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Physical Properties of a Hapludox after Three Decades under Different Soil Management Systems

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ABSTRACT: Changes in soil physical properties due to different management systems occur slowly, and long-term studies are needed to assess soil quality. The objectives of this study were to evaluate the effects of soil management systems and liming methods on the physical properties of a *Latossolo Bruno Alumínico típico* (Hapludox). A long-term experiment that began in 1978 with conventional and no-tillage systems was assessed. In addition, different liming methods (no lime, incorporated lime, and lime on the soil surface) have been applied since 1987 and were also evaluated in this study. Moreover, an area of native forest was evaluated and considered a reference for the natural condition of the soil. Soil physical properties were evaluated in layers to a depth of 1.00 m. Compared to native forest, the conventional tillage and no-tillage systems had higher soil bulk density, penetration resistance, and microporosity, and lower aggregate stability and macroporosity. Compared to the conventional tillage system, long-term no-tillage improved the structure of the Hapludox, as evidenced by increased microporosity and aggregate stability, especially in the soil surface layer. In no-tillage with lime applications sporadically incorporated, soil physical properties did not differ from no-tillage without lime and with lime applied on the soil surface, indicating that this practice maintains the physical quality of soil under no-tillage. Liming in a conventional tillage system improved soil aggregation and reduces penetration resistance in the soil layers near the soil surface. No-tillage was the main practice related to improvement of soil physical quality, and liming methods did not influence soil physical properties in this soil management system.

Keywords: no-tillage, conventional tillage, soil structure, long term.

INTRODUCTION

The choice of a soil management system will influence soil quality, as well as the long term sustainability of the agricultural production system. This occurs because soil management substantially alters the soil structure and consequently the properties related to structure, such as aeration, water retention, and penetration resistance. Some of these modifications occur rapidly, while others occur slowly; thus, the long term experiment is an important tool for evaluating the impact of soil management on soil quality (Reichert et al., 2016).

Conventional tillage system disrupts the soil and increases erosion (Bertol et al., 2004), and decreases soil aggregate stability (Marcolan et al., 2007) and water retention in the soil (Vieira and Klein, 2007). In addition, it can compact the soil in deeper layers, forming a "plow pan" a compacted area which occurs below the tilled soil layer (Reichert et al., 2007). However, periodic soil turnover in this system incorporates lime and fertilizers (Ciotta et al., 2004) and can increase porous spaces, thus increasing air permeability in soil surface layers (Rodrigues et al., 2011).

Low soil disturbance in no-tillage system, on the other hand, preserves the soil from degradation, keeps crop residues on the soil surface, and increases soil organic matter in comparison to the conventional tillage system (Bayer and Mielniczuk, 2008). No-tillage may also increase soil aggregate stability, improve soil structure, and increase resistance to erosion (Secco et al., 2004; Bertol et al., 2004). However, tillage performed without crop rotation and/or machine traffic at times of elevated soil moisture can increase soil compaction (Albuquerque et al., 1995), and even form a "no-tillage pan" (Reichert et al., 2009).

Soil compaction in no-tillage system must be evaluated, especially when used for long periods (Reichert et al., 2007). Upon evaluating the physical quality of an Ultisol cultivated under a no-tillage system for less than three years, Reinert et al. (2001) observed an increase in soil bulk density and restriction to root growth for *Raphanus sativus* L., *Zea mays*, and summer cover crops. However, in a study in a Hapludox after 30 years under no-tillage, Betioli Júnior et al. (2012) observed that soil compaction did not decrease crop production, even after three decades without turning over the soil. In an Oxisol cultivated for 20 years, Oliveira et al. (2004) verified that no-tillage did not compact the soil compared to conventional tillage up to the depth of 0.40 m. Similarly, Gonçalves and Moraes (2012) did not verify differences in total porosity of an Ultisol cultivated for 19 years with no-tillage and conventional tillage.

Thus, when changes in soil structure need to be evaluated, the effect of soil management systems on soil physical and hydric properties must be monitored over time, since this is a determining factor regarding the magnitude of tillage effects. However, there are few studies that evaluate the effects of tillage systems applied for 30 years on the physical properties of subtropical Oxisols, and few that evaluate soil layers below the depth of 0.40 m.

The hypotheses of the study were: the conventional tillage, used for a long time, degrades soil structure compared to native forest, while the introduction of the no-tillage system for long term recovers soil structure, especially the aggregate stability; and the application of lime at recommended rates does not alter the physical attributes. The objectives of this study were to evaluate the effects of soil tillage systems and lime application methods on the physical properties of a *Latossolo Bruno Alumínico típico* (Hapludox) after three decades.

MATERIAL AND METHODS

The study was carried out in a 31-year old experiment at the experimental station of the Fundação Agrária de Pesquisa Agropecuária – FAPA, Colônia de Entre Rios, Guarapuava, PR, Brazil. The climate of the region, according to the Köppen classification, is humid

subtropical, without a dry season and with the occurrence of frequent and severe frost. The soil of the experimental area is a *Latossolo Bruno Alumínico típico*, according to Santos et al. (2013), a Hapludox (Soil Survey Staff, 2014), with a prominent A horizon, with 570 g kg^{-1} of clay, 370 g kg^{-1} of silt, and 60 g kg^{-1} of sand, with a basalt substrate and slope of 0.05 m m^{-1}. The main minerals in the clay fraction are kaolinite, iron oxides (goethite and hematite), and aluminum oxide (gibbsite) (Costa, 2001).

The native vegetation of the area was forest, which was clear cut in the 1920's, and a pasture was established composed of native species, mainly grasses. In 1950, the soil was plowed for the first time for wheat and rice cultivation under a conventional tillage system until 1962. From 1962 until 1968, the area was under pasture improved with white clover and winter grasses for dairy cattle. From 1968 until 1977, the area was again cultivated under conventional tillage system for production of wheat and soybean. In the winter of 1978, 1.5 Mg ha^{-1} of lime and 0.3 Mg ha^{-1} of Thomas Slag (phosphate rich slag) were applied, and soybean was planted in the summer as the first crop of the experiment (Jaster et al., 1993).

The experiment was set up in a randomized block design, with three replicates. From 1978 to 1987, the treatments were different combinations of tillage systems in winter and summer. In this study, only two combinations involving no-tillage and conventional tillage in both the winter and summer seasons were evaluated. After 1987, the plots were split and the liming factor was inserted in the experiment. Two liming methods (without lime and with lime incorporated in the soil) were evaluated in the conventional tillage system (CTwl and CTinc), while three liming methods (without lime, lime incorporated in the soil, and lime applied on the soil surface) were evaluated in the no-tillage system (NTwl, NTinc, and NTsurf). The main plots are 12 × 100 m, and the split-plots are 12 × 30 m. Details of the experimental design are presented in Ciotta et al. (2004) and Costa et al. (2004).

All operations of soil and crop management, sowing, and harvest were carried out with equipment and commercial tillage machines similar to those used by farmers in the area. In the conventional tillage system, before sowing the winter and summer crops, the soil is periodically plowed to a soil depth of 0.25 m and then disked twice. For the no-tillage system, sowing equipment with a cutting disk was used for sowing the winter and summer crops. At the beginning of the experiment, after lime application, the soil was plowed and disked for lime distribution and incorporation. After 1987, lime was applied in 1995 (3.0 Mg ha^{-1}) and 2007 (4.7 Mg ha^{-1}), and followed the different liming treatments. In these two years, the soil was plowed and disked for lime distribution and incorporation (CTinc and NTinc).

The crops cultivated in the experiment, in a rotation scheme, from the beginning until the date of soil sampling, were: wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), white oat (*Avena sativa* L.), radish (*Raphanus sativus* L.), vetch (*Vicia sativa* L.), corn (*Zea mays* L.), and soybean (*Glycine max* L.). Except for radish and vetch that were used as cover crops, all crops were used for grain production. Crop management practices (sowing periods, fertilization, disease treatments, harvesting, etc) followed technical recommendations for the region.

In May 2009, 31 years after implementation of the experiment (1978) and two years after the last lime application (2007), after harvest of the soybean crop, trenches were opened down to 1 meter to obtain undisturbed soil samples for physical measurements. Soil sampling was performed in between the rows of the recently harvested soybean. Samples with an undisturbed soil structure were collected in volumetric cylinders of 0.025 m height and 0.06 m internal diameter, vertically inserted in the soil, in the center of the 0.0-0.025, 0.025-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.40, 0.40-0.60, 0.60-0.80, and 0.80-1.00 m soil layers to determine soil bulk density, total porosity, microporosity, and macroporosity, according to Claessen (1997). Soil samples from an adjacent native

forest, considered a reference for the native condition of the soil, were taken following a similar procedure.

Additional soil samples were collected in duplicate in the center of the 0.0-0.025, 0.025-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.40 m soil layers, in order to determine aggregate stability. The soil aggregate stability was determined by wet sieving of 25 g subsamples that were pre-wetted for 10 min, as described by Kemper and Chepil (1965). These samples were then placed in vertical oscillation equipment for 10 min over a set of sieves of 4.76, 2.00, 1.00, and 0.25 mm diameter. From the weight of soil aggregates retained in each sieve and dried at 105 °C, geometric mean diameter (GMD) was calculated for each sample.

Penetration resistance, evaluated in May 2009 and March 2011, was determined to a depth of 0.40 m at five points in each plot through a Falker® penetrographer equipped with a 12.82 mm diameter cone and maximum measuring speed of 30 mm s^{-1}, manually controlled. At those times, soil samples were collected in the 0.0-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.40 m soil layers for determination of soil moisture.

Statistical analysis was made in the SAS 9.2 program for statistical analysis (SAS, 2010) using two statistical procedures. In the first, only the results of soil tillage systems and liming factors were subjected to analysis of variance and the F test, at a significance level of 5 %, using a mixed model with a split-split-plot design and repeated measurements. In this design, soil tillage systems were analyzed as the main plot and liming factors as split-plots, considering them as fixed effect factors, the layers sampled in the soil profile considered as measurements repeated through time (split-split-plot) and the blocks with a random effect factor, according to the statistical procedure described by Littell et al. (2006).

The choice was made to consider the soil layers as a measurement repeated throughout time due to the absence of their randomization in the soil profile in each treatment. The averages of management systems were compared according to soil layers using univariate and multivariate contrasts: Conventional tillage without lime and with incorporated lime *versus* No-tillage without lime, with incorporated lime, and with surface lime (CTs × NTs); Conventional tillage without lime *versus* Conventional tillage with lime (CTwl × CTinc); No-tillage without lime *versus* No-tillage with incorporated lime and surface lime (NTwl × NTinc and NTsurf), and No-tillage with incorporated lime *versus* No-tillage with surface lime (NTinc × NTsurf).

A second statistical procedure was used to evaluate soil properties in land use, where forest soil was compared only with soil that did not receive lime application (CTwl and NTwl). For analyses of these data, tests were first performed in each soil layer to verify some assumptions of the analysis of variance, such as data normality and deviations by the Shapiro-Wilk test and homogeneity of variances by the Bartlett test. Since the assumptions were met, the data were subjected to analysis of variance and mean values of the treatments were compared through the Student (t) test in each soil layer. This procedure was adopted due to lack of meeting one of the assumptions of analysis of variance, the causality of the experimental plots, because the forest was adjacent but was not part of the experiment.

RESULTS AND DISCUSSION

Soil under the forest had higher macroporosity than in NTwl and CTwl, in the 0.10-0.20, 0.20-0.40, and 0.40-0.60 m soil layers (Figure 1a). However, soil microporosity in the forest was lower down to a depth of 0.40 m compared to NTwl, and, with the exception of the 0.20-0.40 m soil layer, the forest soil did not differ from CTwl down to a depth of 1.00 m (Figure 1b). Changes in macro- and microporosity did not affect total soil porosity,

which was equal to the forest down to a depth of 1.00 m, with the exception of the 0.20-0.40 m soil layer, when compared to CTwl and NTwl (Figure 1c). Soil bulk density for the forest was lower in relation to CTwl and NTwl down to a depth of 0.40 m and did not differ in the deepest soil layers (Figure 1d). The lower soil bulk density observed in the forest is due to higher biological activity, which promotes the formation of galleries of varied sizes (Lima et al., 2005), higher organic matter content (Braida et al., 2006), and the absence of machine traffic in the native forest (Collares et al., 2008).

Conventional tillage had the highest soil bulk density in the 0.0-0.025 and 0.10-0.20 m soil layers in relation to the conservation soil management system (Figure 2, Table 1). Such results are contrary to those obtained by Bertol et al. (2000) and by Stone and Silveira (2001), who compared soil tillage systems and verified higher soil bulk density in NT in relation to CT. These authors attribute the higher soil bulk density in NT to the absence of soil disturbance. The lower soil bulk density in NT observed in this study was possibly due to soil resistance to compaction resulting from the granular structure common in oxidic soils and also present in this Hapludox (Alves, 2002). In addition, the high input of crop residues, and consequent high organic matter content in NT in comparison to CT (Ciotta et al., 2003), may have contributed to the lower soil bulk density in the no-tillage system.

In the 21st year of this experiment, Costa et al. (2003) also did not observe soil compaction in the no-tillage system. The authors emphasized that the soil type, the moisture condition in which the operations are performed along the crop cycle, and the length of time that soil management practices are adopted are important variables that must be considered in evaluation of soil structure.

Total soil porosity did not differ between the management systems, with the exception of the 0.60-1.00 m soil layer (Figure 2, Table 1). This situation differs from that observed by Albuquerque et al. (2001) in an Ultisol, and Stone and Silveira (2001) and Secco et al. (2005) in an Oxisol, who verified that conventionally tilled soil has higher total porosity in relation to soils under no-tillage system. These differences can be related to the distinct soil moisture conditions at the time of soil tillage, to the different crop treatments applied, and to the diverse contributions of biomass addition from different crops.

The conventional tillage systems had higher macroporosity down to a depth of 0.10 m in comparison to the no-tillage systems (Figure 2, Table 1). This is mainly due to soil mobilization in the winter and spring-summer in the conventional system.

Lime application and liming methods (incorporation or on the soil surface) had no effect on soil bulk density or on total soil porosity in the tillage systems. However, in the conservation tillage system, liming affected soil macroporosity in the 0.025-0.05 m soil layer (Figure 2a, Table 1). The higher macroporosity in the conservation tillage system after lime application may be related to higher shoot and root biomass production by crops (Pértile et al., 2012), increasing organic matter and soil microbial activity, which are factors that contribute to aggregate stabilization and consequently improve soil aeration (Vezzani and Mielniczuk, 2011). However, differences in total porosity and macroporosity in the deepest soil layers may be due to variability that occurs in the soil, since the effect of acidity correction in deeper layers was not observed by Ciotta et al. (2004). These authors observed that lime application in this soil corrected acidity to a depth of 0.15 m 12 years after the first application. Regardless of the soil tillage systems and liming methods, macroporosity was higher than 0.12 m^3 m^{-3} (Figure 2a). Thus, aeration in this soil is higher than the minimum considered restrictive to root development, which is 0.10 m^3 m^{-3} (Xu et al., 1992).

The soil under the conservation tillage system had greater microporosity in relation to the conventional tillage system (Figure 2b, Table 1), especially in surface layers (0.00-0.10 m). Machine traffic, low mobilization, and natural soil arrangement when the soil is not disturbed in the long term decreases macroporosity and increases microporosity, mainly
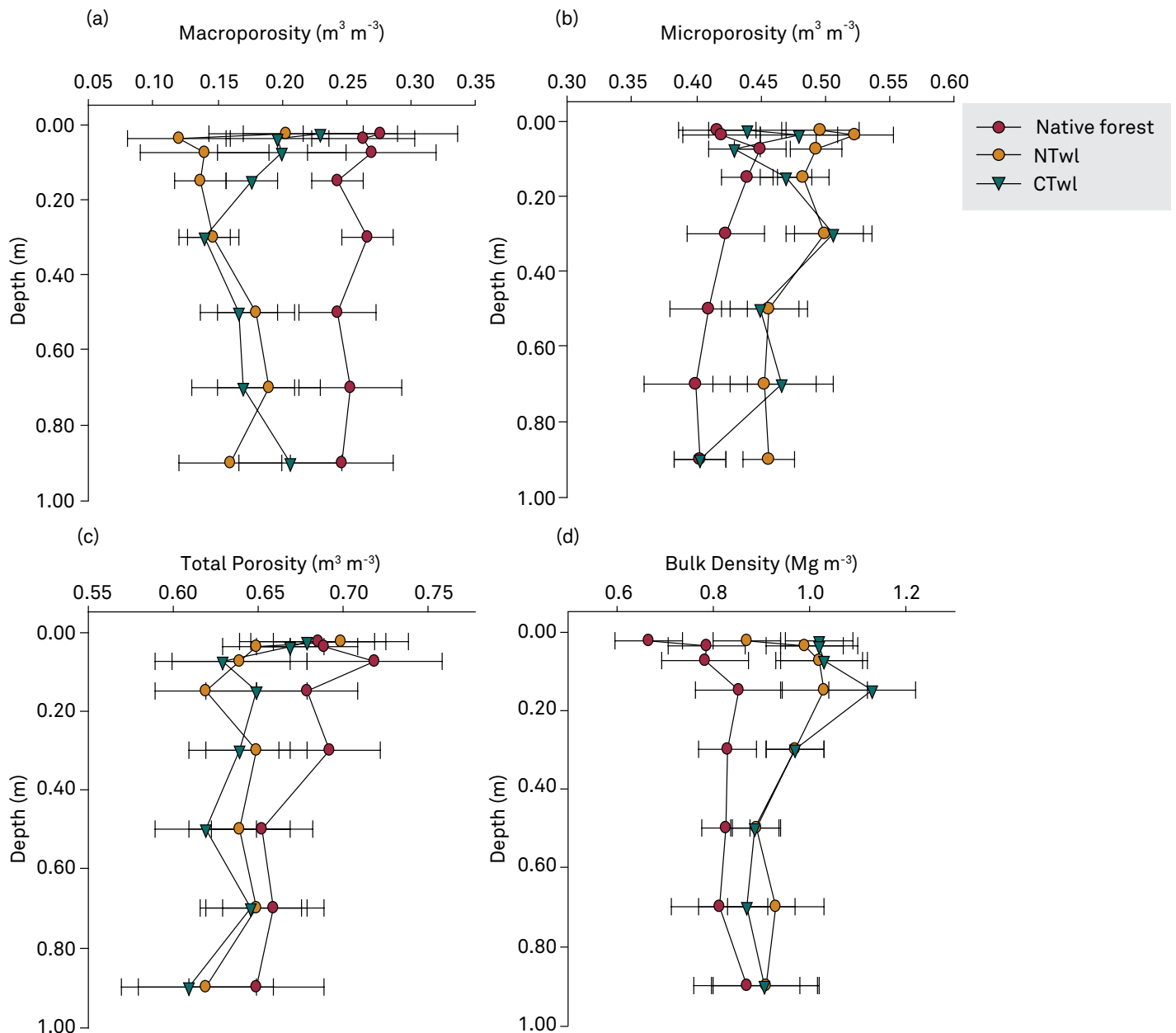
Figure 1. Macroporosity (a), microporosity (b), total porosity (c), and bulk density (d) in a *Latossolo Bruno Alumínico típico* (Hapludox) subjected to different tillage systems and liming methods. Horizontal bars indicate the interval of least significant difference for the t test and their overlap in the same soil layer means the absence of difference between the averages of the systems. CTwl: conventional tillage without lime; and NTwl: no-tillage without lime.

in soil surface layers (Vieira and Muzilli, 1984). Higher microporosity in the conservation system in relation to the conventional system in the 21st year of the same experiment was observed by Costa et al. (2003). Lime application or non-application in the conservation system or in the conventional system did not influence soil microporosity.

Soil aggregates stability in the forest, measured by geometric mean diameter (GMD), did not differ from NTwl down to a depth of 0.40 m (Figure 3). In contrast, the effects of soil tillage in the conventional tillage system decreased aggregate stability to the depth of 0.10 m compared to the conservation tillage system (Figure 3). This is due to the soil not being turned over, maintenance of crop residues on the soil surface, and, therefore, higher contribution of organic matter throughout the years in the conservation tillage system (Vezzani and Mielniczuk, 2011). Therefore, the conservation tillage system allows recovery of soil structure in the long term.

Table 1. Contrasts of combinations between tillage systems and liming methods for macroporosity, microporosity, total porosity, soil bulk density and geometric mean diameter of soil aggregates in a *Latossolo Bruno Alumínico típico* (Hapludox)

Contrast	Soil layer (m)							
	0.0-0.025	0.025-0.05	0.05-0.10	0.10-0.20	0.20-0.40	0.40-0.60	0.60-0.80	0.80-1.00
	Macroporosity (Pr>F)							
CTs × NTs	**	**	*	ns	ns	ns	ns	ns
CTwl × CTinc	ns	ns	ns	ns	ns	**	ns	*
NTwl × NTinc e NTsurf	ns	*	ns	ns	ns	ns	ns	ns
NTinc × NTsurf	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	29	27	21	19	15	23	22	19
	Microporosity (Pr>F)							
CTs × NTs	**	**	**	ns	ns	**	ns	**
CTwl × CTinc	ns	ns	ns	ns	ns	ns	**	ns
NTwl × NTinc e NTsurf	ns	ns	ns	ns	ns	ns	ns	ns
NTinc × NTsurf	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	9	6	7	5	4	8	9	6
	Total porosity (Pr>F)							
CTs × NTs	ns	ns	ns	ns	ns	ns	**	**
CTwl × CTinc	ns	ns	ns	ns	ns	ns	**	ns
NTwl × NTinc e NTsurf	ns	ns	ns	ns	ns	ns	ns	ns
NTinc × NTsurf	ns	ns	ns	ns	ns	ns	ns	*
CV (%)	5	5	3	4	4	6	6	5
	Bulk density (Pr>F)							
CTs × NTs	*	ns	ns	*	ns	ns	ns	*
CTwl × CTinc	ns	ns	ns	ns	ns	ns	ns	ns
NTwl × NTinc e NTsurf	ns	ns	ns	ns	ns	*	*	ns
NTinc × NTsurf	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	8	8	6	7	7	12	12	10
	Geometric mean diameter (Pr>F)							
CTs × NTs	**	ns	**	ns	*	-	-	-
CTwl × CTinc	ns	ns	*	*	ns	-	-	-
NTwl × NTinc e NTsurf	ns	ns	ns	ns	ns	-	-	-
NTinc × NTsurf	ns	ns	ns	ns	**	-	-	-
CV (%)	18	18	19	19	33	-	-	-

ns: not significant; * and **: significant at 5 and 1 %, respectively. CTinc: conventional tillage with incorporated lime; CTwl: conventional tillage without lime; NTinc: no-tillage with incorporated lime; NTwl: no-tillage without lime; and NTsurf: no-tillage with surface lime. CV: coefficient of variation.

In the conservation tillage systems, liming did not alter aggregate stability (Figure 4, Table 1). The positive effects of organic C on soil aggregation avoided the dispersive effect of lime. According Albuquerque et al. (2000, 2003) and Bayer and Mielniczuk (2008), this is due to the direct effect of organic matter on the soil physical attributes and the indirect effect of liming on the aggregation and stimulation of biological activity. Nevertheless, lime addition in the conventional tillage system increased aggregate stability in the 0.05-0.20 m soil layer (Figure 4, Table 1). Liming neutralizes exchangeable Al and increases pH and negative electrical charges, mechanisms that can disperse soils with variable charges (Costa et al., 2004). However, lime adds Ca and Mg, which are adsorbed by the negative electrical charges and promote clay flocculation (Charlet and Sposito, 1989). The intensity of the dispersion and flocculation determines changes in the soil structure.
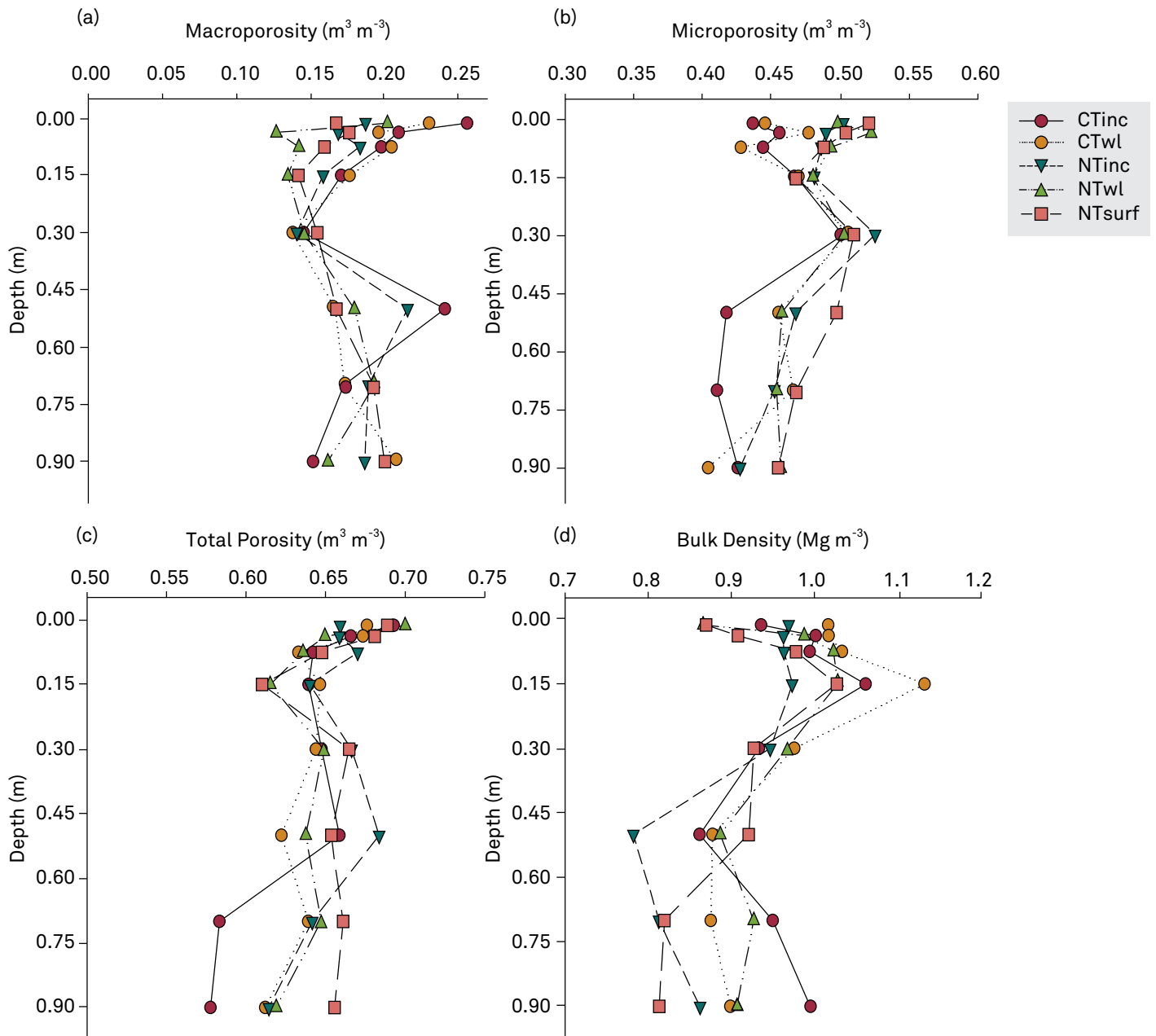
Figure 2. Macroporosity (a), microporosity (b), total porosity (c), and bulk density (d) in a *Latossolo Bruno Alumínico típico* (Hapludox) subjected to different tillage systems and liming methods. CTinc: conventional tillage with incorporated lime; CTwl: conventional tillage without lime; NTinc: no-tillage with incorporated lime; NTwl: no-tillage without lime; and NTsurf: no-tillage with surface lime.

The soil under forest had lower penetration resistance (PR) down to a depth of 0.35 m in comparison to CTwl and down to a depth of 0.15 m in comparison to NTwl in measurements taken at both times (Figures 5a and 5b). In the forest, the absence of pressure exerted on the soil surface by farm machines and the higher organic matter content determined lower PR in relation to the CT and NT systems. In analyzing both sampling dates, a small variation in PR was observed, which can be associated with the differences in soil moisture (Figures 6b and 6d).

The conservation tillage system had higher PR to a depth of 0.10 m in relation to the conventional tillage system in May of 2009. In March 2011, the conservation tillage system had higher PR in the 0.10 to 0.40 m depth (Figure 6, Table 2). Lower PR in conventional tillage is directly related to periodic soil mobilization prior to sowing crops in these systems. Similar results were obtained by Beutler et al. (2001), Albuquerque et al. (2001), and Ralisch et al. (2008).
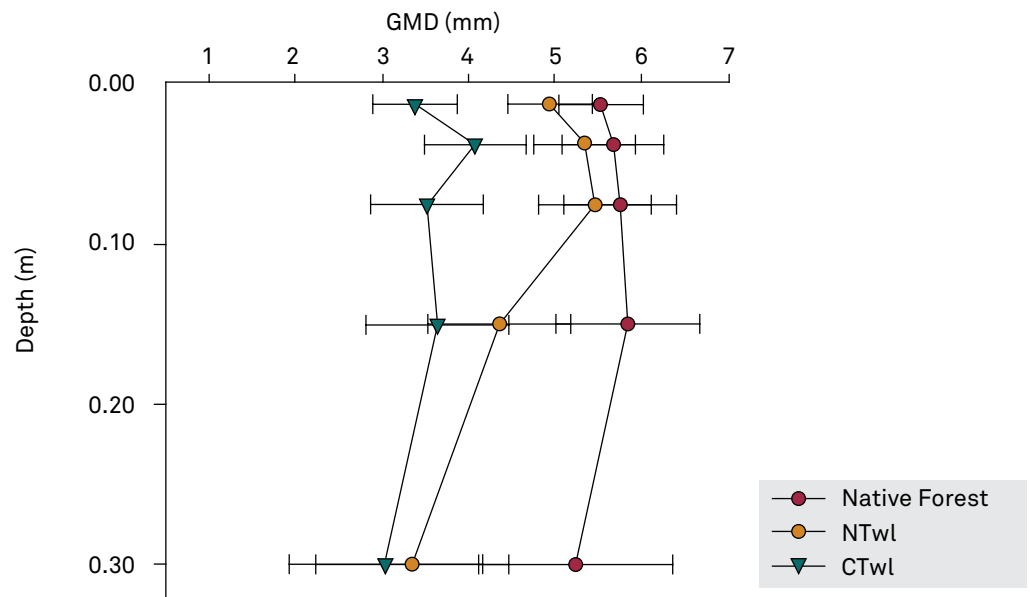
Figure 3. Geometric mean diameter (GMD) of the soil aggregates as affected by soil use and tillage systems in a *Latossolo Bruno Alumínico típico* (Hapludox). Horizontal bars indicate the interval of least significant difference for the t test and their overlap in the same soil layer means the absence of differences between the averages of the systems. CTwl: conventional tillage without lime; and NTwl: no-tillage without lime.
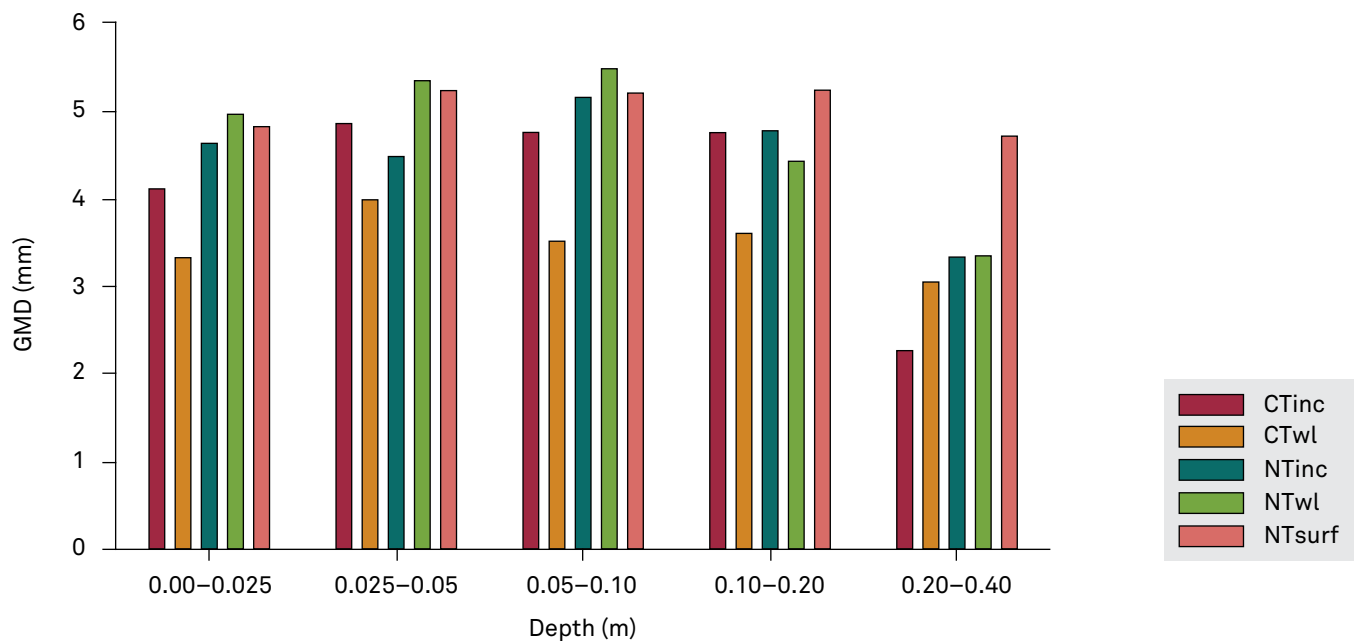

Figure 4. Geometric mean diameter (GMD) of soil aggregates as affected by tillage systems and liming methods at different depths of a *Latossolo Bruno Alumínico típico* (Hapludox). CTinc: conventional tillage with incorporated lime; CTwl: conventional tillage without lime; NTinc: no-tillage with incorporated lime; NTwl: no-tillage without lime; and NTsurf: no-tillage with surface lime.

No-tillage without lime was the treatment with the highest PR in the surface soil layer (0.00-0.10 m), an average of 2.4 MPa in May 2009 and 2.1 MPa in March 2011 (Figures 6a and 6c). Higher PR in NTwl seems to indicate soil subsurface compaction, since the soil under no-tillage had the highest soil water content in both years of testing (Figures 6b and 6d). Similar effects were also observed by Costa (2001) in the 21st year of the same experiment. However, this possible compaction was not proven by soil bulk density results in the measurements of the 21st year (Costa, 2001) and 31st year (this study) of the experiment since, in both evaluations, soil bulk density showed little difference between tillage systems (Figure 2d, Table 1).

Table 2. Contrasts of combinations of tillage systems and liming methods for penetration resistance, in May 2009 and March 2011, in a *Latossolo Bruno Alumínico típico* (Hapludox)

Contrast	Soil layer (m)				
	0.00-0.05	0.05-0.10	0.10-0.20	0.20-0.30	0.30-0.40
May 2009 (Pr>F)					
CTs × NTs	*	**	ns	ns	*
CTwl × CTinc	ns	ns	ns	ns	ns
NTwl × NTinc e NTsurf	ns	*	ns	ns	ns
NTinc × NTsurf	ns	ns	ns	ns	ns
CV (%)	48	30	19	25	24
March 2011 (Pr>F)					
CTs × NTs	ns	ns	**	**	*
CTwl × CTinc	ns	**	**	ns	ns
NTwl × NTinc e NTsurf	**	**	**	ns	ns
NTinc × NTsurf	ns	ns	*	ns	ns
CV (%)	34	27	23	20	18

ns: not significant; * and **: significant at 5 and 1 %, respectively. CTinc: conventional tillage with incorporated lime; CTwl: conventional tillage without lime; NTinc: no-tillage with incorporated lime; NTwl: no-tillage without lime; and NTsurf: no-tillage with surface lime. CV: coefficient of variation.
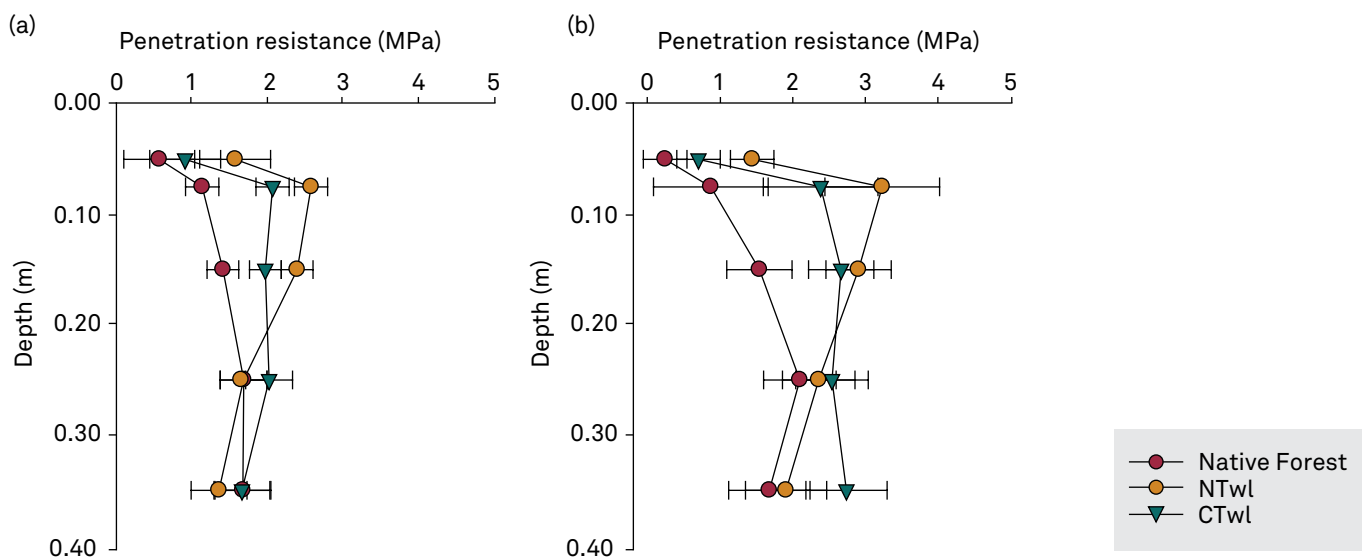

Figure 5. Penetration resistance in a *Latossolo Bruno Alumínico típico* (Hapludox) under different soil use and tillage systems in May 2009 (a) and March 2011 (b) after more than 30 years of the tillage system adopted. Horizontal bars indicate the interval of least significant difference for the t test and the overlapping of them in the same soil layer indicates the absence of differences between the averages of the systems. CTwl: Conventional tillage without lime; and NTwl: No-tillage without lime.

Higher PR values in the conservation tillage system may be related to higher cohesion among soil particles. In soils with high aggregate stability, cohesion is higher due to strong interaction among primary particles (Braida et al., 2007; Reichert et al., 2016). In addition, in conservation tillage systems, the higher number of organic filaments, such as fungus hyphae and roots, promote union of soil particles, increasing cohesion between them (Soane, 1990), which is a mechanism that may have contributed to increasing aggregate stability. Thus, increase in PR over time, along with other properties such as soil bulk density, allow better interpretation of the effect of PR on plant root growth, since isolated PR measurements indicate only if soil resistance is high or low (Kaiser, 2010).

In the conventional tillage system, liming decreased PR in the evaluation made in March 2011 in the 0.05-0.20 m soil layer (Figure 6,Table 2) and in the conservation system,
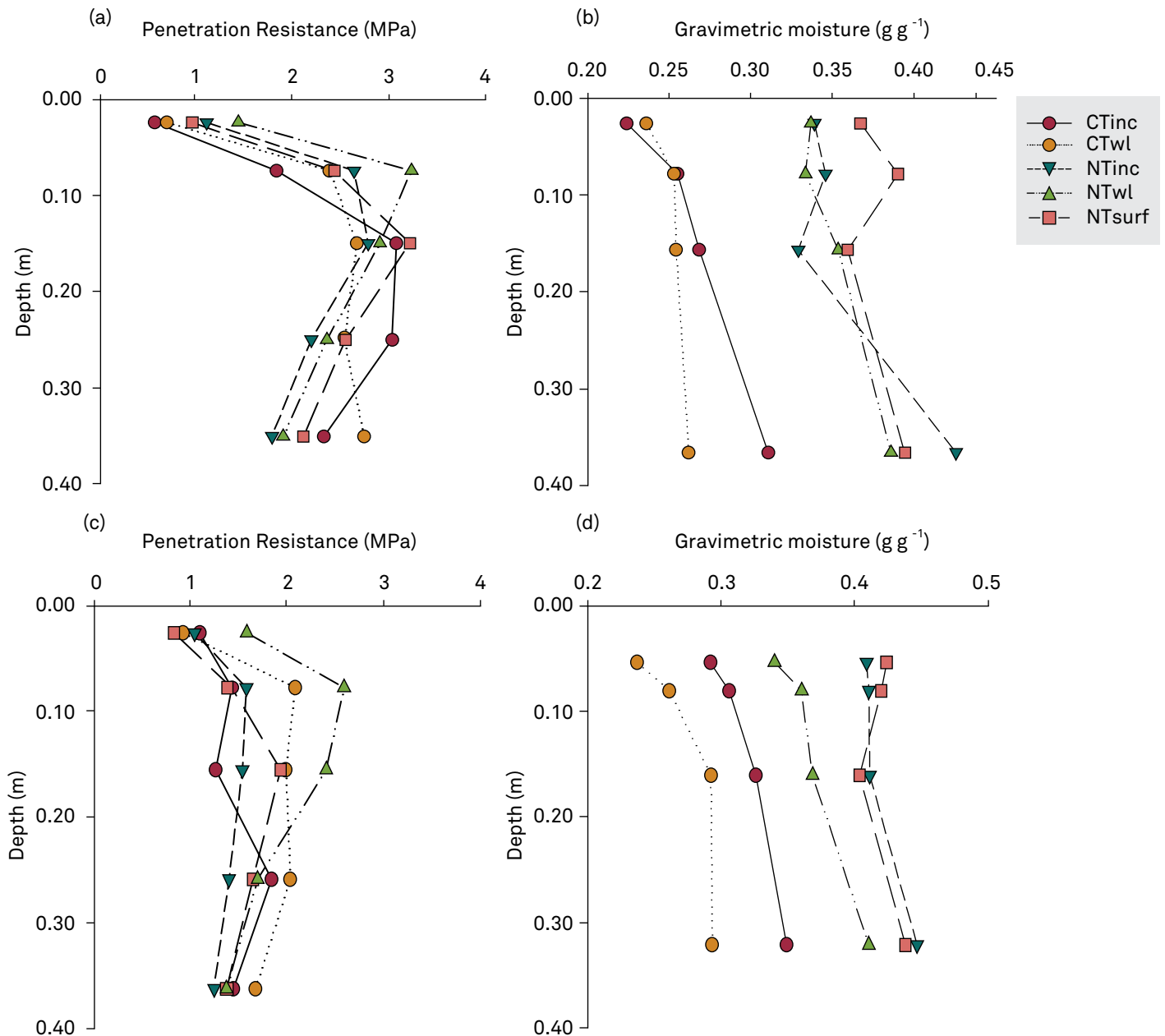
Figure 6. Penetration resistance (a, c) and gravimetric soil moisture (b, d) as affected by the tillage system and liming methods, in May 2009 (a, b) and March 2011 (c, d) in a *Latossolo Bruno Alumínico típico* (Hapludox). CTinc: conventional tillage with incorporated lime; CTwl: conventional tillage without lime; NTinc: no-tillage with incorporated lime; NTwl: no-tillage without lime; and NTsurf: no-tillage with surface lime.

PR decreased in the 0.05-0.10 m soil layer in May 2009 and in the 0.00-0.30 m soil layer in March 2011 (Figure 6, Table 2). In this specific case, liming may have stimulated root growth, with consequent formation of channels after root decomposition, which can alleviate penetration resistance. In the study of Pértile et al. (2012) in a Humudept, it was observed that roots grew deeper in treatments with higher addition of lime. The liming effect can affect soil chemical properties (Ciotta et al., 2004), crop growth, organic matter input (Pértile et al., 2012), and biological activity and, in addition, can benefit soil physical properties.

CONCLUSIONS

Changing land use from native forest to agriculture under conventional tillage affects several soil properties, such as increases in soil bulk density, penetration resistance and microporosity, and decreases soil aggregate stability and macroporosity.

Long-term (three decades) no-tillage system improves soil structure of Oxisol, by increasing soil aggregate stability, mainly in the soil surface layer, compared to conventionally tilled soil.

Lime sporadically incorporated into the soil in no-tillage system has no impact on bulk density, porosity and aggregate stability in very stable Hapludox soil. In the conventional tillage system, lime application improves soil aggregation and reduces penetration resistance in the soil surface layers.

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