMPLE CORRECTION METHOD OF SOIL PENETRATION RESISTANCE FOR SOIL WATER CONTENT

Thiago F. Duarte[1*], Tonny J. A. da Silva[1], Edna M. Bonfim-Silva[1], Gabrielly F. Lima[1]

[1*]Corresponding author. Institute of Agricultural and Technological Sciences, Federal University of Rondonópolis/ Rondonópolis - MT, Brazil. E-mail: thiago.duarte@ufr.edu.br | ORCID ID: https://orcid.org/0000-0002-8471-104X

KEYWORDS

soil compaction, penetrometers, soil modelling, soil physical properties.

ABSTRACT

Soil penetration resistance (PR) assessment is a physical assessment of soil to identify compacted soil layers. Its results are influenced by soil moisture. In this study, a method for correcting PR as a function of soil water content is proposed. The proposed method employs the same function that represents the relationship between PR and soil moisture to calculate the correction that should be applied to the data. The method was evaluated in a Quartzipmment and an Oxisol, at reference moistures of 0.05 to 0.25 kg kg^{-1} and 0.10 to 0.30 kg kg^{-1}, respectively. In addition, the efficiency was evaluated based on mean absolute error (MAE), bias, and mean absolute percentage error (MAPE). Following correction, the PR data of both soil classes followed the reference PR values (calculated for reference moisture). The largest errors were -0.474 (bias), 0.360 (MAPE), and 0.505 (MAE) for the Oxisol, and 0.112 (bias), 0.616 (MAPE), and 0.286 (MAE) for the Quartzipmment. Furthermore, the best performance occurred at a reference moisture of 0.25 and 0.10 kg kg^{-1} for Oxisol and Quartzipmment, respectively. Moreover, these moistures were close to the suction pressure of 10 kPa for both soils.

INTRODUCTION

The evaluation of soil penetration resistance (PR) is among the primary methods used to identify and monitor the degree of soil compaction (Benevenute et al., 2020). It can be determined in the laboratory with benchtop penetrometers or in open fields using manual and automatic penetrometers. PR is largely influenced by soil moisture, and the relationship between PR and moisture generally exhibits a nonlinear behavior. Consequently, by varying the moisture, the same soil can present different PR values. Thus, the evaluation and interpretation of experimental results or monitoring of the physical state of the soil in the field is challenging and may even lead to erroneous conclusions (Fernandes et al., 2020).

Attempts have been made to measure PR under standard soil moisture conditions, such as by inducing soil samples to the same soil water tension value (Fernandes et al., 2020) and correcting the PR values measured at any moisture to a standard soil moisture value (Vaz et al., 2013; Duarte et al., 2020). In the case of using a standard soil moisture value, mathematical methods are employed, such as those proposed by Busscher et al. (1997) and Vaz et al. (2011). Busscher's method, wherein the PR correction is calculated using the first term of the Taylor's series expansion, is among the most widespread in literature. Vaz et al. (2011) proposed the normalization of the PR for moisture corresponding to a suction pressure of 10 kPa. To realize the correction, the authors used an exponential model with three parameters, with soil moisture and bulk density as independent variables.

Duarte et al. (2020) proposed an empirical correction method based on the sequential steps. The method comprises the following aspects: choice of a function that represents the relationship between PR and soil moisture; calculation of PR for a reference soil moisture with the previously fitted function; determination of deviations or the difference between the PR measured at any soil moisture and the PR at the reference moisture; fitting of a function that represents the relationship between the deviations and

[1] Institute of Agricultural and Technological Sciences, Federal University of Rondonópolis/ Rondonópolis - MT, Brazil.

Area Editor: Fernando António Leal Pacheco
Received in: 12-20-2021
Accepted in: 5-8-2022

soil moisture; and finally, the correction of the PR for the reference soil moisture using the function fitted in the previous step.

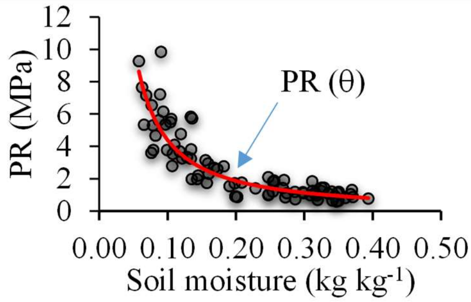
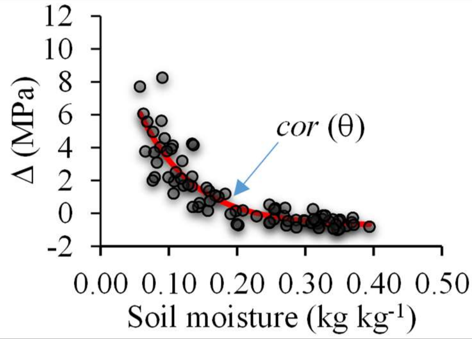
The efficiency of the method proposed by Duarte et al. (2020) was evaluated using an Oxisol. The proposed method required fitting of two different functions for data correction: a function of the type $PR = a\theta_m^b$ to represent the relationship between PR and soil moisture (PR(θ)), and a third-degree polynomial function to represent the relationship between deviations and soil moisture (Δ(θ)). Thus, this method became slightly difficult to use. To further simplify the method, this study aims to modify the correction method of Duarte et al. (2020), by proposing the use of the same type of function to represent both PR(θ) and Δ(θ). The method was evaluated for two contrasting texture soils: a Quartzipmment (sand texture) and an Oxisol (clay loam texture).

MATERIAL AND METHODS

Description of correction method

The proposed correction method is based on four sequential steps, which are presented schematically in Table 1 and described in detail below.

TABLE 1. Steps of PR correction method as a function of soil moisture.

Steps	Description	Example
1	Find the relationship between PR and soil moisture, and fit the function – PR(θ).	
2	Set a reference moisture value (θ_{ref}). Calculate the difference (Δ) between PR at any moisture value ($PR(\theta_i)$) and PR at reference moisture ($PR(\theta_{ref})$).	$\Delta = \boldsymbol{PR(\theta_i) - PR(\theta_{ref})}$
3	Relating the differences found above with the soil moisture Δ(θ). Fit a mathematical function, defined as the correction equation (cor).	
4	Calculate the correction according to the logical condition.	$PR_{cor} = \begin{cases} PR_i - \lvert cor \rvert, & if\ PR_i > PR_{ref} \\ PR_i + \lvert cor \rvert, & if\ PR_i < PR_{ref} \end{cases}$

Initially, a model that represents the relationship between PR and soil moisture (θ)–PR (θ) must be obtained. In this case, soil moisture was considered the main factor influencing PR. Several models were evaluated by Vaz et al. (2011), where the choice was based on statistical parameters that assess goodness of fit.

Subsequently, the adjusted model was used to calculate the PR for the standard soil moisture. This moisture is referred to as the reference moisture (θref) (i.e., moisture in field capacity). Further, the PR is referred to as the reference PR (PR_{ref}). Vaz et al. (2011) adopted a moisture equivalent to a suction pressure of 10 kPa as the reference moisture for PR correction.

The next step was to calculate the difference (Δ) between the PR measured for any soil moisture value, $PR(\theta_i)$, and the PR calculated for the reference soil moisture, $PR(\theta_{ref})$. Subsequently, a function representing the relationship between Δ and soil moisture was fitted, Δ(θ), which represented the correction (cor (θ)) to be applied to the PR data. The correction value applied to the data can be either positive or negative depending on the soil moisture.

The fourth and final step involved the application of the correction to the measured PR data using the previously obtained function (cor (θ)). Thus, a logical condition based on the relationship between the PR and soil moisture must be inserted, as shown in Figure 1, where the highlighted point represents the PR_{ref} value (PR_{ref} = 1.40 MPa) associated with θ_{ref} (θ_{ref}: 0.23 kg kg^{-1}). PR values greater than PR_{ref} were associated with moisture values lower than θ_{ref}, whereas those lower than PR_{ref} were associated with soil moisture values greater than θ_{ref}. Based on this observation, both soil moisture and PR can be used as logical conditions to add or subtract the correction value (cor) to the measured PR data.

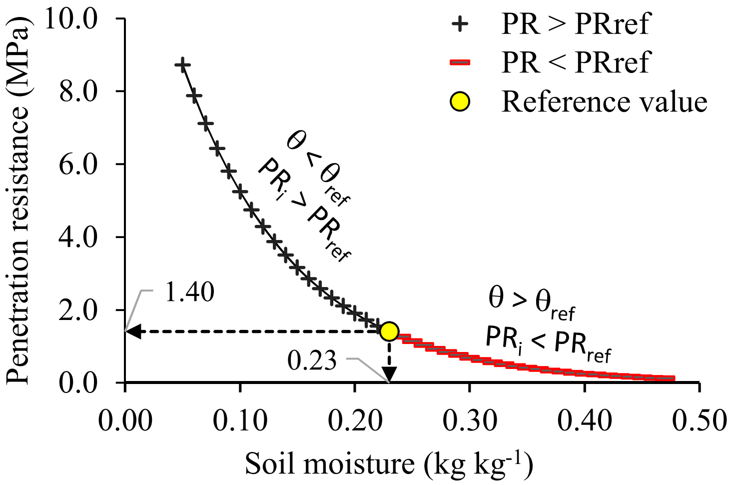


FIGURE 1. Theoretical example of the difference between the PR measured in any soil moisture (PR_i) and the reference PR (PR_{ref}). For moistures (θ_m) lower than the reference moisture (θ_{ref}), PRi > PR_{ref}. Conversely, PRi < PR_{ref}.

Duarte et al. (2020) proposed that the logical condition is based on soil moisture values. In this study, the logical condition was based on the PR value itself. This circumvented certain situations outside the example described above, wherein the measured PR is not higher than PRref even if the soil has lower moisture than θ_{ref}, (that is, drier). Conversely, even if the soil has greater moisture than θ_{ref}, PR is not lower than PR_{ref}. These situations can occur because of experimental variability itself. Thus, the logical condition that must be satisfied is:

$$PR_{cor} = \begin{Bmatrix} PR_i - |cor|,\ if\ PR_i > PR_{ref} \\ PR_i + |cor|,\ if\ PR_i < PR_{ref} \end{Bmatrix} \quad (1)$$

where:

PR_i represents the PR at any soil moisture.

Evaluation of the correction method

To evaluate the correction method, two classes of soils with different textures were used: Quartzipmment and Oxisol. The physical characteristics of the two soil classes are presented in Table 2. The soil samples were collected in the 0–0.10 m layer, with stainless steel rings with 4.9 cm, 5.3 cm, and 100 cm^3 in diameter, height, and volume, respectively. In the Oxisol area, soil is used as a conventional cotton crop. In the Quartzipmment, the soil is native to the cerrado.

TABLE 2. Soil physical data of Oxisol and Quartzipsamments used to evaluate the PR correction method.

Soil class	Sand	Silt	Clay	Soil bulk density (g cm^{-3})		
		%		Minimum	Mean	Maximum
Oxisol	40	20	40	1.07	1.27	1.47
Quartzipsamments	89	4	7	1.30	1.39	1.47

In step 1 (fit of the PR(θ) function), for the Oxisol, a set of 80 data was used, whose PR and soil moisture ranged within 0.58–9.85 MPa and 0.06–0.39 kg kg^{-1}, respectively. For the Quartzipmment, a set of 70 data was used, with a variation of PR and θ of 0.21–5.51 MPa, and 0.01–0.30 kg kg^{-1}, respectively. The variation in soil moisture was obtained by drying the soil in a drying oven at predetermined times as reported by Duarte et al. (2020). Further, the PR data were obtained using the bench top electronic penetrograph, model MA-933, with a rod travel speed of 10 mm min^{-1} and cone base area of 7.1×10^{-6} m^2 (Duarte et al., 2020).

The model fitted to the Oxisol data was of the power type (Equation 2), and for Quartzipmment, of the logarithm type (Equation 3):

$$PR = a - bc^{\theta} \quad (2)$$

$$PR = a + bln(\theta) \quad (3)$$

where:

PR is the penetration resistance (MPa);

θ is the soil moisture (kg kg^{-1}), and

a, *b* and *c* are the model fit coefficients.

The correction method was evaluated for the different θ_{ref}. For the Oxisol, the evaluated θ_{ref} were 0.10, 0.15, 0.20, 0.25, and 0.30 kg kg^{-1}, whereas for Quartzipmment, they were 0.05, 0.10, 0.15, 0.20, and 0.25 kg kg^{-1}.

In the data correction step (step 4), independent data were used for those used in the previous steps (steps 1 to 3). For the Oxisol, a set of 30 data was used, ranging from 0.65–3.13 MPa and 0.15–0.25 kg kg^{-1} for PR and the soil moisture, respectively. For the Quartzipmment, a total of 26 data were used with a variation of 0.33–4.69 MPa, and 0.02–0.21 kg kg^{-1} for PR and the soil moisture, respectively.

The error of the proposed correction method was evaluated based on three statistical parameters: mean absolute error (MAE), bias, and the mean absolute percentage error (MAPE).

$$MAE = \frac{1}{N}\sum_{i=1}^{n}\left|PR_{ref} - PR_{cor(i)}\right| \quad (4)$$

$$Bias = \frac{1}{N}\sum_{i=1}^{n}\left(PR_{ref} - PR_{cor(i)}\right) \quad (5)$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{n}\left|\frac{PR_{ref}-PR_{cor(i)}}{PR_{ref}}\right| \quad (6)$$

where:

PR_{ref} represents the reference PR;

PR_{cor} is the corrected PR, and

N is the total number of observations.

RESULTS AND DISCUSSION

The PR data as a function of soil moisture are shown in Figure 2. The functional parameters, coefficients of determination, and residual errors are listed in Table 3. The PR of the Quartzipmment was lower than that of the Oxisol for all soil moisture values. In addition, the range of variation, that is, the difference between PR associated with lower and higher soil moistures, was also higher for Oxisol. Thus, for Oxisol, the maximum and minimum values obtained were 9.84 and 0.58 MPa, associated with moistures of 0.06 and 0.39 kg kg^{-1}, respectively. In contrast, the Quartzipmment obtained values of 5.51 and 0.21 MPa, associated with moistures of 0.01 and 0.30 kg kg^{-1}, respectively.

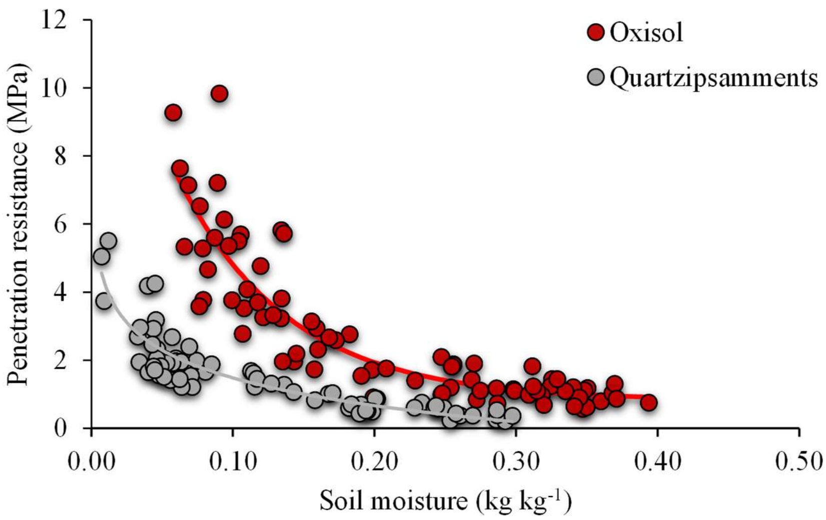


FIGURE 2. PR for Oxisol and Quartzipsamments as a function of soil moisture.

TABLE 3. Fitted functions to PR data as a function of soil moisture for Oxisol and Quartzipsamments.

Soil	Penetration resistance models*	Adjusted parameters			R^2	RSS
		a	b	c		
Oxisol	$PR = a - bc^{\theta_m}$	0.82006	-14.3117	2.85E-06	0.79	77.02
Quartzipsamments	$PR = a + b\ln(\theta_m)$	-1.22455	-1.1759	-	0.80	17.60

The representation of the differences (Δ) between the PR and PR_{ref} values for the two soil classes in different θ_{ref}, are shown in Figure 3. The differences can be both positive and negative, depending on the interaction between soil moisture and θ_{ref}. The values are negative if PR is less than PR_{ref}, and positive if PR is more than PR_{ref}. The first condition occurred when the moisture associated with the PR value was greater than θ_{ref}. In contrast, when the moisture content was less than θ_{ref}, the difference was positive. Thus, for the lowest θ_{ref} (0.10 and 0.05 kg kg^{-1} for Oxisol and Quartzipmment, respectively), a greater number of negative values were observed; conversely, for higher θ_{ref} (0.30 kg kg^{-1} for Oxisol and 0.25 kg kg^{-1} for Quartzipmment), more positive values were observed (Figure 3).

For each dataset, referring to each θ_{ref}, a mathematical function was fitted to represent the correction (cor) that should be applied to the PR data. For example, in Figure 3, the correction functions for the smallest and largest θ_{ref} are shown. Moreover, the function type fitted for each soil was the same as previously adjusted according to Figure 2 and Table 3, that is, the potential and logarithmic functions, for Oxisol and Quartzipmment, respectively. The fit with the same function type was justified from the observation that the variation tendency shown in Figure 3 was the same as that shown in Figure 2, with only a "shift of the curves" occurring when θ_{ref} was changed. In addition, only the "a" parameter of the functions fitted in this step and those fitted previously (Table 3) was different for both the potential and logarithmic functions. Thus, on analyzing the variation of parameter "a" as a function of PR_{ref} (this value is calculated based on θ_{ref}), the relationship can be obtained, as shown in Figure 4.

As evident, the change in the "a" parameter in the correction function depends only on PR_{ref}, such that for both soils, only the value of PR_{ref} needs to be subtracted from the "a" value initially fitted. Specifically, consider the PR_{ref} in the θ_{ref} of 0.05 and 0.25 kg kg^{-1} for the Quartzipmment, and 0.10 and 0.30 kg kg^{-1} for the Oxisol.

For Oxisol:

$$a_{0.10} = 0.8201 - PR_{ref} = 0.8201 - 4.812 = -3.992$$

$$a_{0.30} = 0.8201 - PR_{ref} = 0.8201 - 1.131 = -0.3105$$

For Quartzipmment:

$$a_{0.05} = -1.2244 - PR_{ref} = -1.2244 - 2.298 = -3.5224$$

$$a_{0.25} = -1.2244 - PR_{ref} = -1.2244 - 0.406 = -1.6300$$

Subsequently, the recalculated "a" parameters were inserted into the complete function, as shown in Figure 3.

Thus, the correction equations for Oxisol and Quartzipmment are:

$$cor = (a - PR_{ref}) - bc^{\theta} \quad (7)$$

$$cor = (a - PR_{ref}) + b\ln(\theta) \quad (8)$$

Thus, as evident, the use of a single function to represent both the relationship between PR and soil moisture, as well as the correction of PR data as a function of soil moisture, considerably simplified the correction method, particularly when modifying the θ_{ref} value.

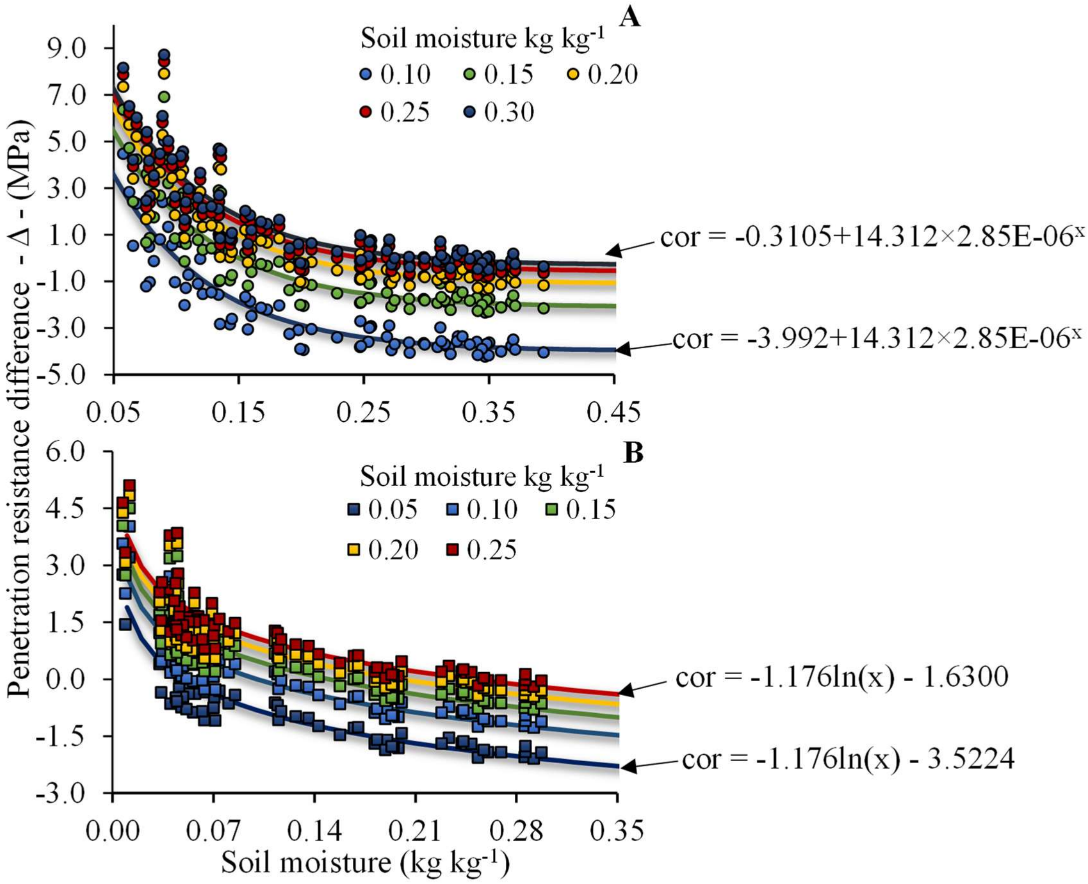


FIGURE 3. Difference between PR and reference PR (PR_{ref}) at different reference soil moistures (θ_{ref}) for (A) Oxisol and (B) Quartzipsamments.

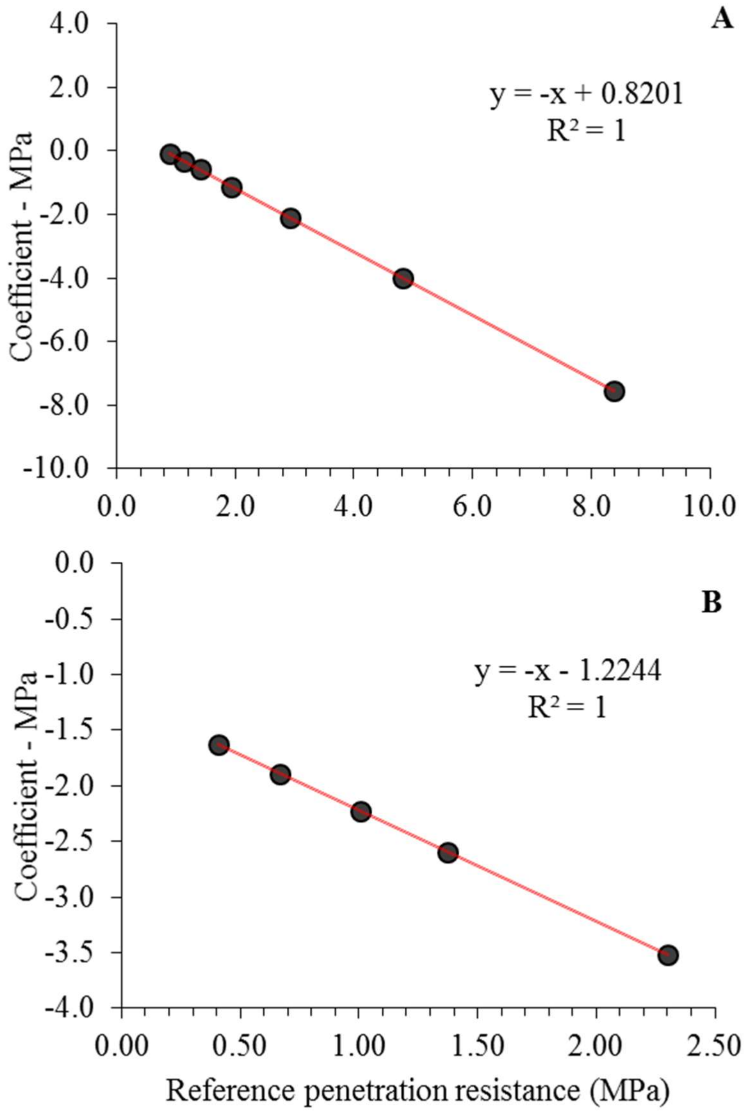


FIGURE 4. Intercept variation of the PR(θ) functions fitted for the (A) Oxisol (potential) and for the (B) Quartzipsamments (logarithmic), as a function of reference PR (PR_{ref}).

The PR data used to evaluate the correction method are presented in Figure 5. The soil moisture and PR ranged from 0.02 to 0.21 kg kg^{-1} and from 0.33 to 4.69 MPa for Quartzipmment; and from 0.15 to 0.25 kg kg^{-1} and 0.65 to 3.13 MPa for Oxisol, respectively. Regarding data correction, they can be represented by the respective functions fitted in Figure 2, implying that the soil has physical characteristics (e.g., bulk density, granulometry, degree of cohesion, etc.) similar to the soil used to construct the PR(θ) function. This is important because, as demonstrated by Silva et al. (2016), for the same soil moisture range, the function that represents PR varies with changes in soil bulk density.

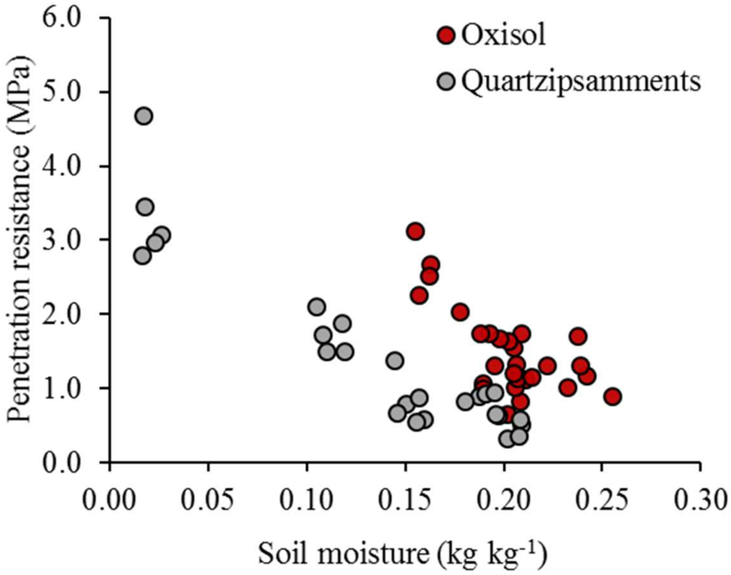


FIGURE 5. PR of Quartzipsamments and Oxisol used for validation of correction method.

The corrected data, absolute and average, for the two soil classes and for different θ_{ref}, are shown in Figures 6 and 7. For both soils, the absolute PR data were close to the lines representing the PR_{ref} values. In general, for Oxisol, the corrected data were lower than the PR_{ref} value (Figure 6 A–E). This can be further verified by observing the mean values (Figure 6 F–J) and the negative values of the bias parameter (Table 5). In contrast, for Quartzipmment, the corrected values were generally higher than those of PR_{ref} (Figure 7).

Considering the statistical errors, it can be concluded that for Oxisol, the correction method presented better results for θ_{ref} of 0.25 kg kg^{-1}. Thus, the average PR_{cor} and PR_{ref} were 1.38 and 1.41 MPa, respectively. For Quartzipmment, the best performance was for θ_{ref} of 0.10 kg kg^{-1}, whose PR_{cor} and PR_{ref} values were 1.46 and 1.48 MPa, respectively.

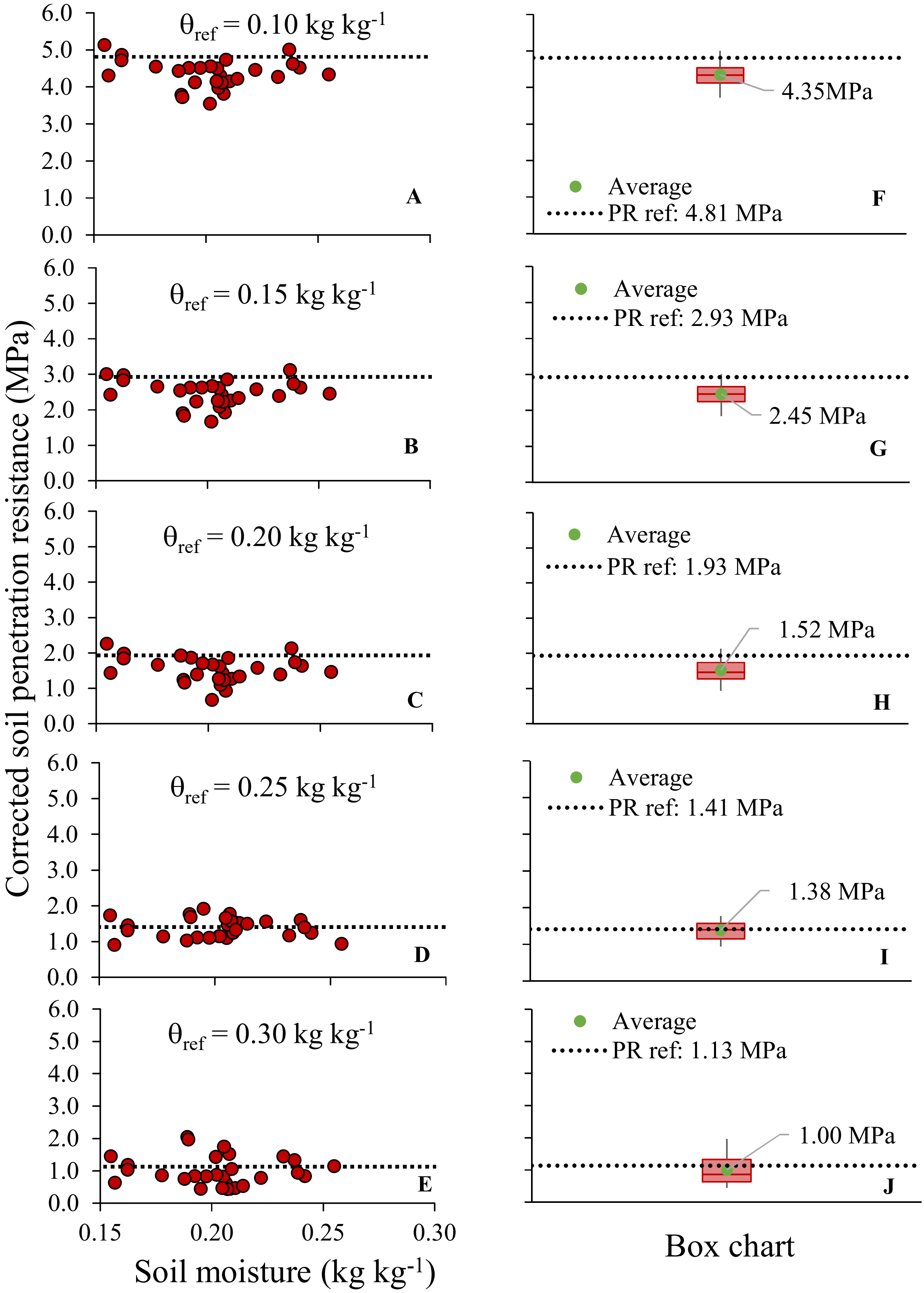


FIGURE 6. PR correction of Oxisol for different reference soil moistures. A, B, C, D, and E represent absolute PR data after correction. F, G, H, I, and J are boxplots (Q1–25%, Q2–50%, Q3–75%), and the bars delimit the 5th and 95% percentiles.

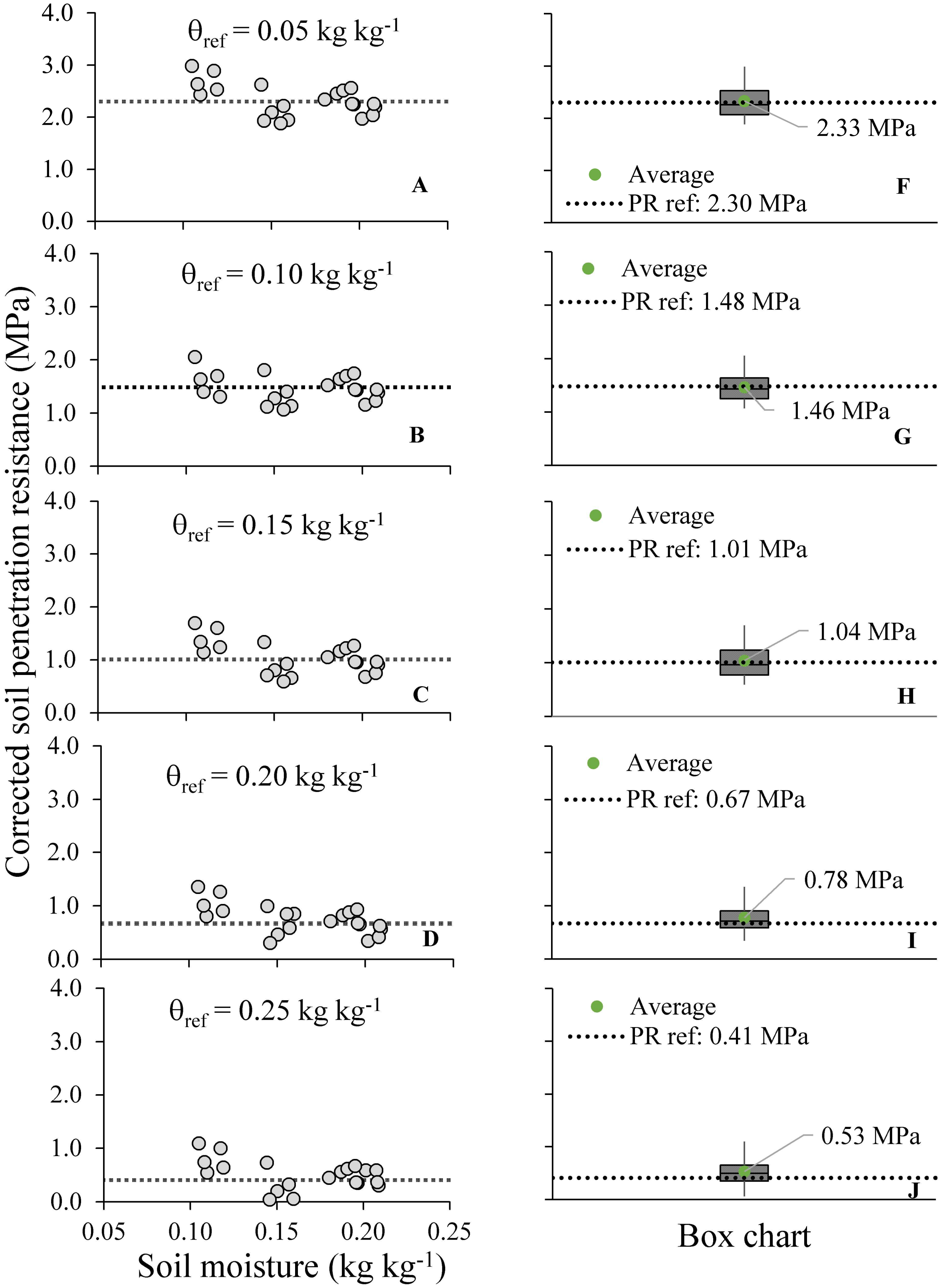


FIGURE 7. PR correction of Quartzipsamments for different reference soil moistures. A, B, C, D, and E represent absolute PR data after correction. F, G, H, I, and J are boxplots (Q1–25%, Q2–50%, Q3–75%), and the bars delimit the 5th and 95% percentiles.

TABLE 4. Statistical errors of soil PR correction method for soil moisture.

Soil	θ_{ref} (kg kg^{-1})	Bias	MAPE	MAE
Oxisol	0.10	-0.465	0.105	0.505
	0.15	-0.474	0.169	0.496
	0.20	-0.414	0.235	0.454
	0.25	-0.025	0.168	0.236
	0.30	-0.134	0.360	0.407
Quartzipsamments	0.05	0.064	0.115	0.286
	0.10	0.011	0.158	0.256
	0.15	0.066	0.261	0.284
	0.20	0.112	0.369	0.246
	0.25	0.102	0.616	0.250

Correction of PR as a function of soil moisture is a recurrent theme in soil science research. Correction is required for a correct interpretation of the experimental results, particularly in the field, where control or standardization of soil moisture is generally not feasible.

Considering this well-known problem, several authors have proposed alternatives. Busscher et al. (1997) suggested that the correction is based on the first term of the Taylor series expansion. Although this method offers advantages, Vaz et al. (2011) observed that in certain situations, the method resulted in inconsistencies; thus, the difference between the original soil moisture and θ_{ref} is recommended to be within a small variation range. Moreover, the Busscher method was evaluated by Duarte et al. (2020) for different θ_{ref}, and the best performance was verified in moisture ranges close to θ_{ref}.

Vaz et al. (2011) fitted an exponential function to the PR data considering bulk density and soil moisture as independent variables. The corrected PR was obtained by calculating its value based on the bulk density and soil moisture standardized at a pressure of 0.01 MPa. Thus, the correction was independent of the new PR measurements but dependent on the soil moisture and bulk density.

Fernandes et al. (2020) proposed a correction method that involved estimating the PR measured in the laboratory (with standardized soil moisture at 0.01 MPa pressure) from the PR and moisture measurements performed in the field. The estimate was evaluated using regression-fitted functions and a computational method for artificial neural networks. Through comparisons of the two methods, the authors recommended the estimate to be based on artificial neural networks.

The method proposed in this study, although empirical, offers the advantage of being simple. This is because it uses only a single function to represent the relationship between PR and soil moisture and calculate the necessary correction to the PR data for standard moisture. In addition, the method also demonstrates versatility as it allows changing the PR_{ref} value to another desired value.

The method was tested for different θ_{ref}, ranging from a drier (0.05 and 0.10 kg kg^{-1}) to a wetter condition, with the results demonstrating the stability of the method. However, the performance depended on the soil texture, wherein the smallest errors occurred for Quartzipmment. This is probably because of the better fit of the PR(θ) function to the PR data (Table 3), that is, less variability of the data, compared to Oxisol. Furthermore, in soils with a higher clay content, a more pronounced effect of the adhesion forces between the soil and the metal rod is observed, particularly at lower moisture levels (Vaz et al., 2011), which can also contribute to greater variability.

Further, although the method exhibited good performance for different values of θ_{ref}, the best results were obtained for moisture of 0.25 and 0.10 kg kg^{-1} for Oxisol and Quartzipmment, respectively. Consequently, based on the soil water characteristic curve determined in another study for each soil, these values were close to the suction pressure of 10 kPa. Specifically, for a suction pressure of 10 kPa, the soil moisture values were 23.4 and 11.4% for Oxisol and Quartzipmment, respectively (Figure 8). Based on this verification, the correction is recommended to be made to the θ_{ref} equivalent to a suction pressure of 10 kPa. Similarly, Vaz et al. (2011) demonstrated that for a suction pressure of 10 kPa, the PR is less influenced by the soil texture and suggested that measurements between pressures in the range of 0 to 10 kPa.

However, the data used for the correction step should originate from soils with physical characteristics similar to those used in the function fit. This similarity can be verified using the soil bulk density as a reference parameter, as many functions that represent PR use it as an independent variable. The soil bulk density will be implemented in the proposed correction method in future studies.

Finally, although the correction method was based on a benchtop penetrometer, its performance is likely to be acceptable in field measurements. This contributes to the practical aspect of the identification of subsurface compacted layers, whose precise detection remains challenging because of the influence of soil moisture on data interpretation.

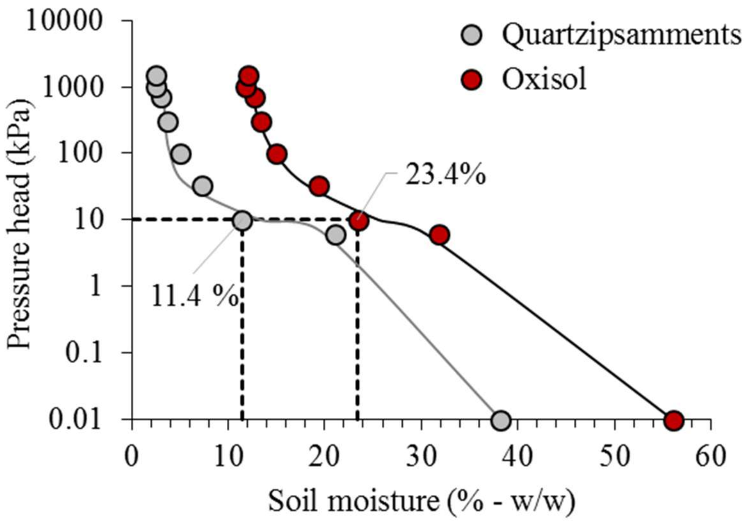


FIGURE 8. Soil water characteristic curve for Quartzipsamments and Oxisol demonstrating the soil moisture at a suction pressure of 10 kPa.

CONCLUSIONS

In this study, a PR correction method as a soil moisture function was proposed. Its primary characteristic was the simplicity owing to the use of a single function to represent the relationship between PR and soil moisture and calculate the correction that should be applied to the data. The proposed method was tested on two soils with highly contrasting textures: Quartzipmment (89% sand; 7% clay) and Oxisol (41% clay; 40% sand), in reference moistures ranging from 5 to 25% and 10 to 30%, respectively. However, despite the stability of the method, the best performance was verified at moisture close to a suction pressure of 10 kPa, particularly for the soil with higher clay content. Thus, the soil moisture equivalent to a suction pressure of 10 kPa should be used as the reference moisture for PR correction, and the proposed correction method can be routinely implemented in data analysis to aid in identifying compacted layers.

ACKNOWLEDGMENTS

This work was supported in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES - PRÓ-EQUIPAMENTOS – 2014).

REFERENCES

Benevenute PAN, de Morais EG, Souza AA, Vasques ICF, Cardoso DP, Sales FR, Severiano EC, Homem BGC, Casagrande DR, Silva BM (2020) Penetration resistance: An effective indicator for monitoring soil compaction in pastures. Ecological Indicators 117: 106647. DOI: https://doi.org/10.1016/j.ecolind.2020.106647

Busscher WJ, Bauer PJ, Camp CR, Sojka RE (1997) Correction of cone index for soil water content differences in a coastal plain soil. Soil and Tillage Research 43:205-217. DOI: https://doi.org/10.1016/S0167-1987(97)00015-9

Duarte TF, Silva TJ, Bonfim-Silva E.M, Fenner W (2020) Resistance of a Oxisol to penetration: comparison of penetrometers, model adjustment, and soil water content correction. Engenharia Agrícola 40: 462-472. DOI: https://doi.org/10.1590/1809-4430-Eng.Agric.v40n4p462-472/2020

Fernandes MMH, Coelho AP, da Silva MF, Bertonha RS, de Queiroz RF, Furlani CEA, Fernandes C (2020) Estimation of soil penetration resistance with standardized moisture using modeling by artificial neural networks. Catena. 189: 104505. DOI: https://doi.org/10.1016/j.catena.2020.104505

Silva WM, Bianchini A, Cunha CA (2016) Modeling and correction of soil penetration resistance for variations in soil moisture and soil bulk density. Engenharia Agrícola 3: 449- 459. DOI: https://doi.org/10.1590/1809-4430-Eng.Agric.v36n3p449-459/2016

Vaz CMP, Manieri JM, De Maria IC, Tuller M (2011) Modeling and correction of soil penetration resistance for varying soil water content. Geoderma 166: 92-101. DOI: https://doi.org/10.1016/j.geoderma.2011.07.016

Vaz CMP, Maria IC, Genuchen MTV (2013) Scaling the dependency of soil penetration resistance on water content and bulk density of different soils. Soil Science of Society of American Journal 77:1488-1495. DOI: https://doi.org/10.2136/sssaj2013.01.0016