Open Access Library Journal
2022, Volume 9, e9528
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Evaluation of a Penetration Resistance Model in Oxisol under No-Till and Texture Variation

João Tavares Filho*, **Stephanie dos Santos Locatelli, Tamires Firmino, Lucas Augusto De Assis Moraes, Thadeu Rodrigues De Melo**

State University of Londrina, CCA-AGR., Londrina, Brazil
Email: *tavares@uel.br, stephanie.locatelli@uel.br, tamiresfirmino.tf@uel.br, lucas_moraes1002@hotmail.com, thadeu@uel.br

How to cite this paper: Tavares Filho, J., Locatelli, S.S., Firmino, T., Moraes, L.A.A. and De Melo, T.R. (2022) Evaluation of a Penetration Resistance Model in Oxisol under No-Till and Texture Variation. *Open Access Library Journal*, **9**: e9528.
https://doi.org/10.4236/oalib.1109528

Received: November 4, 2022
Accepted: November 27, 2022
Published: November 30, 2022

Abstract

The no-tillage system influences the structure of the soil, as the absence of plows combined with the intensive use of heavy machinery contributes to variations in soil density and soil compaction. On the other hand, a no-tillage system tends to increase soil organic matter, which probably increases soil elasticity acting on the soil structure and possibly helping to increase the soil's mechanical resistance to compaction. In a 2012 study, to evaluate the fit of the resistance curve to soil penetration and study the compaction of a very clayey Oxisol (clay content ~ 665 g·kg^{-1}) under no-till, a model was proposed with very good results. Good for data collected in the field. However, only one type of texture was considered and, therefore, the objective of this work was to evaluate this model for Latosols under no-tillage conditions, but with varying clay contents. Here, 355 soil penetration resistance points were made with a dynamic impact penetrometer, and samples were collected to determine soil density, moisture, and organic matter in Oxisols with varying clay content. The results confirmed that the non-linear model which includes density, moisture, and soil organic matter content, proved to be efficient for the adjustment of the penetration resistance curve in the studied Latosols with significant variation in clay content and under no-tillage. The inclusion of organic matter allowed, in relation to the control model, a more excellent approximation of the resistance values obtained in the field of the 1:1 line and improved the coefficient of determination by 27% and the correlation coefficient by 13% and the relative error absolute was reduced by 5.26 times compared to a model that used only soil density and moisture.

Subject Areas

Soil Science

Keywords

Penetration Resistance Model, Oxisol, No-Till, Compaction, Physical Properties

1. Introduction

The State of Paraná-Brazil is responsible for approximately 20% of all cereal production in the country due to its excellent climatic conditions and the Oxisolsare distributed in 31% of the state territory [1] [2]. This high production with more than one crop per year in a no-tillage system tends to cause structural damage, as the absence of plows combined with the intensive use of heavy machinery in inadequate humidity conditions contributes to variations in soil density and soil compaction. On the other hand, a no-tillage system tends to increase soil organic matter, which probably increases soil elasticity [3], more than mineral particles and promotes the formation and stabilization of soil aggregates acting on the soil structure and possibly helping to increase the soil's mechanical resistance to compaction [4]. This process changes the soil's mechanical strength, structure, water storage, nutrient availability, and mechanical strength [5].

Mechanical strength is an important property that can be evaluated using an impact penetrometer. The importance of its determination lies in the correlation with the effect of the passage of heavy machinery on the soil, affecting root growth and soil physical properties. It is a way to get results quickly [6] [7].

The penetrometer works according to the principle of soil resistance to penetration of a cone of a specific size and to the vertical impact represented by a Force (F) on a rigid rod [8] [9]. The resistance to penetration is influenced by several soil physical characteristics and properties, such as density, moisture content, water potential, texture, aggregation, cementation, organic matter content, and mineralogy, leading some authors to propose empirical models to describe these properties [4]-[19].

Among these models, the most used is that of [10] developed in temperate soils. This model is composed of two main terms: the first is based on the degree of soil compaction and structuring (represented by the soil density), and the second is attributed to the water content in the soil, which allows the comparison of measurements made under different water conditions, mass-based grades for the study of the resistance to penetration curve and regression parameters, measure the influence of a variable ("a", "b" and "c") on a regression equation, obtained through non-linear fits that vary from one terrain to another.

This model works for any type of soil. Still, when considering a set of soils, additional pedo transfer functions are often used, and the coefficients "a", "b" and "c" are determined by experimentation and regression [15]. Thus, to validate the data obtained with a penetrometer, if it is used correctly, the soil must have been characterized, which is not always the case [6]. Furthermore, according to [5]

[7], few models to predict penetrometer resistance are applicable without detailed knowledge of soil texture, organic matter content, soil water status, and soil density, and few models allow a simple prediction of the effects of management on resistance of the penetrometer.

Thus, quantifying soil moisture content, density, and organic matter content is essential for penetrometer measurements and identifying soil class and clay content. [13] tried to estimate the resistance to penetration of a very clayey Eutroferric Red Latosol (Red Latosol) under different soil moisture conditions, in addition to considering density, clay content, and organic matter content. The results showed that, when the soil is drier, the influential properties for resistance to penetration estimates are density and organic matter content. The most influential properties in resistance to penetration estimates are density and moisture at higher soil moisture.

To evaluate the fit of the soil penetration resistance curve and study the compaction of a very clayey Latosol (clay content ~ 665 $g \cdot kg^{-1}$) under no-tillage, [6] proposed a model with good results for the data collected in the field. However, only one type of texture was considered and, therefore, the objective of this work was to evaluate this model for Latosols under no-tillage conditions, but with varying clay contents.

2. Study Location and Methodology

2.1. Study Location

Data were collected from 13 locations throughout the state of Paraná-Brazil containing Oxisols with varying clay content (from 147.7 to 855.3 $g \cdot kg^{-1}$). These soils were cultivated with soybean, corn, wheat, and oats under a no-tillage system (**Figure 1**).

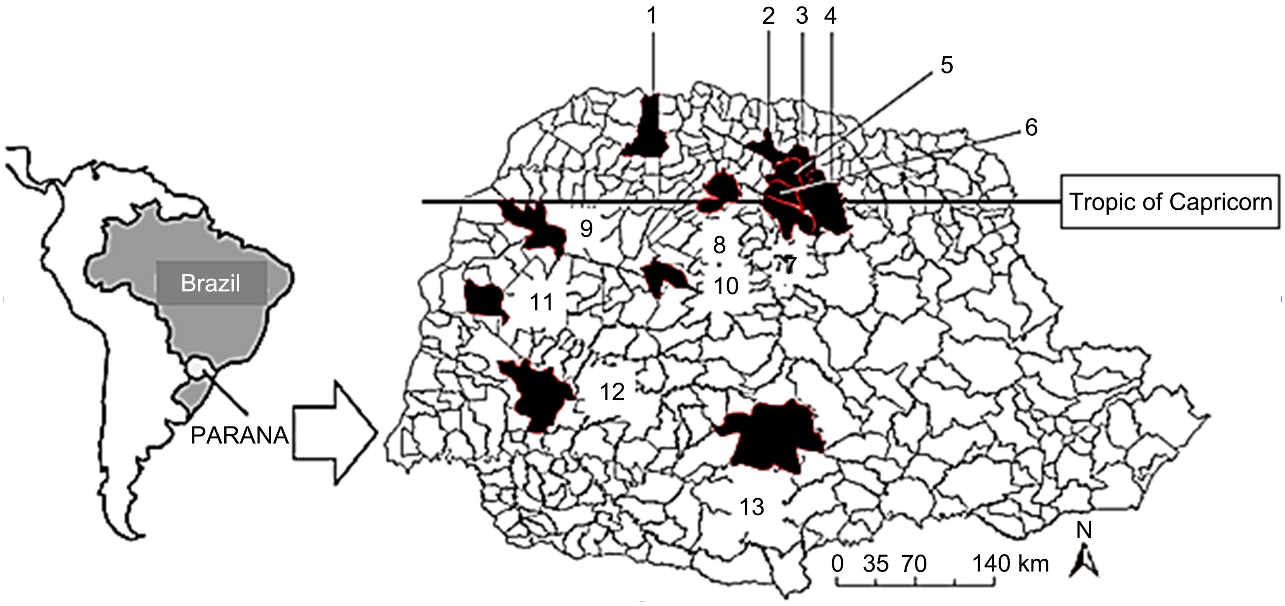


Figure 1. Location of the 13 sampling areas containing Oxisols of varying clay content and cultivated under no-tillage conditions.

2.2. Methodology

A total of 355 soil resistance points (N = 355) to penetration were created using a dynamic impact penetrometer, model IAA/Planalsucar [20] with a guide rod of 70 cm in length, basal cone diameter of 1.28 cm, the cone angle of 30˚, and impact the weight of 4 kg from a free fall height of 40 cm. The cone geometry complied with the American Society of Agricultural and Biological Engineers [21] Standard.

The impact of the cone on the soil and expressing the resistance against the penetration of the cone into the soil in pressure units can be described according to the formula: soil resistance penetration (PR) ($kgfcm^{-2}$) = 5.6 + 6.89 N, where N is the number of sample points evaluated in the field (in the present study, N = 355). To convert PR from $kgfcm^{-2}$ to MPa, the result was multiplied by a constant (0.0981). Intact samples were collected with volumetric rings 6 cm in diameter and 6 cm in height to determine soil density (ρs), while disturbed samples were collected with an auger to determine gravimetric moisture (θs), clay content (αs, determined after oxidation of organic matter [22], and soil organic matter content (Ωs), according to the methodology described by [23].

2.3. Data Analysis and Model Projections

Regression analysis generates an equation to describe the statistical relationship between one or more predictor variables and a response variable. Thus, to study the PR curve, we used the nonlinear model proposed by [6] ($PR = a{*}\rho s^{b}{*}\theta s^{c}{*}\Omega^{d}$). The results were compared with those obtained with the model proposed by [10] ($PR = a{*}\rho s^{b}{*}\theta s^{c}$), where PR is the resistance to soil penetration (MPa), ρs is soil density ($Mg{\cdot}m^{-3}$), θs is soil gravimetric density, moisture content ($kg{\cdot}kg^{-1}$), and Ωs is soil organic matter content ($g{\cdot}kg^{-1}$). The parameters "a", "b", "c" and "d" are the model fit coefficients.

These models were linearized by applying the natural logarithmfunction $\ln PR = \ln a + b\ln\rho s + c\ln\theta s$, and $\ln PR = \ln a + b\ln\rho s + c\ln\theta s + d\ln\Omega s$; the PR curves were adjusted from regression studies. After adjusting the obtained data, the estimated coefficients were used to transform the linearized models into nonlinear ones. To test the significance level of the regression and confirm the hypothesis that the means of the variables were statistically equal, we used a significance level (F) of 5%. Additionally, we verified the explanatory power of the models according to the number of variables and the extent to which the model fits the population data through adjustedR^2 (R^2_{aj}).

Regression analysis was performed with Excel (2019) software/Analysis Tools Package Regression Tools/Statistical functions. All sampled points (355) were used to analyze, build, and validate models.

Finally, the associated models and coefficients were used to calculate the absolute PR (PR_{ab}) and estimated PR (PR_{est}) values to evaluate the accuracy of the results, considering the correlation (r) between these results and the deviations between the estimates based on the models and the experimental data. For this purpose, we used the Coefficient of Variation (CV) to compare the variability among the mean results when CV < 30% (homogeneous series with low dispersion) or CV ≥ 30% (heterogeneous series with strong dispersion).The mean absolute relative error (ε) was determined as described by [24] using the equation $\varepsilon = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{|\mathrm{Y}-\mathrm{Y0}|}{\mathrm{Y}}\right)$, where Y is the observed experimental value, Y0 is the value calculated using the models, and n is the number of experimental observations. The simulation was considered good (adjustments close to the experimental data) when $\varepsilon < 10$ and bad (adjustments further from the experimental data) when $\varepsilon \geq 10$ [25].

3. Results

3.1. Statistical Moments

Table 1 shows a CV > 20% for PR, θs, and Ωs due to the large amplitude of the values of these properties, and a low CV ≤ 20% for ρs due to their lower amplitude, indicating that the data collected in the field were accurate. The results are in line with [5] [6] [13] who also observed CV > 20% for PR, θs, and Ωs and low CV ≤ 20% for ρs when working on Oxisol under annual crops.

3.2. Adjustments to the PR Data Models as a Function of θs, ρs, and Ωs (Table 2)

Note that Model 1, with the PR data adjusted as a function of ρs and θs, explains 71% ($\mathrm{R}^2_{\mathrm{aj}} = 0.71$) of the variability of PR, whereas Model 2, with PR adjusted as a function of ρs, θs, and Ωs, explains 90% ($\mathrm{R}^2_{\mathrm{aj}} = 0.90$) of the variability of PR, improving prediction by 27%. Therefore, Model 2 fits better to the PR curve than Model 1, based on the resulting $\mathrm{R}^2_{\mathrm{aj}}$, mainly because Ωs is normally a variable soil property.

The coefficients of the two models (**Table 2**) were signed by the t-test ($p \leq 0.05$), indicating the existence of differences between groups referring to each model, and the signs indicate that PR varied positively with ρs and negatively with θs, in line with [5] [6] [13]. For Ωs, the variation in PR was also negative,

Table 1. Descriptive statistics for the variables analyzed at depths of 0 - 20 cm in Oxisols under no-tillage.

Variables*	N	Estatística Descritiva					
		Average	Standard Deviation	Mode	Minimum	Maximum	Variation Coefficient (%)
PR (MPa)	355	5.28	1.01	5.23	3.10	7.31	21.07
θs ($\mathrm{kg \cdot kg^{-1}}$)		0.18	0.05	0.21	0.08	0.33	28.78
ρs ($\mathrm{Mg \cdot m^{-3}}$)		1.46	0.14	1.54	1.12	1.73	09.57
Ωs ($\mathrm{g \cdot kg^{-1}}$)		16.33	6.39	10.33	8.45	33.66	39.14

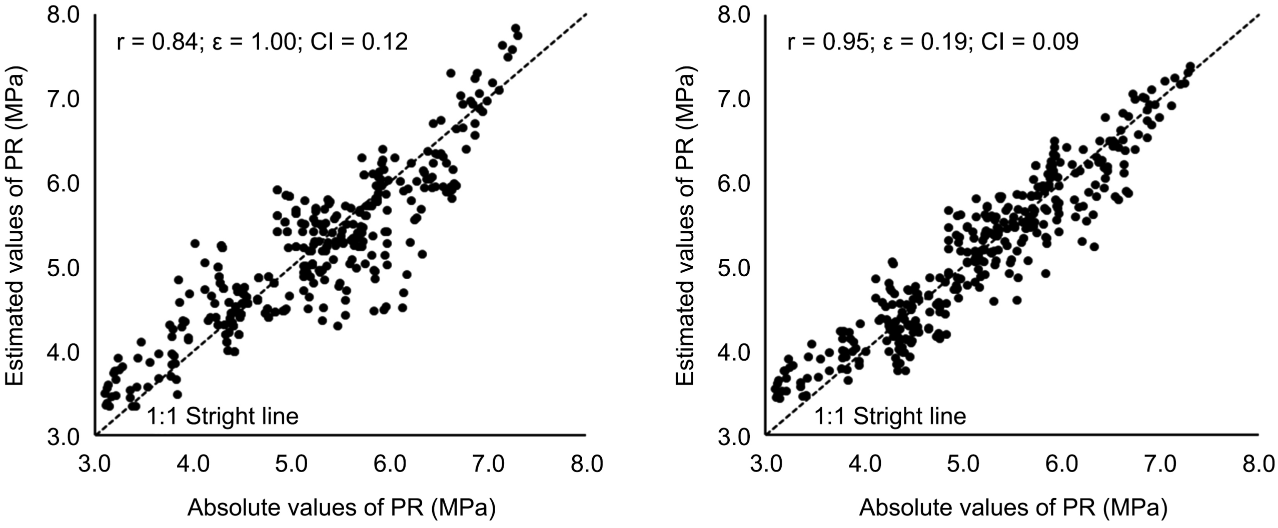
*PR = soil penetration resistance; ρs = bulk density; θs = soil gravimetric moisture content; and Ωs = soil organic matter content.

in disagreement with [6]. The highest absolute values for coefficients "a", "b" and "c" for Model 1 (**Table 2**) indicate that the PR estimates (**Figure 2**) adjusted in this model were higher than with the adjustments allowed in Model 2 (**Table 2**), including the variable Ωs.

Table 2. Linear regression coefficient estimated for soil penetration resistance curves ($\ln PR = \ln a + b\ln\theta s + c\ln\rho s$; $\ln PR' = \ln a + b\ln\theta s + c\ln\rho s + d\ln\Omega s$) for Oxisols under annual no-till farming.

Coefficient	Estimate	Standard Error	t	P-value
Model 1 (Without Organic Matter): $PR = 1.97{*}\theta s^{-0.23}{*}\rho s^{1.51}$ (R^2_{aj} = 0.71; F > Fsig.)				
a	0.725270	0.03497654	20.7361	0.000000
b	−0.205029	0.02115799	−9.6904	0.000000
c	1.488736	0.06225204	23.91465	0.000000
Model 2 (With Organic Matter): $PR' = 1.56{*}\theta s^{-0.19}{*}\rho s^{1.11}{*}\Omega s^{0.14}$ (R^2_{aj} = 0.90; F > Fsig.)				
a	0.261447	0.046913864	05.5730	0.000000
b	−0.284545	0.018364237	−15.4945	0.000000
c	1.254871	0.054029591	23.2256	0.000000
d	0.149589	0.012028303	12.4364	0.000000

PR: soil penetration resistance (MPa); ρs: bulk density ($Mg\cdot m^{-3}$); θs: soil gravimetric moisture content ($kg\cdot kg^{-1}$); Ωs: soil organic matter ($g\cdot kg^{-1}$).



(a): $PR = 1.97{*}\theta s^{-0.23}{*}\rho s^{1.51}$
(Without Organic Matter)

(b): $PR' = 1.56{*}\theta s^{-0.19}{*}\rho s^{1.11}{*}\Omega s^{0.14}$
(With Organic Matter)

Figure 2. Absolute (real) and estimated values for soil Penetration Resistance (PR) in Oxisol under annual no-till cropping. r: coefficient of correlation; ε: mean absolute relative error; CI: confidence interval.

4. Discussion

Our results showed that there is a close relationship between PR, θs, ρs, and Ωs. The direct relationship between PR and soil density results from the compaction and degradation of its structure [8] [9] [10] [11] [26]. The soil water content and organic matter inversely influence the PR [6] [10] [12] [27] [28] [29]. Water has a lubricating effect on the surrounding soil particles, that is, with its decrease, there is an increase in PR. The impact of organic matter is, probably, because she collaborates with the formation and stabilization of aggregates, acting in the structuring of the soil and increasing its porous space [30]-[35]. Besides this, organic matter affects soil cohesion and elasticity more than coarse mineral particles [3] and influences the friction between the particles by absorbing more water (lubricating effect around the soil particles) [6]. Therefore, the influence of Ωs on PR is considerable: PR decreases when the effects of Ωs on soil structure predominate (density reduction with an increase in porosity) and increases, when the impact of organic matter predominates in increasing soil tension, capillary action, cohesion between soil particles, soil plasticity, and shear parameters with reduced effect of water in reducing friction between particles [36] [37]. Therefore, it should not be disregarded in PR models.

A study [38] on mechanisms that make soils (Acrysols) vulnerable to compaction showed that the parameter "a" of an exponential model indicates the intrinsic resistance of dry soil, and the parameter "b" describes the influence of soil properties, such as mineralogical texture, organic matter, and density in soil resistance. Since our study investigated a Latosolo (Oxisol) soil with textural variation, the values obtained for parameter "b" (in this study named b, c, and d), and consequently the estimated PR, are probably more influenced by soil moisture content, bulk density, and organic matter content, as shown in Model 2 and withas reported by [6] [13].

The correlation (r) between the absolute and estimated values of PR in Oxisol under annual no-till cropping (**Figure 2**) was 0.84 for Model 1 and 0.95 for Model 2 (improving correlation by 13 %), revealing a high degree of positive correlation between the real and estimated values, as can be seen from the dispersion of points around the 1:1 straight line (**Figure 2**), indicating the ideal adjustment, *i.e.* the closer to the straight line, the greater the accuracy of the estimate [39]. In addition, the confidence interval (95 %) is not great, indicating the viability of the chosen model.

About deviations of the model-based estimated data from the experimental data (**Figure 2**), the mean absolute relative errors (ε) of the two models studied were adequate to describe PR, since $\varepsilon < 10\%$ (simulation – adjustments close to the experimental data) [25]. However, for Model 2, which includes Ωs in addition to θs and ρs, ε was 5.26 times smaller than the model. Thus, the proposed model, including Ωs as well as θs and ρs, allowed satisfactory fitting, based on the values of R^2, r, ε, and CI. Esses resultados estão em acordo com [6] [40].

5. Conclusion

The State of Paraná-Brazil is responsible for approximately 20% of all cereal production in the country, with more than one crop per year in a no-tillage system, which tends to cause soil compaction. Therefore, a 2012 study proposed a model with excellent results, good for data collected in the field, to evaluate the fit of the soil penetration resistance curve and study the compaction of a very clayey Latosol (clay content ~ 665 $g \cdot kg^{-1}$) in no-till. As only one type of texture was considered, this work aimed to evaluate the referred model in Latosols with varying clay contents under no-tillage. The results confirmed that the non-linear model which includes density, moisture, and soil organic matter content, proved to be efficient for the adjustment of the penetration resistance curve in the studied Latosols with significant variation in clay content and under no-tillage. The inclusion of organic matter allowed, in relation to the control model, a more excellent approximation of the resistance values obtained in the field of the 1:1 line and improved the coefficient of determination by 27% and the correlation coefficient by 13% and the relative error absolute was reduced by 5.26 times compared to a model that used only soil density and moisture.

Acknowledgments

We thank the National Council for Scientific Development for the scholarship and research grant to the first author and the Coordination for the improvement of the personnel of higher education for the scholarship granted to the third author.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Telles, T.S., Dechen, S.C.F. and Guimaraes, M.F. (2013) Institutional Landmarks in Brazilian Research on Soil Erosion: A Historical Overview. *Revista Brasileira de Ciência do Solo*, **37**, 1431-1440. https://doi.org/10.1590/S0100-06832013000600001

[2] Fuentes-Llanillo, R., Telles, T.S., Junior, D.S., Melo, T.R., Friedrich, T. and Kassam, A. (2021) Expansion of No-Tillage Practice in Conservation Agriculture in Brazil. *Soil and Tillage Research*, **208**, Article ID: 104877. https://doi.org/10.1016/j.still.2020.104877

[3] Soane, B.D. (1990) The Role of Organic Matter in Soil Compatibility: A Review of Some Practical Aspects. *Soil and Tillage Research*, **16**, 179-201. https://doi.org/10.1016/0167-1987(90)90029-D

[4] Da Silva, W.M., Bianchini, A. and Da Cunha, C.A. (2016) Modeling and Correction of Soil Penetration Resistance for Variations in Soil Moisture and Soil Bulk Density. *Engenharia Agrícola*, **36**, 449-459. https://doi.org/10.1590/1809-4430-Eng.Agric.v36n3p449-459/2016

[5] Gao, W., Watts, C.W., Ren, T. and Whalley, W.R. (2012) The Effects of Compaction and Soil Drying on Penetrometer Resistance. *Soil and Tillage Research*, **125**, 14-22. https://doi.org/10.1016/j.still.2012.07.006

[6] Tavares Filho, J., Feltran C.T.M., Oliveira, J.F. and Almeida, E. (2012) Modeling of Soil Penetration Resistance for an Oxisol under No-Tillage. *Revista Brasileira de Ciência do Solo*, **36**, 89-95. https://doi.org/10.1590/S0100-06832012000100010

[7] Jones, M. and Arp, P. (2017) Relating Cone Penetration and Rutting Resistance to Variations in Forest Soil Properties and Daily Moisture Fluctuations. *Open Journal of Soil Science*, **7**, 149-171. https://doi.org/10.4236/ojss.2017.77012

[8] Vaz, C.M.P., Bassoi, L.H. and Hopmans, J.W. (2001) Water Content and Bulk Density Contribution to Field Soil Penetration Resistance as Measured by a Combined Cone Penetrometer—TDR Probe. *Soil and Tillage Research*, **60**, 35-42. https://doi.org/10.1016/S0167-1987(01)00173-8

[9] Vaz, C.M.P., Manieri, J.M., De Maria, I.C. and Tuller, M. (2011) Modeling and Correction of Soil Penetration Resistance for Varying Soil Water Content. *Geoderma*, **166**, 92-101. https://doi.org/10.1016/j.geoderma.2011.07.016

[10] Busscher, W.J. (1990) Adjustment of Flat-Tipped Penetrometer Resistance Data to Common Moisture Content. *Transactions of the ASAE*, **33**, 519-524. https://doi.org/10.13031/2013.31360

[11] Busscher, W.J., Bauer, P.J., Camp, C.R. and Sojka, R.E. (1997) Correction of Cone Index Water Content Differences in Coastal Plain Soil. *Soil and Tillage Research*, **43**, 205-217. https://doi.org/10.1016/S0167-1987(97)00015-9

[12] Ribon, A.A. and Tavares Filho, J. (2004) Model Propositions for the Estimation of the Physical Quality of a Yellow Red Latosol (Oxisol) under Pasture. *Brazilian Archives of Biology and Technology*, **47**, 25-31. https://doi.org/10.1590/S1516-89132004000100004

[13] Ribon, A.A. and Tavares Filho, J. (2008) Estimativa da resistência mecânica à penetração de um Latossolo Vermelho sob cultura perene no norte do estado do Paraná. *Revista Brasileira de Ciência do Solo*, **32**, 1817-1825. https://doi.org/10.1590/S0100-06832008000500003

[14] To, J. and Kay, B.D. (2005) Variation in Penetrometer Resistance with Soil Properties: The Contribution of Effective Stress and Implications for Pedo Transfer Functions. *Geoderma*, **126**, 261-276. https://doi.org/10.1016/j.geoderma.2004.08.006

[15] Dexter, A.R., Czyz, E.A. and Gate, O.P. (2007) A Method for Prediction of Soil Penetration Resistance. *Soil and Tillage Research*, **93**, 412-419. https://doi.org/10.1016/j.still.2006.05.011

[16] Whalley, W.R., To, J., Kay, B.D. and Whitmore, A.P. (2007) Prediction of the Penetrometer Resistance of Soils with Models with Few Parameters. *Geoderma*, **137**, 370-377. https://doi.org/10.1016/j.geoderma.2006.08.029

[17] Santos, F.L., De Jesus, V.A.M. and Valente, D.S.M. (2012) Modeling of Soil Penetration Resistance Using Statistical Analyses and Artificial Neural Networks. *Acta Scientiarum. Agronomy*, **34**, 219-224. https://doi.org/10.4025/actasciagron.v34i2.11627

[18] Duarte, T.F., Da Silva, T.J.A., Bonfim-Silva, E.M. and Fenner, W. (2020) Resistance of a Red Latosol to Penetration: Comparison of Penetrometers, Model Adjustment, and Soil Water Content Correction. *Engenharia Agrícola*, **40**, 462-472. https://doi.org/10.1590/1809-4430-eng.agric.v40n4p462-472/2020

[19] Fernandes, M.M.H., Coelho, A.P., Da Silva, M.F., Bertonha, R.S., De Queiroz, R.F., Furlani, C.E.A. and Fernandes, C. (2020) Estimation of Soil Penetration Resistance with Standardized Moisture Using Modeling by Artificial Neural Networks. *Catena*, **189**, Article ID: 104505. https://doi.org/10.1016/j.catena.2020.104505

[20] Stolf, R. (1991) Teoria e teste experimental de fórmula de transformação dos dados de penetrômetro de impacto em resistência do solo. *Revista Brasileira de Ciência do*

Solo, **15**, 229-235.

[21] ASABE Standards (2010) S313.3. Soil Cone Penetrometer. 57th Edition, ASABE, St. Joseph.

[22] Tavares-Filho, J. and Magalhães, F.S. (2008) Dispersão de amostras de Latossolo Vermelho eutroférrico influenciadas por pré-tratamento para oxidação da matéria orgânica e pelo tipo de agitação mecânica. *Revista Brasileira de Ciência do Solo*, **32**, 1429-1435. https://doi.org/10.1590/S0100-06832008000400007

[23] Claessen, M.E.C. (1997) Manual de métodos de análise de solo. 2nd Edition, Embrapa-CNPS, Rio de Janeiro, 212 p.

[24] Khoury Júnior, J.K., Dias, G.P., Cordeiro, R.R. and Souza, C.M.A. (2004) Modelagem da estabilidade de tratores agrícolas de pneus. *Pesquisa Agropecuária Brasileira*, **39**, 459-468. https://doi.org/10.1590/S0100-204X2004000500008

[25] Mohapatra, D. and Rao, P.S. (2005) A Thin Layer Drying Model of Parboiled Wheat. *Journal of Food Engineering*, **66**, 513-518. https://doi.org/10.1016/j.jfoodeng.2004.04.023

[26] Lin, J., Sun, Y. and Schulze Lammers, P. (2014) Evaluating Model-Based Relationship of Cone Index, Soil Water Content and Bulk Density Using Dual-Sensor Penetrometer Data. *Soil and Tillage Research*, **138**, 9-16. https://doi.org/10.1016/j.still.2013.12.004

[27] Carter, M.R. (1990) Relations of Strength Properties to Bulk Density and Macroporosity in Cultivated Loamy Sand to Loam Soils. *Soil and Tillage Research*, **15**, 257-268. https://doi.org/10.1016/0167-1987(90)90082-O

[28] Balland, V., Pollacco, J.A.P. and Arp, P.A. (2008) Modeling Soil Hydraulic Properties for a Wide Range of Soil Conditions. *Ecological Modelling*, **219**, 300-316. https://doi.org/10.1016/j.ecolmodel.2008.07.009

[29] Vega-Nieva, D.J.D., Murphy, P.N.C., Castonguay, M., Ogilvie, J. and Arp, P.A. (2009) A Modular Terrain Model for Daily Variations in Machine-Specific Forest Soil Trafficability. *Canadian Journal of Soil Science*, **89**, 93-109. https://doi.org/10.4141/CJSS06033

[30] Tisdall, J.M. and Oades, J.M. (1982) Organic Matter and Water-Stable Aggregates in Soil. *European Journal of Soil Science*, **33**, 141-163. https://doi.org/10.1111/j.1365-2389.1982.tb01755.x

[31] Horn, R., Taubner, H., Wuttke, M. and Baumgartl, T. (1993) Soil Physical Properties Are Related to Soil Structure. *Soil and Tillage Research*, **30**, 187-216. https://doi.org/10.1016/0167-1987(94)90005-1

[32] Macedo, S.F.S., Grimaldi, M., Medina, C.C., Cunha, J.E., Guimarães, M.F. and Tavares Filho, J. (2017) The Physical Properties of Soil Structures Are Identified by the Profile Culture under Two Soil Management Systems. *Revista Brasileira de Ciência do Solo*, **41**, e0160503. https://doi.org/10.1590/18069657rbcs20160503

[33] Watanabe, R., Tormena, C.A., Guimarães, M.F., Tavares Filho, J., Ralisch, R., Franchini, J. and Debiasi, H. (2018) Is the Structural Quality as Assessed by the "Profil Cultural" Method Related to Quantitative Soil Physical Quality Indicators? *Revista Brasileira de Ciência do Solo*, **42**, e0160393. https://doi.org/10.1590/18069657rbcs20160393

[34] Melo, T.R., Pereira, M.G., Barbosa, G.M.C., Neto, E.C.S. andrello, A.C. and Tavares Filho, J. (2019) Biogenic Aggregation Intensifies Soil Improvement Caused by Manures. *Soil and Tillage Research*, **190**, 186-193. https://doi.org/10.1016/j.still.2018.12.017

[35] Melo, T.R., Figueiredo, A. and Tavares Filho, J. (2021) Clay Behavior Following

Macroaggregate Breakdown in Ferralsols. *Soil and Tillage Research*, **207**, Article ID: 104862. https://doi.org/10.1016/j.still.2020.104862

[36] Tavares Filho, J., Grimamldi, M. and Tessier, D. (2005) Compressibilidade de agregados de um Latossolo Amarelo da Amazônia em resposta ao potencial da água do solo. *Revista Brasileira de Ciência do Solo*, **29**, 489-495. https://doi.org/10.1590/S0100-06832005000400001

[37] Tavares Filho, J. and Tessier, D. (2009) Characterization of Soil Structure and Porosity under Long-Term Conventional Tillage and No-Tillage Systems. *Revista Brasileira de Ciência do Solo*, **33**, 1837-1844. https://doi.org/10.1590/S0100-06832009000600032

[38] Peng, X.H., Horn, R., Zhang, B. and Zaho, Q.G. (2004) Mechanisms of Soil Vulnerability to Compaction of Homogenized and Recompacted Ultisols. *Soil and Tillage Research*, **76**, 125-137. https://doi.org/10.1016/j.still.2003.09.006

[39] Zhuang, J., Jin, Y. and Miyazaki, T. (2001) Estimating Water Retention Characteristics from Soil Particle-Size Distribution Using a Non-Similar Media Concept. *Soil Science*, **166**, 308-321. https://doi.org/10.1097/00010694-200105000-00002

[40] Smith, C.W., Johnston, M.A. and Lorentz, S. (1997) The Effect of Soil Compaction and Soil Physical Properties on the Mechanical Resistance of South African Forest Soils. *Geoderma*, **78**, 93-111. https://doi.org/10.1016/S0016-7061(97)00029-3