MODELING OF SOIL LOAD-BEARING CAPACITY AS A FUNCTION OF SOIL MECHANICAL RESISTANCE TO PENETRATION

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ABSTRACT

Estimation of soil load-bearing capacity from mathematical models that relate preconsolidation pressure (σp) to mechanical resistance to penetration (PR) and gravimetric soil water content (U) is important for defining strategies to prevent compaction of agricultural soils. Our objective was therefore to model the σp and compression index (CI) according to the PR (with an impact penetrometer in the field and a static penetrometer inserted at a constant rate in the laboratory) and U in a Rhodic Eutrudox. The experiment consisted of six treatments: no-tillage system (NT); NT with chiseling; and NT with additional compaction by combine traffic (passing 4, 8, 10, and 20 times). Soil bulk density, total porosity, PR (in field and laboratory measurements), U, σp, and CI values were determined in the 5.5-10.5 cm and 13.5-18.5 cm layers. Preconsolidation pressure (σp) and CI were modeled according to PR in different U. The σp increased and the CI decreased linearly with increases in the PR values. The correlations between σp and PR and PR and CI are influenced by U. From these correlations, the soil load-bearing capacity and compaction susceptibility can be estimated by PR readings evaluated in different U.

Keywords: Rhodic Eutrudox, no-tillage system, machinery traffic, soil compaction.

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RESUMO: ***MODELAGEM DA CAPACIDADE DE SUPORTE DE CARGA EM RAZÃO DA RESISTÊNCIA MECÂNICA DO SOLO À PENETRAÇÃO***

A estimativa da capacidade de suporte de carga do solo a partir de modelos matemáticos que relacionam a pressão de preconsolidação (σp), a resistência mecânica do solo à penetração (RP) e o conteúdo gravimétrico de água do solo (U) é importante na definição de estratégias para prevenção da compactação de solos agrícolas. Portanto, objetivou-se modelar a σp e o índice de compressão (IC) em função da RP (em campo com penetrômetro de impacto e em laboratório com penetrômetro digital de bancada) e do U em um Latossolo Vermelho. O experimento foi composto por seis tratamentos: sistema plantio direto (SPD); SPD com escarificação; e SPD com compactação adicional pelo tráfego de uma colhedora por 4, 8, 10 e 20 passadas. Os valores de densidade do solo, porosidade total, RP (no campo e no laboratório), U, σp e IC foram determinados nas camadas de 5,5-10,5 cm e 13,5-18,5 cm. A modelagem da σp e do IC foi realizada em função da RP em diferentes U. A σp aumentou e o IC diminui linearmente com incremento nos valores de RP. As relações entre σp e RP e IC e RP são influenciadas pelo U. A partir dessas relações, é possível estimar a capacidade de suporte de carga e a suscetibilidade do solo à compactação por meio das leituras de RP, avaliadas em diferentes U.

Palavras-chave: Latossolo Vermelho distroférrico, sistema plantio direto, tráfego de máquinas, compactação do solo.

INTRODUCTION

Compaction is a major cause of soil physical degradation and stunted plant growth. The process is defined as a reduction in the volume (compression) of an unsaturated soil induced by causes of an anthropogenic nature that reduce pore space by expulsion of air and, in some cases, of water (Hillel, 1982). The physical condition resulting from the soil compaction process is called the state of compaction, evaluated by degrees, and, to some extent, all soils have a degree of compaction (Silva et al., 2002). However, soil is considered compacted when the magnitude of compaction exceeds a certain threshold, above which restrictions to plant development are observed.

Continuous traffic of agricultural machines, especially at high soil moisture, can lead to excessive compaction in the soil surface and subsurface (Saffih-Hdadi et al., 2009). A very common way to assess the state of soil compaction is by means of soil penetration resistance (PR) with a cone penetrometer (Moraes et al., 2013, 2014a,b), due to its practicality, speed, and low cost. However, the variation in PR according to change in bulk density (Bd) is influenced by soil water content, which can be a source of misinterpretation (Moraes et al., 2013, 2014a,b). Another method of assessing the state of soil compaction is by the compression curve, from which the preconsolidation pressure (σp) and compression index (CI) can be determined (Saffih-Hdadi et al., 2009; An et al., 2015). However, these mechanical parameters are also influenced by the water content and the initial state of soil compaction (Suzuki et al., 2008; Saffih-Hdadi et al., 2009). Therefore, the establishment of Bd correlations, of gravimetric water content in the soil (U), and of PR with CI and σp can more precisely indicate the degree of compaction of agricultural soils.

Avoiding pressures exceeding the load-bearing capacity, estimated by σp, constitutes the main strategy for prevention of soil compaction (Saffih-Hdadi et al., 2009). However, collection and analysis of soil samples to determine σp are expensive and time-consuming procedures, difficult to carry out on a field scale (Dias Júnior et al., 2004). Mathematical models must therefore be fitted through which σp can be estimated from readily measurable variables on the field scale, such as PR. In this regard, several research studies have demonstrated the existence of significant mathematical correlations between σp and PR (Mosaddeghi et al., 2003; Dias Júnior et al., 2004; Lima et al., 2006; Suzuki et al., 2008), indicating the possibility of accurate estimates of soil load-bearing capacity using PR as a dependent variable. However, most of these models do not consider the effect of U at the time of PR determination, or their databases have small variations in the degree of soil compaction, limiting their application. In addition, the ratio of σp *versus* PR depends on all factors that influence either one of the variables (soil moisture, Bd, texture, and organic matter content, among others), so it must be determined under different soil conditions.

Thus, the hypothesis is that σp and CI values can be estimated by soil functions correlated to the PR in each U range. The aim of this study was to model the correlations of preconsolidation pressure and compression index according to PR at different moisture and degrees of compaction in a Rhodic Eutrudox.

MATERIAL AND METHODS

The experiment was carried out on an experimental farm of Embrapa Soja in Londrina, PR, Brazil (23° 11’ S and 51° 11’ W). The soil of the study area has been farmed under no-tillage (NT) since 1996, and was classified as a *Latossolo Vermelho distroférrico* (Santos et al., 2013) or Rhodic Eutrudox (Soil Survey Staff, 2010). The soil properties of the 0-20 cm layer were a very clayey texture (731 g kg^{-1} clay, 146 g kg^{-1} silt, and 123 g kg^{-1} sand), particle density of 2.96 kg dm^{-3}, and 18.50 g kg^{-1} of organic carbon.

The experiment was arranged in a completely randomized block design, with two replications. The treatments, allocated in plots (evaluated area of 2.5 × 20 m), consisted of six degrees of compaction: (a) chiseled no-tillage (CNT); (b) NT without chiseling and without additional compaction (NTWC); and compacted NT, under additional compaction of a self-propelled grain harvester (combine) at four traffic intensities, passing (c) 4 times (NTC4); (d) 8 times (NTC8); (e) 10 times (NTC10); and (f) 20 times (NTC20). The additional compaction was applied on 08/16/2010 by means of a combine (weight, 66 kN) equipped with a platform header (weight, 12 kN) and filled grain tank (wheat - weight, 22kN), for a total weight of 100 kN (70 kN on the front axle). The combine had a total mass of 10.28 Mg, with a static distribution of 70 % of the weight on the front axle, and front tire contact pressure with the ground. The combine was equipped with front tires, 18.4-30 R1, diagonal, and inflation pressure of 180 kPa; and rear tires 9.00-16 10PR F2, diagonal, with inflation pressure of 410 kPa, and a track width of 2.4 m. The tire-soil contact pressure under the front axle was estimated at 230 kPa, by a procedure proposed by O'Sullivan et al. (1999). According to this method, the tire-soil contact area was estimated considering the width and height of the tire, inflation pressure, and load on the axles, using an empirical model developed for rigid surfaces. Chiseling was performed by means of a chisel plow with five shanks spaced 35 cm apart, to a depth of 30 cm. The soil had a friable consistency (U = 0.28 kg kg^{-1}) at chiseling.

After application of the treatments, the experiment was irrigated (water level 100 mm) to standardize and raise U to values above 0.2 kg kg^{-1} (field capacity determined by Moraes et al., 2012). In the field, PR was determined (PR_F) as described by Moraes et al. (2013), eight times (2, 4, 7, 9, 11, 14, 23, and 31 days after irrigation), which resulted in a wide range of variation in U values since no rain fell throughout the experimental period (see table 1). The PR_F was determined in the 5.5-10.5 and 13.5-18.5 cm layers, as described in ASABE (2010), with an impact penetrometer (IAA/Planalsucar -Stolf) (Stolf, 1991), equipped with a cone (base area 130 mm^2 and solid angle 30º). The PR_F was measured at eight points at a spacing of 15 cm on a transect transversal to the tracks of the combine and/or of the chiseler. For each evaluation, we used two replications (transects) per degree of compaction. Along each transect, two soil samples were collected (5.5-10.5 and 13.5-18.5 cm layers) to determine U, as described by Embrapa (1997).

Table 1. Range of variation of gravimetric water content in the soil (U) for each evaluation of soil resistance to penetration, measured with a field penetrometer (PR_F)

Evaluation (DAI)	Layer			
	5.5-10.5 cm		13.5-18.5 cm	
	U Min	U Max	U Min	U Max
	g g^{-1}			
2	0.315	0.341	0.330	0.348
4	0.304	0.323	0.322	0.336
7	0.275	0.309	0.314	0.323
9	0.247	0.298	0.305	0.320
11	0.237	0.288	0.291	0.313
14	0.230	0.263	0.309	0.276
23	0.213	0.249	0.256	0.289
31	0.205	0.226	0.236	0.263

Evaluation (DAI): time of evaluation of PR_F estimated in days after irrigation; U Min: lowest gravimetric water content in the soil for all treatments (CNT, NTWC, NTC4, NTC8, NTC10, NTC20); U Max: highest gravimetric water content in the soil for all treatments (CNT, NTWC, NTC4, NTC8, NTC10, NTC20).

Undisturbed soil samples were collected in stainless steel rings (height 5 cm × diameter 5 cm) inserted horizontally by means of a hydraulic jack into the center of the 5.5-10.5 and 13.5-18.5 cm layers, on the sides of open trenches in each plot, resulting in a total of 312 samples. Initially, the samples were divided into two groups, from which 240 samples were used to assess PR with a static penetrometer (PR_L) (group 1) and 72 samples to determine the soil compression curve (group 2).

The 240 soil samples of group 1 were divided into 5 groups of 48 samples, which were subjected to the following matric potentials: -6 kPa (by tension table), -10, -33, -100, and -500 kPa (Richards extractors). After equilibration at the different potentials, the samples were used to determine PR_L, by means of a horizontal penetrometer equipped with a cone (base area of 12.56 mm^2, angle 60°) and inserted into the soil at a speed of 20 mm min^{-1}. The 72 samples of group 2 were water saturated, balanced at a potential of -6 kPa by tension table, and then subjected to the uniaxial compression test by a Masqueto pneumatic consolidometer. Sequential loads of 25, 50, 100, 200, 400, 800, and 1,600 kPa were applied for 5 min (Silva et al., 2007). After the tests, the samples were dried at 105-110 °C for 24 h, allowing the calculation of Bd and total porosity (Pt), as suggested by Embrapa (1997).

Maximum soil bulk density (Bd_{max}) was obtained with the application of a load of 1,600 kPa; the relative soil bulk density (Bd_{rel}) was obtained by the ratio of Bd and Bd_{max}. The correlation between σp and PR was obtained by equation 1:

$$\text{Ratio } \sigma p{:}PR = 1/a \quad \text{Eq. 1}$$

where ratio σp:PR is the correlation between preconsolidation pressure (σp) and soil mechanical resistance to penetration (PR); and a is the slope coefficient of the linear equation fitted to estimate σp as a function of PR.

Means were subjected to analysis of variance by the F test ($p<0.05$). In the case of significance of the treatment effects, the means were compared by the Tukey test ($p<0.05$) using the Statistical Analysis System (SAS, 1999). The equations to estimate σp from PR_F or PR_L were fitted by regression analysis, using the software Sigmaplot® 12.5 (Systat Software, Inc.).

RESULTS

In the CNT system, the Bd_{Rel} was lower and Pt higher than in the other treatments in the 5.5-10.5 cm and 13.5-18.5 cm layers (Figures 1a and 1b). In the soil layer nearer the surface (5.5-10.5 cm), the Bd_{Rel} was lower in NTWC than in all treatments with additional compaction (NTC4, NTC8, NTC10, and NTC20). In contrast, in the 13.5-18.5 cm layer, the Bd_{Rel} values in treatment NTWC did not differ from the treatments with additional compaction, except in NTC10 (Figure 1a). With regard to Pt, it was observed that, in the 5.5-10.5 cm layer, the values were highest in CNT. The NTWC resulted in higher values compared to NTC10 and NTC20, which did not differ. In the same layer, the Pt values were intermediate in the treatments NTC4 and NTC8, with no difference from the treatments NTWC, NTC10, and NTC20. In the deeper layer however, the Pt values had the following order: CNT>NTWC>NTC4 = NTC8>NTC10, and NTC20.

In both layers evaluated, the σp values were significantly higher in treatments with additional compaction by combine traffic than in CNT (Figure 1c). In most situations, the σp values in NTWC were intermediate, not differing from the other treatments. However, in the 13.5-18.5 cm layer, σp was significantly lower in NTWC than NTC10. In the 5.5-10.5 cm layer, the CI was higher in CNT than in the other treatments, lower in NTC10 and NTC20, and statistically different from all treatments but NTC8 (Figure 1d). In the deeper layer, the largest CI of all treatments was once more observed for CNT. In this layer, NTWC had a higher CI in relation to NTC10, but did not differ significantly from NTC4, NTC8, and NTC20.

The CI had a negative exponential correlation to the increase in Bd_{Rel} values (Figure 2). The significant correlation between Bd_{Rel} and CI values indicates that both variables may be used to identify soils with higher degrees of compaction and, consequently, lower physical quality.

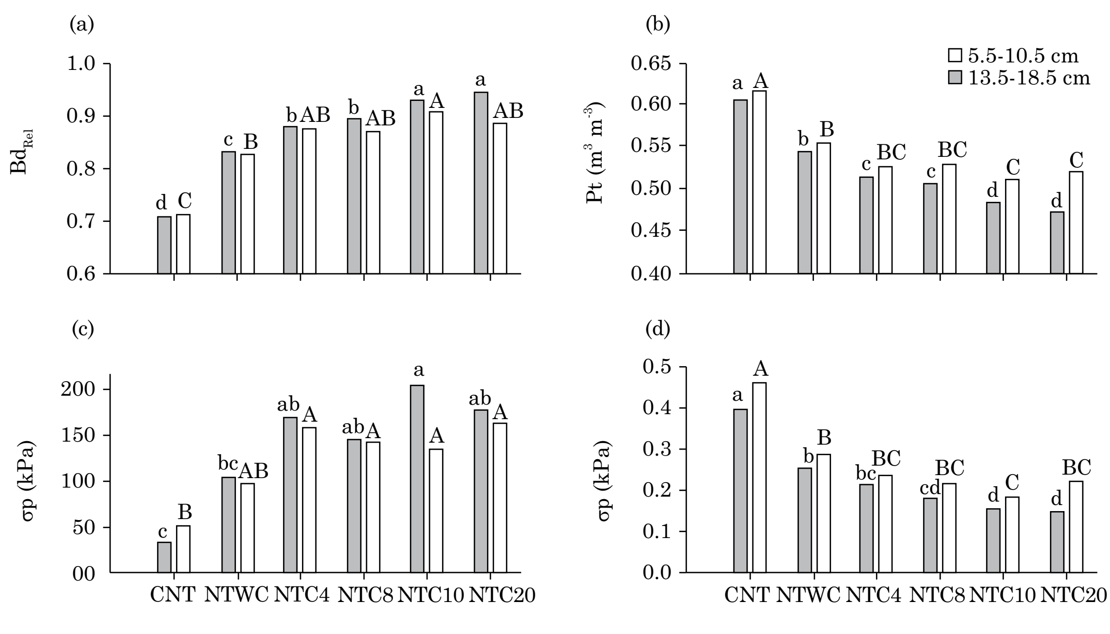

Figure 1. Relative bulk density (Bd_{Rel}) (a), total porosity (Pt) (b), preconsolidation pressure (σp) (c), and compression index (CI) (d) as related to degrees of compaction [no-tillage (NT) chiseled (CNT); NT without additional compaction (NTWC); NT with additional compaction of a combine passing 4 (NTC4), 8 (NTC8), 10 (NTC10), and 20 (NTC20) times] over a Rhodic Eutrudox. Means followed by the same uppercase letter (5.5 - 10.5 cm layer) or lowercase letter (13.5-18.5 cm layer) do not differ by the Tukey test (p<0.05).

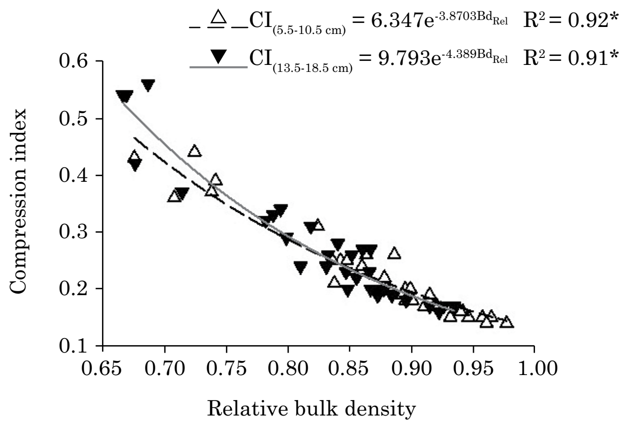

Figure 2. Correlation of relative density (Bd_{Rel}) and compression index (CI) in the 5.5-10.5 cm and 13.5-18.5 cm layers of a Rhodic Eutrudox.

The PR_F varied due to variations in U in the different evaluations (Figure 3). In general, PR_F increased over time, due to the reduction in U, and this increase was greater in treatments with higher degrees of compaction. At the time of assessment, PR_F was little influenced by the degree of soil compaction. In contrast, the effects of degree of compaction on PR_F depended on U. Thus, in both layers evaluated, PR_F was generally lower in CNT than in the other treatments, regardless of the time of evaluation. In the 5.5-10.5 cm layer, the traffic treatments induced a higher PR_F than NTWC, except for the evaluations performed at higher U values. This was observed at 2 days and 4 days after irrigation, when NTWC did not differ significantly from NTC4 at 5.5-10.5 cm layer (Figure 3a); and NTWC was similar to NTC4, NTC8 and NTC10 at 5.5-10.5 cm layer (Figure 3b). Significant differences in PR_F between traffic treatments appeared only in the last two evaluations (Figures 3g and 3h) at lower U values. In these cases, PR_F increased with the increase in traffic intensity of the combine. The differences for U, however, were significant for the 5.5-10.5 m layer at 2, 9, and 23 days after irrigation (Figures 3a, 3d, and 3g, respectively) and for the 13.5-18.5 cm layer at 23 days after irrigation (Figure 3g). In the 13.5-18.5 cm layer, consistent differences between NTWC and traffic treatments were only detected in the last three evaluations (Figures 3f, 3g, and 3h). In these assessments, PR_F was higher in the traffic treatments than in NTWC. Comparing only the traffic treatments, the PR_F in the 13.5-18.5 cm layer was generally higher for treatments with greater traffic intensity, although these differences were only significant in the last two evaluations (Figures 3g and 3h). This may have occurred particularly because of cracks formed at the time of penetration of the penetrometer cone, mainly at lower U, causing reductions in PR in NTC20 and reducing the differences between traffic treatments.

The PR_L increased due to the decrease in U as a result of the balance of the samples at more negative potentials (Figure 4). Regardless of the matric potential of the samples, the PR_L was significantly lower in CNT compared to the treatments with additional combine traffic, in both layers. However, unlike what was observed for PR_F, PR_L was significantly lower in CNT than in NTWC only in samples with the highest U, equilibrated at -6 kPa (Figure 4a), -10 kPa (Figure 4b), and -33 kPa (Figure 4c), in both layers. In general, in the upper soil layer evaluated, PR_L in NTWC was similar to NTC4, but lower than in NTC8, NTC10, and NTC20. In the 13.5-18.5 cm layer, the NTWC had similar PR_L values for all traffic treatments when the samples were equilibrated at -100 (Figure 4d) and -500 (Figure 4e) kPa. At other potentials (Figures 4a, 4b, and 4c), the PR_L in the 13.5-18.5 cm layer in NTWC was similar to NTC4, NTC8, and NTC10, but lower than at the higher traffic intensities.

Considering the same soil water potential, the correlation between the CI and PR_L was negatively linear in both layers (Figures 5a and 5b), indicating that the higher the initial degree of soil compaction, the lower the susceptibility to this process. The straight lines representing the CI × PR_L interaction (Figures 5a and 5b) were shifted to the right as the water potential diminished. This shows that increasing PR_L values resulting from a reduction in U at the time of penetrometer testing result in similar CI values. Additionally, there was an increase in slope (in module) of the equations with increasing soil moisture, indicating that the more compacted the soil, the greater the influence of U on the estimate of CI from PR_L.

At the same water potential of the soil, σp exhibited a linear increase with increasing PR_L (Figures 5c and 5d). Like CI, the straight lines that represent the σp × PR_L interaction were shifted to the right as the water potential became more negative, showing that increasing PR_L, induced by a reduction in U, results in values similar to σp. Likewise, the slope of the equations increased as the water potential in the soil increased (from -500 kPa to -6 kPa) (Table 2), indicating that the effect of U on σp estimates as related to PR_L is highest at the highest degrees of soil compaction.

The coefficients of determination (R^2) of the equations between CI and σp with the PR_F were greater than 0.80, indicating that the data are satisfactorily explained by these equations. As also observed for PR_L (Figure 5), at the same evaluation time, the CI variables (Figure 6a and 6b) and σp (Figure 6c and 6d) had positive and negative linear correlations, respectively, with PR_F, in both layers. However, the effect of U on CI and σp estimated

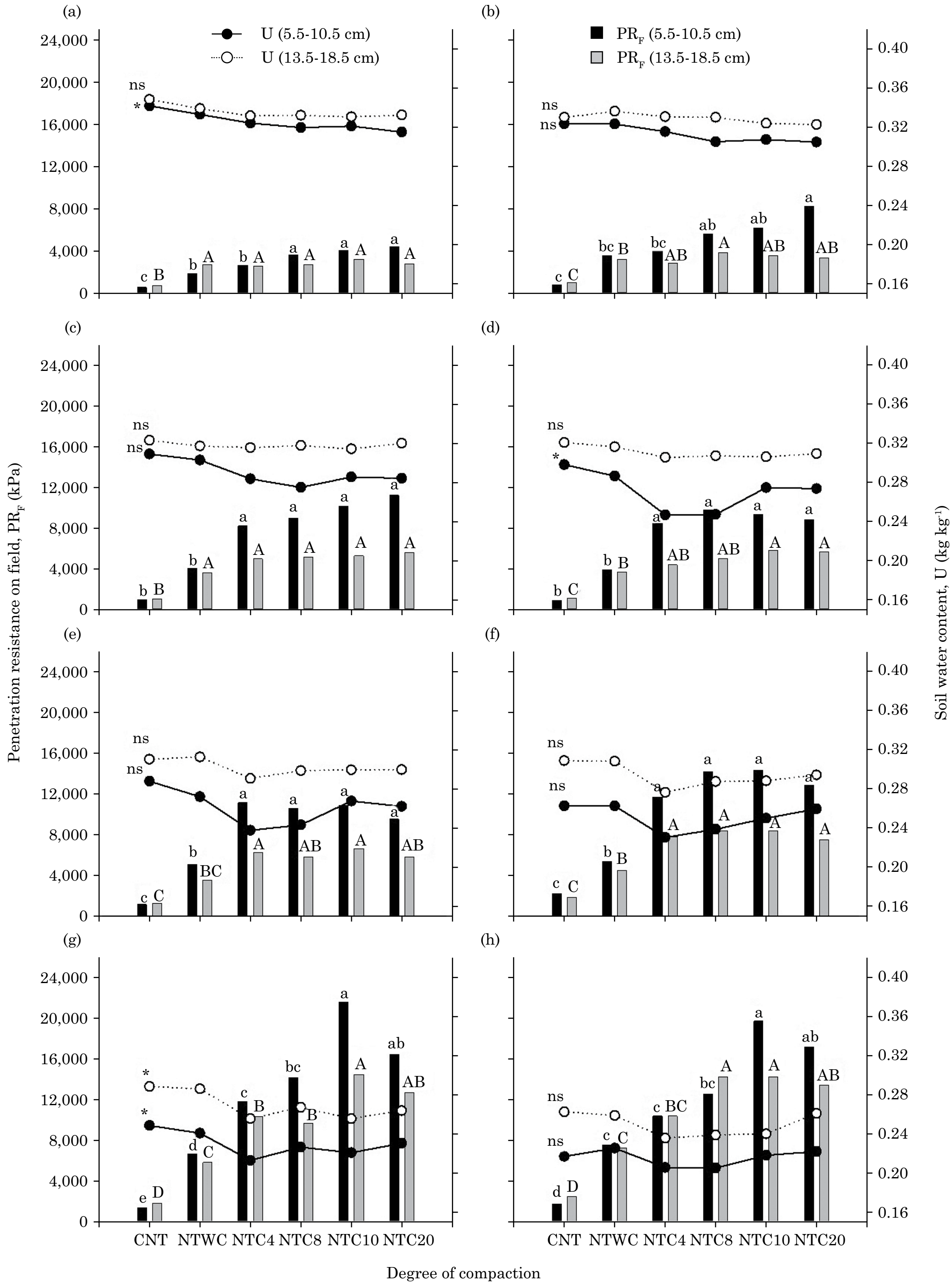

Figure 3. Values of soil mechanical resistance to penetration in the field (PR_F) and gravimetric content of the soil as related to degrees of compaction [no-tillage (NT) chiseled (CNT); NT without additional compaction (NTWC); NT with additional compaction of a combine passing 4 (NTC4), 8 (NTC8), 10 (NTC10), and 20 (NTC20) times] over a Rhodic Eutrudox, in the 5.5-10.5 and 13.5-18.5 cm layers (adapted from Moraes et al, 2013) for each evaluation period: 2 (a), 4 (b), 7 (c), 9 (d), 11 (e), 14 (f), 23 (g), and 31 (h) days after irrigation. Means followed by the same uppercase letter (5.5-10.5 cm layer) or lowercase letter (13.5-18.5 cm layer) do not differ by the Tukey test (p<0.05); ns: not significant by the F test (p<0.05).

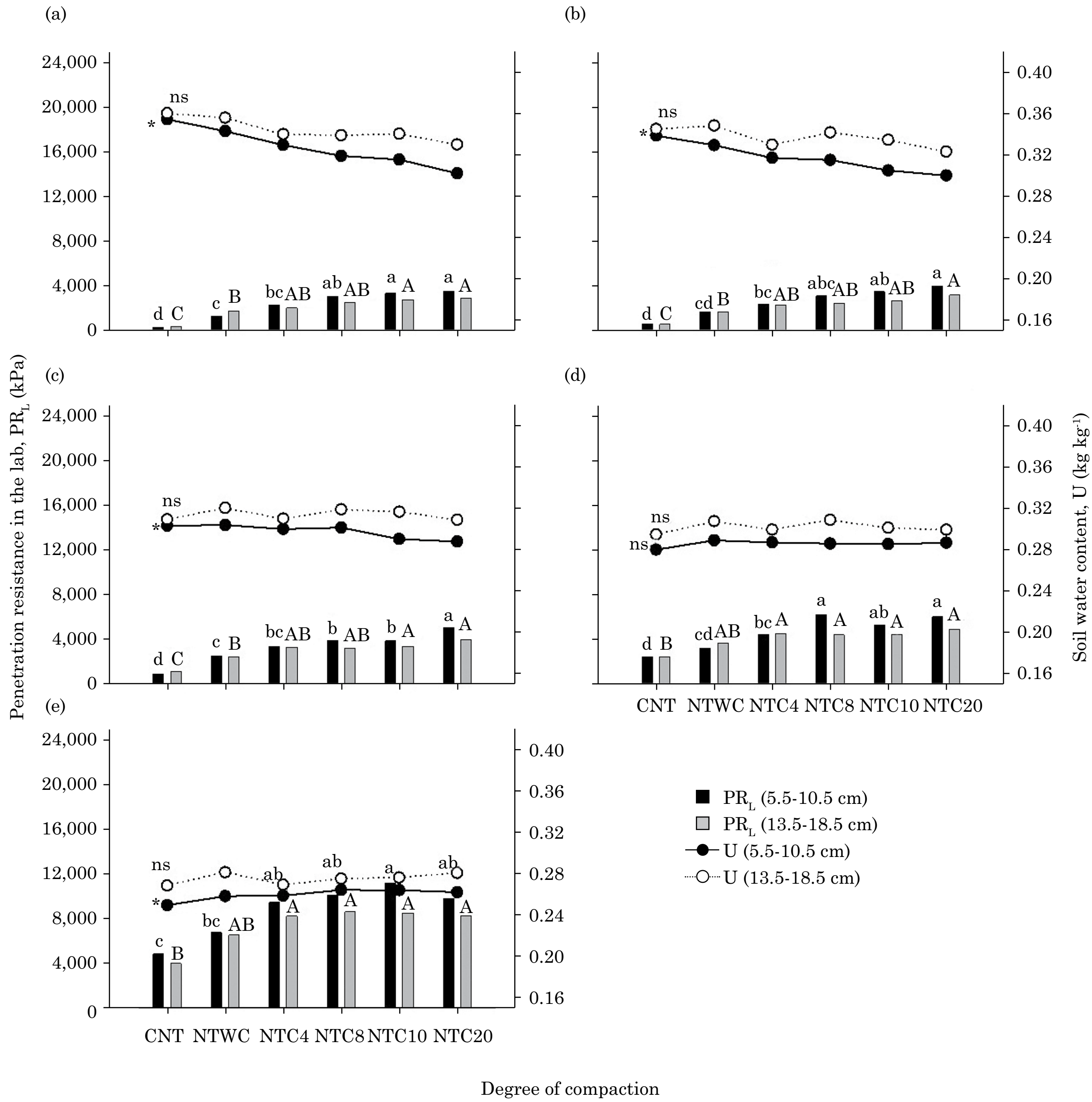

Figure 4. Mechanical strength of soil penetration in the laboratory (PR_L) and gravimetric soil water content, as related to degrees of compaction [no-tillage (NT) chiseled (CNT); NT without additional compaction (NTWC); NT with additional compaction of a combine passing 4 (NTC4), 8 (NTC8), 10 (NTC10), and 20 (NTC20) times] over a Rhodic Eutrudox, in the 5.5-10.5 and 13.5-18.5 cm layers, the matric potential of -6 (a), 10 (b), -33 (C), -100 (D), -500 KPa (e). Means followed by the same uppercase letter (5.5-10.5 cm layer) or lowercase letter (13.5-18.5 cm layer) do not differ by the Tukey test (p<0.05); ns: not significant by the F test (p<0.05).

from PR_F was contrary to that observed when the independent variable was PR_L. At low degrees of initial soil compaction, the influence of the time interval between irrigation and PR_F evaluation on CI and σp estimated from PR_F was small. As this interval increases, resulting in lower U values, the slope of the equations CI × PR_F and PR_F × σp (Table 2) decreased, due to the greater amplitude of variation of PR_F values as a function of the degree of soil compaction. Thus, the effect of U on the CI and σp estimates derived from PR_F and PR_L increases with increasing degrees of soil compaction.

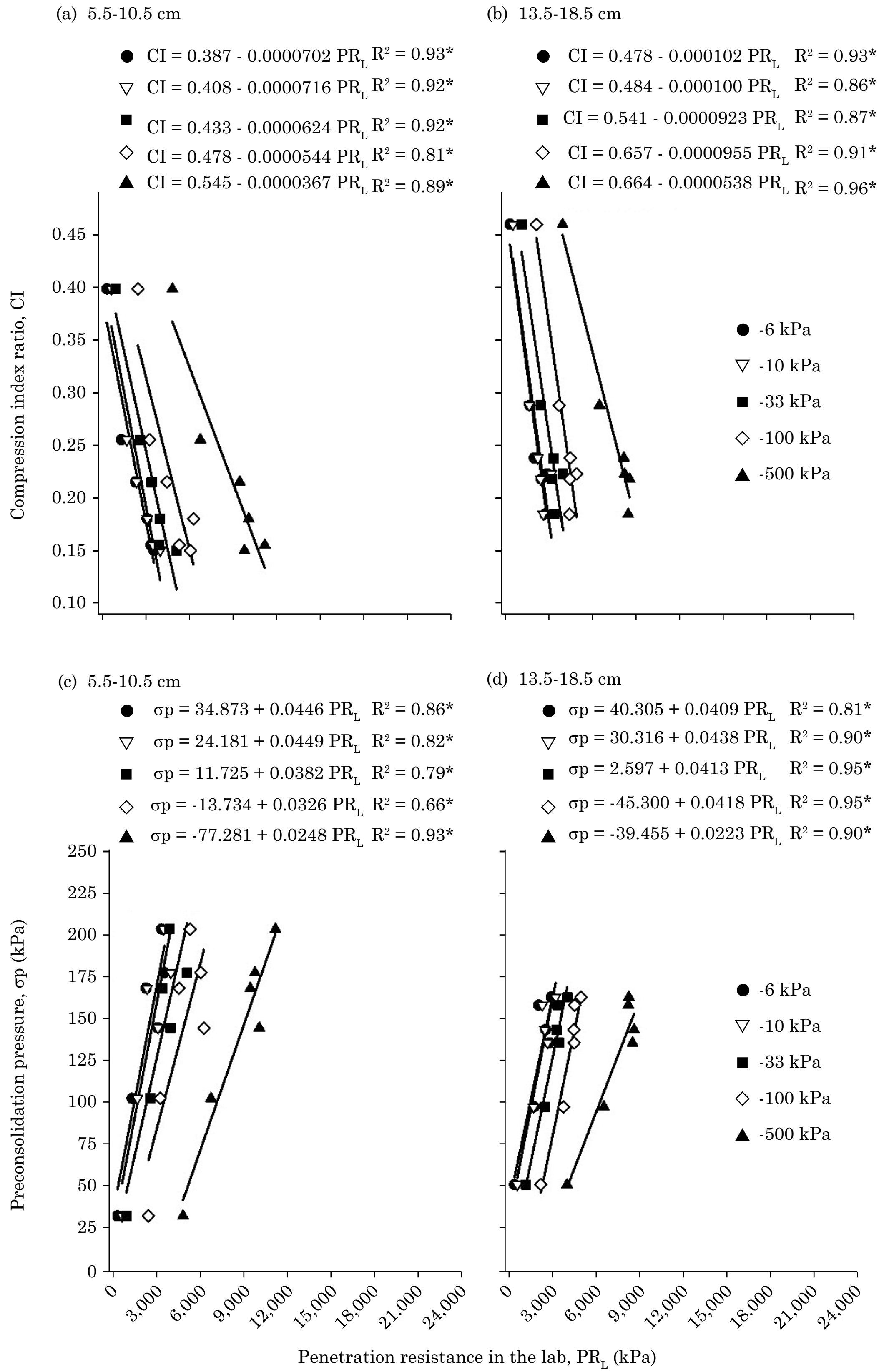

Figure 5. Compression index ratio - CI (a, b) and preconsolidation pressure - σp (c, d) with the soil mechanical resistance to penetration of a Rhodic Eutrudox measured with a static penetrometer (PR_L) at different soil water potentials, in the 5.5-10.5 and 13.5-18.5 cm layers.

Table 2. Angular coefficients of the first degree equation(1) of the correlation between preconsolidation pressure (σp) and penetration resistance (PR), as related to the variation in soil water content due to different water potentials in the soil (static penetrometer) or to the number of days after irrigation (impact penetrometer)

Potential	Slope	Ratio σp:PR	Slope	Ratio σp:PR
	5.5-10.5 cm		13.5-18.5 cm	
	Static penetrometer			
	0.0446	1:22	0.0409	1:24
-10 kPa	0.0449	1:22	0.0438	1:23
-33 kPa	0.0382	1:26	0.0413	1:24
-100 kPa	0.0326	1:30	0.0418	1:24
-500 kPa	0.0248	1:40	0.0223	1:45
Seasons	Impact pentrometer			
Evaluation 1st	0.0386	1:26	0.0403	1:25
Evaluation 2nd	0.0187	1:53	0.0334	1:30
Evaluation 3rd and 4th	0.0151	1:66	0.0232	1:43
Evaluation 5th	0.0143	1:70	0.0185	1:54
Evaluation 6th	0.0108	1:93	0.0143	1:70
Evaluation 7th and 8th	0.0087	1:115	0.0085	1:118

(1) $\hat{y} = y_0 + s\,x$,where y: preconsolidation pressure; s: slope; x: soil resistance to penetration.

DISCUSSION

In this study, higher degrees of soil compaction increased the load-bearing capacity (σp) and decreased susceptibility to further soil compaction (CI), which is in line with findings of other papers (Suzuki et al., 2008; An et al., 2015). The increase of σp and reduction of CI due to the greater Bd_{Rel} in the more compacted treatments can be attributed to the greater frictional force and cohesion between particles.

It is noteworthy that, in the CNT, the σp values in the 5.5-10.5 cm and 13.5-18.5 cm layers were less than 50 kPa, below the pressure usually applied to soils by the wheels of agricultural tractors (Silva et al., 2002; Lima et al., 2006). Thus, low load-bearing capacity may be one of the main causes of rapid re-compaction of NT soils after chiseling (An et al., 2015). Silva et al. (2002) evaluated Ultisols and Oxisols and found that chiseling degraded the soil structure, with a consequent reduction in load-bearing capacity and increased susceptibility to soil compaction. Likewise, Vogelmann et al. (2012), in a study on an Acrisol under NT with and without chiseling, with traffic and without traffic, observed increased susceptibility to compaction in the chiseled treatment, which was attributed to physical degradation due to mechanical tillage. The same authors found that agricultural traffic induced increases in the load-bearing capacity and reduced susceptibility to soil compaction to a depth of 20 cm.

The Bd_{Rel} is an indicator of the degree of soil compaction; values above 0.88 can indicate a degree of soil compaction that is critical for plant growth, regardless of the texture (Klein, 2006). Thus, CI values below 0.21 in this very clayey Rhodic Eutrudox could be used as indicators of excessive soil compaction. Similar results were reported by Lima et al. (2006), where pressures higher than 153 kPa may represent favorable conditions for traffic, but inadequate for root growth in a sandy-loam Haplustox.

The CI is related to soil disturbance (Lima et al., 2006; Vogelmann et al., 2012), which is reflected in lower values of this index in soils with higher initial degrees of compaction (Figure 2). The influence of soil water content and initial degree of compaction on PR is cited in several papers (Mosadeghi et al, 2003; Dias Júnior et al., 2004; Lima et al., 2006). In this study, it was observed that the lower the U is, the more sensitive PR_F is to soil structural variations, as also reported by Vaz et al. (2011), resulting in a clearer differentiation of treatments. However, the differences in PR_L among treatments were greater when this variable was determined at U values of field capacity (-10 kPa). These differences can be attributed, first, to the types of forces underlying each penetrometer. While the force exploited in the static penetrometers is stationary, consisting of steady insertion of cones into the soil, the forces underlying the impact penetrometer are dynamic, resulting from the impact of a block on the penetrometer. In addition, the impact penetrometer measures the maximum PR per unit depth, while the static penetrometer measures the mean PR per unit area (Beutler et al., 2007). Another possible cause of different responses of penetrometers to U reduction is the possibility of cracks in the soil contained in the stainless steel rings used in the static penetrometer, formed by the insertion of the rod of the static penetrometer. These cracks were observed mainly in the most compacted treatments at lowest U values. These cracks, especially at the most negative water potential, may have resulted in lower PR_L values in the densest samples, reducing the differences compared to samples with lower bulk density. To and Kay (2005) also observed that, under high Bd and low U, the formation of vertical cracks caused by cone penetration into the soil reduces PR.

Considering the same soil water potential or evaluation time, the σp and the CI had a positive and negative linear correlation with the PR_F and PR_L, respectively, regardless of the layer assessed. The coefficients of determination (R^2) of the equations of this study were mostly above 80 % for CI, as well as for σp, estimated from the PR_F or PR_L values. Similar results were obtained by Lima et al. (2006), who reported a positive linear correlation with an R^2 value of 97 % in an orange orchard, using field

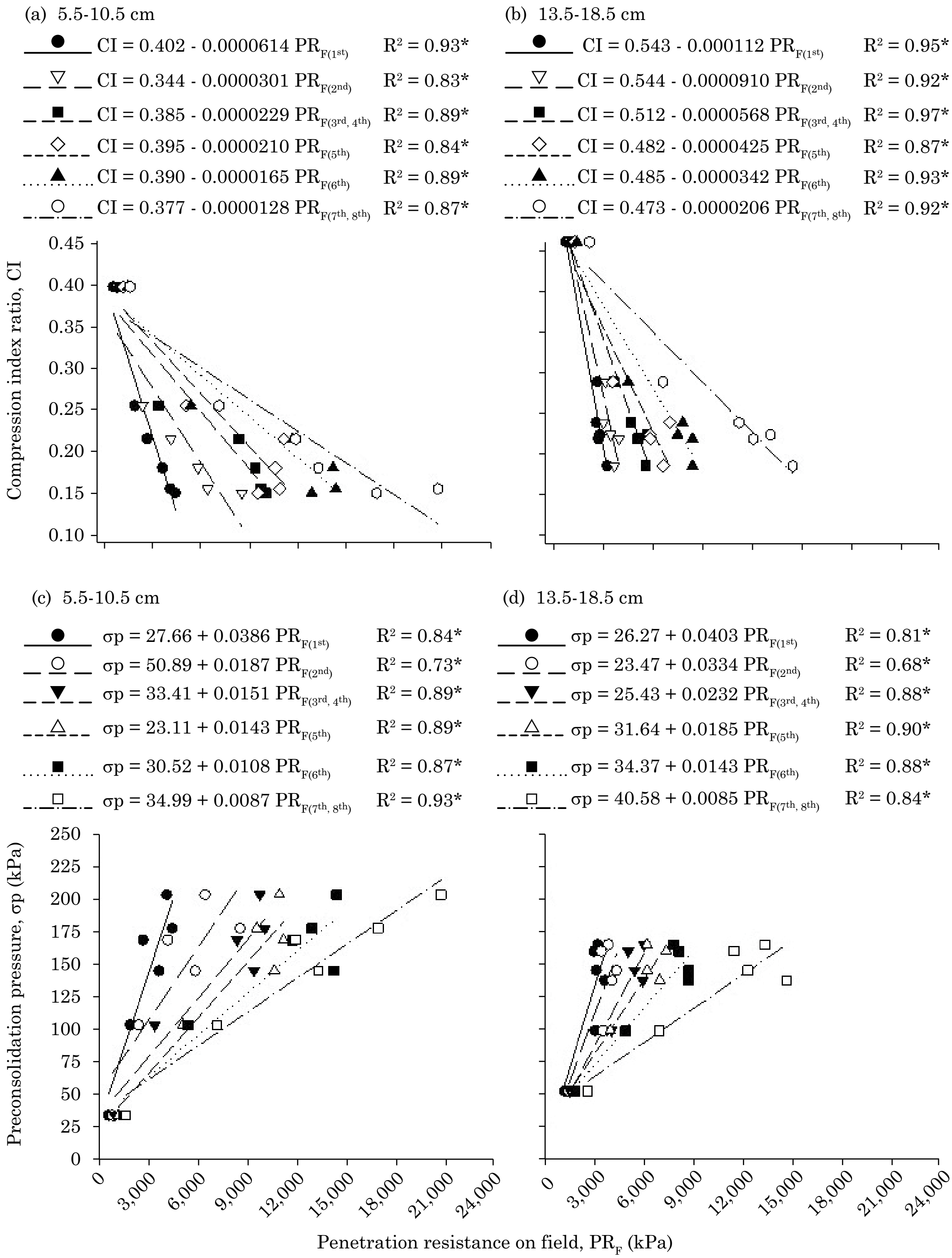

Figure 6. Correlation between compression index ratio (a, b) and preconsolidation pressure (c, d) with soil penetration resistance, using an impact penetrometer at different water content ranges of a Rhodic Eutrudox in the 5.5-10.5 cm (a, c) and 13.5-18.5 cm (b, d) layers.

as well as laboratory penetrometers. In this paper, the σp, whose determination on the field scale is time-consuming and difficult, was estimated from PR_F or PR_L, which proved to be as precise as when using Bd and U as independent variables (Saffih-Hdadi et al., 2009; An et al., 2015).

The results of this study demonstrated that σp and CI estimated from PR were strongly influenced by the U values during the penetrometer tests, regardless of the equipment used (impact or static penetrometer). For example, a PR of 6,000 kPa obtained with an impact penetrometer for the 5.5-10.5 cm layer 4 days after irrigation (2nd evaluation) corresponds to a σp of 163 kPa. In contrast, the σp value estimated from the same PR value (6,000 kPa), but measured 31 DAI (last evaluation), corresponds to 87 kPa. This means that, if the U content is not taken into consideration, the use of these soil functions might significantly over- or underestimate the σp values.

The slope of the σp or CI × PR interaction decreased with the decrease of U at the time of the penetrometer test, for both pieces of equipment and layers. This fact can be attributed to the greater range of variation of PR values when determined in dry soil, indicating that the effect of the U on CI and σp estimation from PR increases when the initial degree of soil compaction is higher. However, the effect of U on the slope of σp or CI × PR equations was higher when using the impact penetrometer. As discussed above, the major differences in PR_F between treatments occurred in drier soil, unlike for PR_L, possibly due to different forces used in the static and impact penetrometers (Beutler et al., 2007). Thus, the data amplitude in drier soil was higher for PR_F than for PR_L, resulting in a lower slope variation due to soil drying when using a static penetrometer. In practical terms, the models showed that at low degrees of compaction, as obtained in chiseled soil, the effect of U on σp and CI estimated from PR_F is small but increases with an increasing degree of soil compaction. In contrast, the effect of U on σp and CI estimated from PR_L is high, regardless of the degree of soil compaction. In practical terms, impact penetrometers are not very sensitive in detecting PR increments due to reduced water contents in chiseled soil. Thus, it mostly detects changes in the other no-tillage treatments or treatments without additional compaction. This differs from the platform penetrometer, which is more sensitive for identifying increases in PR in chiseled soil, due to the reduction of soil water content.

The correlation between σp and PR ranged from 1:22 to 1:45 for the static penetrometer, and from 1:25 to 1:118 for the impact penetrometer, and this variation was determined by U. These values are higher than those obtained by Suzuki et al. (2008), who analyzed six soil types with clay contents ranging from 98 to 658 g kg^{-1} clay, and found a correlation between σp and PR of 1:19. Lima et al. (2006) and Mosaddeghi et al. (2003) also reported lower σp:PR correlations (1:17 and 1:10, respectively) than in this study. Pacheco et al. (2010), however, observed σp:PR correlations in the range of 1:43 and 1:62 in areas of native forest and after four years of winter cultivation, respectively. However, in all these studies, the changes in correlation between σp and PR were not attributed to U in the penetrometer test, but to other factors, such as the mineral fraction of the soil (Lima et al., 2006), or to the initial degree of soil compaction (Suzuki et al., 2008).

CONCLUSIONS

The correlation between preconsolidation pressure and soil penetration resistance is influenced by the water content during the evaluation of penetration resistance, and this effect is stronger for impact penetrometers than when using static penetrometers.

The soil load-bearing capacity estimated from penetration resistance values is influenced by the type of penetrometer.

These considerations show that agricultural practices should be applied at moisture levels in the range of friability, when the load-bearing capacity is adequate and associated with optimal conditions of soil management.

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