

Soil chemical management drives structural degradation of Oxisols under a no-till cropping system

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Abstract. Physical degradation of the subsurface layer of soils reduces the effectiveness of no-till (NT) as a sustainable soil management approach in crop production. Chemical factors may reduce the structural stability of Oxisols and thereby exacerbate compaction from machinery traffic. We studied the relationship between chemical management and structural degradation in Oxisols cultivated under NT at three sites in southern Brazil. The surface and subsurface layers of the soils were characterised chemically and mineralogically and three physical attributes related to soil structural stability (readily dispersible clay in water, mechanically dispersible clay in water, and water percolation) were quantified for each layer. The same characterisations were performed on Oxisols collected from adjacent non-cultivated areas, to provide reference data for non-degraded soil. The levels of dispersed clay in the cultivated soil from the surface layer matched those of the non-cultivated soil, but for the subsurface layer higher dispersed clay levels in the cultivated soil showed that it was physically degraded relative to the non-cultivated soil. Water percolation was found to be slower through the Oxisols cultivated under NT, irrespective of the soil layer. The relationships between the three indicators of soil structural stability and the measured chemical and mineralogical variables of the soils were explored through an analysis of canonical correlation. The principal variables associated with the lower stability of the cultivated vs non-cultivated Oxisols were the lower concentrations of organic carbon and exchangeable aluminium and, for the surface layer, the higher pH. It is argued that structural degradation of Oxisols cultivated under NT, observed predominantly in the subsurface layer, has been aggravated by the accumulation of amendments and fertilisers in the surface soil and reduced levels of organic matter, especially in the subsurface layer.

Additional keywords: aggregate stability, clay dispersion, organic carbon, soil conservation.

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Introduction

The no-till (NT, direct drilling) system has been adopted in more than 150 million ha of agricultural soils in the world, and more than 30 million ha in Brazil (FAO 2016). When a NT system of agriculture is adopted, the soil is only disturbed along the seeding lines, with plant and crop residues remaining on the surface of the soil. This reduction in the intensity of disturbance brings economic and environmental benefits (Babujia *et al.* 2010; Derpsch *et al.* 2014; Corbeels *et al.* 2016). However,

observations of soil cultivated under NT has revealed the formation of a layer, between ~0.07 and 0.20 m depth, of increased bulk density and resistance to penetration, with poor water and air permeability (Reichert *et al.* 2009; Soane *et al.* 2012; Dang *et al.* 2015; Nunes *et al.* 2015a). The existence of this layer promotes soil erosion by water (Denardin *et al.* 2011) and concentration of crop roots near the surface of the soil (Nunes *et al.* 2015b), which reduces the availability of water and nutrients to the plants (Reichert *et al.* 2009). This physical

soil degradation therefore acts to reduce the positive effects expected from the adoption of NT.

Machinery traffic is normally cited as the principal cause of compaction in agricultural soils (Reichert *et al.* 2009; Soane *et al.* 2012). However, in addition to these mechanical processes, chemical factors can also contribute to structural degradation of soils managed under NT. This could be associated with the recurrent applications of limestone and fertilisers onto the surface of the soil, without incorporation. These products are known to promote physicochemical alterations within the soil (Haynes and Naidu 1998; Li and Zhang 2007), which can result in decreased aggregate stability and increased dispersion of clay (Roth and Pavan 1991; Castro and Logan 1991). The damage may principally occur close to the surface layer of soil, where the applied limestone and fertilisers accumulate (Costa and Rosolem 2007; Nunes *et al.* 2014).

For deeply weathered soils, such as the Oxisols of Brazil, the structural degradation stimulated by their chemical management can be especially pronounced because the natural pH of these soils is below the point of zero charge (PZC) for the majority of their minerals (Sposito 2008). In Oxisols, the formation of aggregation occurs at low pH and when there are high concentrations of Al^{3+} and diversified organic matter. Under these conditions, two types of linkages confer stability on the aggregates: electronegative functional groups of the organic matter bind to the electropositive domains of the oxides, and Al^{3+} ions form bridges between oxide domains (Vrdoljak and Sposito 2002; Six *et al.* 2002). However, liming raises the soil pH, which leads to deprotonation of the surfaces of the oxides and kaolinite minerals, resulting in negative charges on soil particles and causing repulsion between them (Fontes *et al.* 1995). High concentrations of mono and bivalent salts are able to remove Al^{3+} from negatively charged sites within the soil. The subsequent occupation of these sites by lower valence cations and greater hydrated radius of cations weakens the intermolecular forces to destabilise the structure of the soil.

The NT system, under a high biomass production, have a high potential to increase organic carbon storage in Oxisols from subtropical (Madari *et al.* 2005) and tropical regions (Corbeels *et al.* 2016; Miranda *et al.* 2016), even being efficient in controlling soil organic matter degradation processes and in partially mitigating climate change (Siqueira Neto *et al.* 2010). However, in some of NT farming systems established in Brazil, the production model is based on monocultures or simple rotations, in which less quantities of organic matter are delivered to the soil. The uninterrupted adoption of NT in these production systems may be rendered impossible by the attendant lack of diversified organic matter inputs for the maintenance of soil stability (Conceição *et al.* 2013; Tivet *et al.* 2013; Derpsch *et al.* 2014). Therefore, the insufficient supply of organic material to the soil can be a factor contributing to the degradation of structure of these soils.

Unlike non-cultivated Oxisols, which have a naturally stable structure, previous studies have indicated that in the areas under NT, the clay dispersed in water by soil cultivation practices can be charged by percolating water, contributing to the obstruction of the natural porosity of the subsurface layers (Haridasan and Chibber 1971; Spera *et al.* 2008). Furthermore, in the surface layer of the soil, the lower stability and fragmentation of the

macroaggregates can elevate the concentration of dispersible clay, leaving the system increasingly susceptible to erosion by water (Hudson 1977).

The majority of studies on fertilisation have evaluated the responses of plants to the application of fertilisers. Until now, few studies have been conducted to evaluate the effects of liming and mineral fertilisers on the structure of tropical and subtropical soils. There are, however, indications that chemical management of these soils can affect their mechanical properties (Chaplain *et al.* 2011), the stability of the aggregates, and the dispersion of clay (Castro and Logan 1991; Roth and Pavan 1991; Spera *et al.* 2008), potentially increasing the susceptibility of the soil to erosion by water (Castro and Logan 1991).

Hypothetically, both soil chemical management and low supply of organic material to the soil are contributing to promote Oxisol structural degradation under NT, which can result in decreased aggregate stability and increased clay dispersion. Thus, the objective of this study was to understand the relationship between chemical management and structural degradation for Oxisols cultivated under NT.

Material and methods

Study areas

Three locations with Oxisols were selected: two in the state of Rio Grande do Sul (RS) and one in the state of Paraná (PR; Fig. 1). At location LV-BR in Bom Recreio, RS (28°7'12"S, 52°28'9"W), the soil was a Haplorthox (USDA 2012) or known as 'Latossolo Vermelho Distrófico' as per the Brazilian system soil classification (Santos *et al.* 2006), cultivated under NT for 12 years. The cropping system comprised soybean (*Glycine max* L.) and maize (*Zea mays* L.) in the summer season (November–May) and the land is left fallow in the winter (May–November). The last liming (5 Mg ha⁻¹) was performed 5 years before soil sampling. At LV-PF in Passo Fundo, RS (28°22'51"S, 52°18'47"W), the soil is a Rhodic Hapludox (USDA 2012) or known as 'Latossolo Vermelho Distroférrico' according to the Brazilian system soil

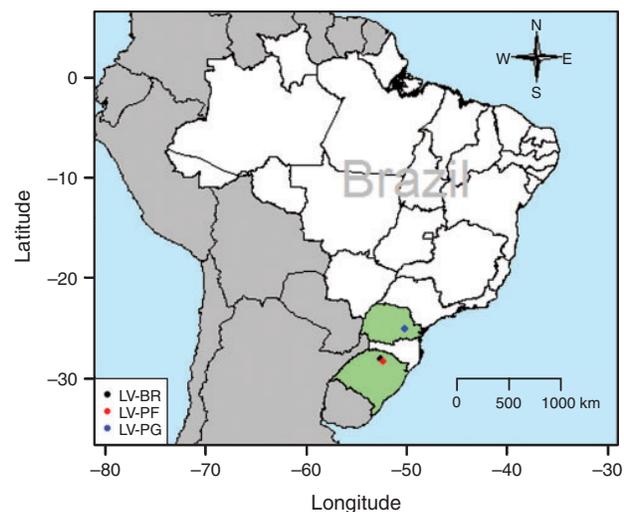


Fig. 1. Location of the experimental sites: LV-BR in Bom Recreio, RS (Haplorthox); LV-PF in Passo Fundo, RS, (Hapludox); LV-PG in Ponta Grossa, PR (Acrorthox).

classification (Santos *et al.* 2006), cultivated under NT for 15 years. Here, soybean and maize were cultivated during the summer season; in the winter season, wheat (*Triticum aestivum* L.) was cultivated or the land was left fallow. The last liming (3 Mg ha⁻¹), was performed 3 years before sample collection. The third site, LV-PG, with an Acrorthox (USDA 2012) or known as 'Latossolo Vermelho Distrófico' according to the Brazilian system soil classification (Santos *et al.* 2006), was located in Ponta Grossa, PR (25°10'0"S, 50°9'57"W) and had been cultivated under NT for 15 years. The crop rotation was soybean and maize, with green manure species (e.g. *Crotalaria breviflora*, *Crotalaria juncea*, *Cajanus cajan*, *Mucuna deeringiana*, and *Pennisetum glaucum*) in the summer, and wheat, black oats, (*Avena strigosa* L.), rye (*Secale cereale* L.) and vetch (*Vicia sativa* L.) in the winter. Liming (3.5 Mg ha⁻¹) was last performed 4 years before sample collection.

The areas selected for the study are used for the commercial production of grains. They are representative of the production models and NT soil management systems practiced by the farmers of the respective regions. Fertilisation of crops involved the application of mineral fertilisers either along the seeding lines or over the surface. The mineral fertilisers used were previously formulated and contained nitrogen (N), phosphorus as P₂O₅ and potassium as K₂O. Liming was performed exclusively by surface application, without incorporation into the soil. In the state of Rio Grande do Sul, calculations of fertilisation and liming requirements were based on analyses of soil collected from the 0–0.1 m layer, whereas in Paraná, the depth range considered was 0–0.20 m. In the three study locations, the crop residues are left on the field.

For each cultivated area, an adjacent reference area with the similar soil (same soil classification, similar relief, and similar texture) was identified. These were under native vegetation (native vegetation from the 'Mata Atlântica' biome, comprising large, medium and small trees), and had not been under cultivation or received any chemical treatments (fertilisers, pesticides and liming) for at least 60 years. The reference area (non-cultivated area) was distant at ~30–50 m from the cultivated areas under NT.

The climate for the two collection sites in RS, LV-BR and LV-PF, is humid subtropical (Cfa; Köppen classification), with average annual precipitation from 1300 to 1800 mm distributed throughout the year, with the greatest rainfall occurring during the months of May and June. Site LV-PG is within a region where the climate is predominantly humid subtropical mesothermal (Cfb). The mean annual precipitation is 1545 mm, distributed throughout the year and the highest values occur in December, January and February. The seasons are less clearly defined in the LV-PF region than in the RS and LV-BR regions.

Soil sampling

Soil samples were collected in December 2014, post-harvest to winter crops for sites LV-PF and LV-PG and before soybean sowing for LV-BR. Ten trenches, 0.30 m wide and 0.20 m deep, were opened at random points under NT cultivation at each site (trenches were located perpendicular the sowing lines). Inspection of the soil profile in the trenches led to the identification of two distinct soil layers. Layer 1 extended from the surface down to ~0.07 m, and was characterised by

high porosity, visible to the naked eye, and an abundance of roots. Layer 2, located at depths between 0.07 and 0.20 m, was denser, had a lower visible porosity, and contained fewer roots. The soil samples were collected from depths of 0 to 0.05 m (Layer 1) and 0.10 to 0.15 m (Layer 2). Soil samples were also collected from the same depths at 10 random points within the previously selected non-cultivated reference areas. Therefore, 120 soil samples were collected in total (3 Oxisols × 2 layers × 2 management types × 10 points = 120 samples). Both Layer 1 and Layer 2 were located within the A horizon. After collection, soil samples were sealed in plastic containers, so as to maintain moisture contents similar to field conditions (Table 1). This procedure was followed to avoid wetting and drying of the soil, processes which affect the stability of soil aggregates and clay dispersion (Dexter *et al.* 2011).

Measurements

Physical, chemical and mineralogical properties

Chemical assessments. Chemical assessments were as follows: pH in water (Donagema *et al.* 2011); calcium (Ca²⁺), magnesium (Mg²⁺), and potassium (K⁺) extracted with ammonium acetate and determined by atomic absorption spectrophotometry; potential acidity (H⁺ + Al³⁺) extracted with calcium acetate and determined by titration; aluminium (Al³⁺) extracted with potassium chloride (1 M) and determined by titration; and phosphorus using Melich-1 extraction and determined by colourimetry. From these, the base sum (SB = K⁺ + Ca²⁺ + Mg²⁺) the cation exchange capacity (CEC = H⁺ + Al³⁺ + SB), the base saturation of CEC (%BS = SB/CEC), and saturation by aluminium (%Al = Al³⁺/(SB + Al³⁺)) were calculated. Organic carbon (OC) was determined by the Walkley–Black method (Donagema *et al.* 2011). Concentrations of the oxides of silicon (SiO₂), aluminium (Al₂O₃), titanium (TiO₂), iron (Fe₂O₃) and manganese (MnO) were determined following extraction with a sodium dithionite-citrate-bicarbonate solution, according to Mehra and Jackson (1960).

Mineralogical measurements. The indices K_f and K_r , defined as the molar ratios SiO₂/Al₂O₃ and SiO₂/(Al₂O₃+Fe₂O₃) were

Table 1. Gravimetric water content of the soil samples at the moment of collection

Soil	Soil use	Layer	Moisture (kg kg ⁻¹)
LV-BR ^A	Cultivated under NT	1	0.19
		2	0.20
	Not cultivated, under native vegetation (reference)	1	0.18
		2	0.17
LV-PF ^B	Cultivated under NT	1	0.18
		2	0.20
	Not cultivated, under native vegetation (reference)	1	0.16
		2	0.16
LV-PG ^C	Cultivated under NT	1	0.18
		2	0.22
	Not cultivated, under native vegetation (reference)	1	0.22
		2	0.22

^AHaplorthox; ^BHapludox; ^CAcrorthox.

respectively calculated. A qualitative mineralogical analysis of the clay fraction of soil samples collected from 0–0.20 m in a non-cultivated area of each of the three sites was also performed. The clay fraction was isolated by processing the soil through the following steps: digestion of the organic matter with hydrogen peroxide, chemical dispersion with 10 mL of 0.1 M sodium hydroxide, mechanical dispersion on a rotisserie-style tube rotator (16 h at 25 rpm), followed by removal of the sand fraction by wet-sieving. The suspension of silt and clay in water was then transferred to a 1000-mL graduated cylinder, where silt and clay were separated by sedimentation for a time calculated from Stokes' Law, and the clay fraction was retrieved by siphoning. The recovered clay fraction was dried, and characterised by powder X-ray diffraction on a Shimadzu XRD 6000 diffractometer. The X-ray diffraction pattern was recorded with Cu K α radiation, over the angular range 3–45° (2 θ). The X-ray tube was operated at a current of 30 mA, and a potential of 30 kV; the angular scan rate was 0.5° min⁻¹.

Granulometry. Clay and silt contents were determined by the hydrometer method, and sand content by the sieving method (Gee and Or 2002).

Structural stability

Soil structural stability was evaluated by means of three physical attributes: (i) clay readily dispersible in water (RDC); (ii) clay mechanically dispersible in water (MDC); and (iii) aggregate stability, assessed through the stability of the water percolation (WP) in soil columns. The reasons for the choice of these parameters and the methodologies adopted for their determination were based upon studies developed and detailed in Dexter *et al.* (2011), and Auerswald (1995; WP).

Readily dispersible clay in water (RDC). The RDC was quantified by measuring the turbidity of a suspension of the soil in water. First, 5 g of soil, with moisture matching soil conditions at the time of the field collection (Table 1) was placed in a 150-mL flask. Next, 125 mL of deionised water was added and the flask was then manually inverted four times and allowed to stand so that particles with diameters larger than clay settled to the bottom of the flask by sedimentation. After 16 h, 30 mL of suspension was withdrawn from the centre of the flask, without disturbance of the sediment at the base, and transferred to a turbidimeter (Hach Turbidimeter 2100AN) to measure turbidity of the suspension in NTU (nephelometric turbidity units). In parallel, the water content of the soil sample was determined, and used to calculate the mass of dry soil ($m(ds)$) in the 5 g aliquot of soil taken for the RDC quantification. The measured turbidity was normalised to a concentration of dry soil of 1 g L⁻¹:

$$\left[\text{RDC/NTU (g L}^{-1}\text{)}^{-1} \right] = \frac{[\text{turbidity/NTU}]}{1000 \times \left(\frac{m(ds)/g}{125} \right)} \quad (1)$$

Triplicate determinations of the RDC were performed for each of the 40 soil samples collected from each site (Layer 1 and Layer 2 from the 10 trenches established in NT cultivated part of the site and Layer 1 and Layer 2 from the 10 uncultivated reference points).

Mechanically dispersible clay in water (MDC). Quantification of the MDC was also based upon turbidity measurements. Once the 30 mL sample of the suspension required for the quantification of the RDC had been withdrawn from the flask, 30 mL of deionised water were added to the flask, making the volume 125 mL. The flask was then turned over continuously about a horizontal axis at 100 rpm for 3 h to promote mechanical dispersion of the clay. The flask was then left to stand undisturbed on a bench for 16 h, so that particles with diameters larger than those of clay settled to the bottom by sedimentation. Upon completion, 30 mL of suspension was withdrawn from the centre of the flask, ensuring that the sediment at the base of the flask was not disturbed, transferred to the turbidimeter, and the turbidity of the suspension was recorded in NTU. As for the RDC, the measured turbidity was normalised to a concentration of dry soil in the flask of 1 g L⁻¹, so that the MDC was expressed in NTU/(g L⁻¹; Eqn 1). All soil samples were analysed in triplicate.

Stability of WP. Soil columns were prepared inside cylindrical glass tubes with an internal diameter of 15 mm and a height of 105 mm. The lower end of the tube was covered with a piece of nylon fabric, and medium sand (diameter 0.25 to 0.50 mm) was added to a height of 2 mm to avoid any obstruction to the departure of water from the tube. Subsequently, 10 g of air-dried aggregates, with particle diameters between 1 and 2 mm was added. A further 2 mm layer of medium sand was created above the column of aggregates to prevent aggregate rupture through direct contact with water. The aggregates within the tube were mechanically homogenised by dropping the tube vertically 10 times from a height of 2 cm onto a rigid surface. Deionised water was then allowed to percolate through the column of aggregates under a constant hydrostatic pressure of 20 hPa for 600 s. The volume of water that percolated through the column during this time is referred to as the percolation stability and provides a measure of the stability of the soil aggregates. The methodology described above has been used and validated in previous studies on soil structural stability (e.g. Auerswald 1995; Mbagwu and Auerswald 1999; Guedes Filho *et al.* 2013).

Statistical analysis

Mean values for the various indicators of soil structural stability were compared between the 12 groups, defined by system of management (NT or not cultivated), layer (1 or 2), and site (LV-BR, LV-PF or LV-PG), by examining their respective confidence intervals ($P < 0.15$; Payton *et al.* 2000). An exploration of the relationships between variables considered to be indicators of structural stability and the other measured soil attributes was conducted through assessments of bivariate scatter plots for each layer. The strength of the relationships between structural stability indicators and chemical variables was evaluated through the canonical correlations, supported by F-tests ($\alpha = 0.05$) following recommendations by Manly (2005). Once the most important variables within each group had been identified, linear regressions with multiple variables were performed to parametrise the stability variables as linear combinations of chemical variables. All analyses were conducted within the R statistical computation environment (R Core Team 2015).

Results

Chemical, physical and mineralogical properties

Soil textural analysis revealed differences among the three sites (Table 2), with soil from site LV-BR showing the lowest clay content and the highest sand content, whereas the soil from LV-PG had the highest clay and the lowest sand contents. The soil from LV-PF was found to have intermediate contents of clay and sand.

The cultivated soils has higher concentrations of nutrients, lower acidity, and lower concentrations of Al^{3+} than the non-cultivated soils. These differences were larger in the surface layer (0–0.05 m) than in the second layer (0.10–0.15 m). The cultivated soil from LV-PF presented the highest concentrations of nutrients, the highest pH in water, and the lowest concentration of Al^{3+} , with the differences from the LV-PG soil being the most pronounced. The highest content of OC was found in the non-cultivated soils, independent of depth. However, for the surface layer at LV-PG, the levels of OC quantified in the cultivated soil were similar to those in the non-cultivated soil.

Soil from LV-BR presented the lowest contents of SiO_2 (96–112 $g\ kg^{-1}$) and Al_2O_3 (100–121 $g\ kg^{-1}$). The highest concentrations of SiO_2 (158–213 $g\ kg^{-1}$) were found in the LV-PF soil, which had intermediate levels of Al_2O_3 (122 to 178 $g\ kg^{-1}$), whereas the LV-PG soil had the highest concentrations of Al_2O_3 (223 to 280 $g\ kg^{-1}$) and intermediate concentrations of SiO_2 (124–139 $g\ kg^{-1}$). The Fe_2O_3 concentrations ranged from 73 to 126 $g\ kg^{-1}$. The highest values for the indices K_i (1.89–2.20) and K_r (1.37–1.62) were observed in the samples collected from LV-PF, and the lowest in the LV-PG soil samples (K_i : 0.77–0.97; K_r : 0.67–0.78). The qualitative mineralogical analyses of the clay fraction by powder X-ray diffraction (Fig. 2) indicated the presence of kaolinite, hematite, and quartz in the soil samples collected from all three of the sites, which is normal for these Oxisols (Ker 1997). Gibbsite was only detected in the LV-PF and LV-PG soils, its peak being more pronounced for the LV-PG soil. Taking into consideration the values of the indices K_i and K_r , with the qualitative mineralogical analyses, it is inferred that the LV-PG soil is the most weathered with higher level of gibbsite, whereas soils from LV-PF and LV-BR are less weathered and richer in kaolinite (Ker 1997).

Structural stability indicators of the soil

Readily dispersible clay (RDC)

Confidence intervals of the mean RDC values show that, irrespective of the layer from which the soil was collected, the soils cultivated under NT had higher levels of RDC than the non-cultivated soils (Fig. 3). The only case in which the cultivated to non-cultivated difference was not significant was for Layer 1 soil from LV-PF. In the subsurface soil (Layer 2), the quantity of RDC in the cultivated soil was approximately four times greater than in the non-cultivated soil from the same site (Fig. 3). Examining the non-cultivated soils, for each site there was no difference in RDC values for the two sampled layers. However, for the cultivated soils, RDC in the subsurface layer was greater than in the surface layer (Fig. 3). There was a clear difference between the cultivated and non-cultivated soils from

the three sites, with the largest concentrations of RDC being invariably found in the cultivated soils, principally in the subsurface layer.

Mechanically dispersible clay in water (MDC)

The concentration of MDC in the soil samples collected from the cultivated areas was significantly greater than in the non-cultivated soils (Fig. 4). The sole exception was the subsurface layer for site LV-PG. Differences in the MDC levels between the layers were only significant for soil taken from the cultivated areas, for which greater quantities of MDC were observed in the subsurface layer. For the cultivated soils, those from LV-PG and LV PF presented the lowest and the highest quantities of MDC (Fig. 4).

Water percolation (WP)

The WP was observed to be faster through the non-cultivated soils than through the cultivated soils (Fig. 5). Differences in WP values between the layers and the sites were not significant. The rate of WP through the soil was inversely correlated with the contents of RDC and MDC (Fig. 6).

Relationships between structural stability indicators and other soil attributes

Exploratory analyses conducted by examining bivariate scatter plots between a variable selected from the set of three structural stability indicators (RDC, MDC, and WP) and a variable selected from the set of soil physical and chemical attributes (Table 2) permitted a global visualisation of the relationships between soil structure stability and the other soil attributes. Separate scatter plots constructed from the data points provided by the characterisation of the soil in the surface layer (0–0.05 m, Layer 1) and the subsurface layer (0.10–0.15 m, Layer 2) revealed the extent to which indicator variables of soil structural stability were related to the measured and calculated chemical variables of the soil in the two layers. This led to the selection of pH, K^+ , Ca^{2+} , Mg^{2+} , Al^{3+} , %Al, OC, and Fe_2O_3 as potential explanatory variables for the three indicators of soil structural stability (RDC, MDC, and WP). Canonical correlation analysis was then utilised to identify and measure the relationships between the indicator variables (Group I) and the explanatory variables (Group II):

$$\left[\begin{array}{c} \text{Group I} \\ \text{Structural stability} \\ \text{indicators} \\ \text{RDC} + \text{MDC} + \text{WP} \end{array} \right] \text{ vs } \left[\begin{array}{c} \text{Group II} \\ \text{Chemical attributes} \\ \text{pH} + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+} + \text{Al}^{3+} \\ + \% \text{Al} + \text{OC} + \text{Fe}_2\text{O}_3 \end{array} \right]$$

Results of the separate canonical correlation analyses for the two soil layers (Table 3) demonstrated a strong correlation between Group I (soil structural stability) and Group II (soil chemical attributes). For the surface layer, the first two canonical pairs were associated with canonical correlations of 0.99 and 0.87 between Group I and Group II respectively, explaining 94 and 4% of the total covariance respectively. In the case of the subsurface layer, the canonical correlations for the first two canonical pairs were 0.99 and 0.94 for Group I and Group II respectively, explaining 82 and 16% of the total covariance

Table 2. Physical and chemical characterisation of the soils from sites LV-BR (Haplorthox), LV-PF (Hapludox), and LV-PG (Acrothox), subdivided by sampling depth, and into cultivated under no-till (C) and not cultivated or under native vegetation (NC)
 Values are reported as means ($n = 10$) followed by standard errors

Soil component ^A	LV-BR			LV-PF			LV-PG					
	0.0–0.05 m			0.10–0.15 m			0.0–0.05 m			0.10–0.15 m		
	C	NC										
Clay (g kg ⁻¹)	358.5 ± 15.1	361.2 ± 16.7	421.5 ± 17.3	403.9 ± 18.7	582.6 ± 35.4	535.3 ± 36.7	614.3 ± 38.1	589.6 ± 34.3	688.5 ± 45.9	648.0 ± 40.1	699.1 ± 40.5	691.9 ± 37.9
Silt (g kg ⁻¹)	53.4 ± 19.6	117.9 ± 20.4	37.0 ± 18.3	108.7 ± 24.3	221.0 ± 24.1	232.0 ± 23.4	203.2 ± 18.6	229.4 ± 19.8	206.8 ± 20.5	229.9 ± 21.7	214.5 ± 19.4	212.2 ± 22.8
Sand (g kg ⁻¹)	588.1 ± 36.8	521.0 ± 38.7	541.5 ± 39.5	487.4 ± 36.4	196.4 ± 21.1	232.7 ± 23.6	182.5 ± 20.4	180.9 ± 19.3	104.7 ± 19.1	122.1 ± 20.3	86.5 ± 18.8	95.9 ± 17.8
pH in water	6.1 ± 0.2	4.9 ± 0.1	5.5 ± 0.2	5.0 ± 0.2	6.3 ± 0.3	5.6 ± 0.2	5.6 ± 0.2	5.1 ± 0.2	5.0 ± 0.2	4.9 ± 0.2	5.2 ± 0.3	5.2 ± 0.2
P (mg kg ⁻¹)	16.0 ± 1.5	18.0 ± 1.9	6.0 ± 1.4	2.0 ± 1.0	21.0 ± 3.4	7.0 ± 1.2	2.0 ± 0.6	3.0 ± 0.5	18.0 ± 3.1	12.0 ± 2.3	8.0 ± 1.4	3.0 ± 1.1
K ⁺ (mmol _c kg ⁻¹)	7.8 ± 0.8	2.7 ± 0.3	5.5 ± 0.6	1.7 ± 0.2	7.4 ± 0.9	3.0 ± 0.7	6.8 ± 0.8	3.2 ± 0.6	7.1 ± 1.2	4.1 ± 1.0	6.9 ± 0.9	1.5 ± 0.3
Ca ²⁺ (mmol _c kg ⁻¹)	35.0 ± 5.1	15.0 ± 3.3	23.0 ± 4.2	12.0 ± 3.1	59.0 ± 6.4	30.0 ± 4.2	48.0 ± 5.3	32.0 ± 4.2	35.0 ± 4.6	23.0 ± 3.1	33.0 ± 4.2	22.0 ± 2.9
Mg ²⁺ (mmol _c kg ⁻¹)	19.0 ± 1.6	10.0 ± 1.3	14.0 ± 1.7	6.0 ± 1.4	29.0 ± 3.4	14.0 ± 2.6	24.0 ± 3.1	17.0 ± 3.0	14.0 ± 2.0	6.7 ± 1.5	16.0 ± 2.2	14.0 ± 1.8
ΣB (mmol _c kg ⁻¹)	61.8 ± 6.7	27.7 ± 4.5	42.5 ± 5.7	19.7 ± 3.2	95.4 ± 7.1	47.0 ± 5.4	78.8 ± 6.1	52.2 ± 5.7	56.1 ± 5.8	33.8 ± 5.0	55.9 ± 5.1	37.5 ± 4.2
Al ³⁺ (mmol _c kg ⁻¹)	0.0 ± 0.0	13.0 ± 1.2	0.0 ± 0.0	12.0 ± 1.3	0.1 ± 0.1	20.0 ± 2.1	0.5 ± 0.1	15.0 ± 2.0	5.0 ± 0.4	8.0 ± 1.0	2.1 ± 0.9	9.0 ± 1.2
CEC (mmol _c kg ⁻¹)	104.7 ± 7.6	86.7 ± 7.1	99.5 ± 8.2	97.7 ± 7.5	142.9 ± 10.0	159.0 ± 9.8	144.3 ± 10.4	136.2 ± 8.7	197.1 ± 12.8	64.7 ± 5.1	170.0 ± 11.2	128.4 ± 8.4
%BS	59.0 ± 7.1	31.9 ± 4.2	42.7 ± 4.8	20.2 ± 1.4	67.0 ± 4.6	29.6 ± 2.4	54.6 ± 4.5	38.3 ± 3.1	28.5 ± 1.9	52.2 ± 4.6	32.9 ± 2.9	29.2 ± 1.8
%Al	0.0 ± 0.0	31.9 ± 2.1	0.0 ± 0.0	37.9 ± 2.6	0.1 ± 0.1	29.9 ± 3.1	0.6 ± 0.1	22.3 ± 2.3	8.2 ± 0.8	19.1 ± 2.1	3.6 ± 1.5	19.4 ± 2.7
OC (g kg ⁻¹)	12.5 ± 1.0	27.1 ± 1.4	12.6 ± 0.9	29.3 ± 2.1	16.7 ± 1.5	31.5 ± 2.1	16.5 ± 1.2	28.1 ± 2.4	26.2 ± 2.4	30.3 ± 2.8	22.0 ± 1.9	24.7 ± 2.0
SiO ₂ (g kg ⁻¹)	112.0 ± 15.8	96.0 ± 11.6	119.0 ± 17.0	108.0 ± 11.4	213.0 ± 22.6	158.0 ± 24.7	198.0 ± 27.9	163.0 ± 25.7	124.0 ± 19.4	127.0 ± 17.6	139.0 ± 18.3	137.0 ± 16.1
Al ₂ O ₃ (g kg ⁻¹)	99.7 ± 10.8	100.2 ± 11.7	121.7 ± 13.5	111.2 ± 10.2	167.3 ± 18.6	122.2 ± 14.4	178.3 ± 26.1	138.7 ± 20.9	275.4 ± 30.1	223.3 ± 26.3	279.9 ± 29.4	250.4 ± 26.2
Fe ₂ O ₃ (g kg ⁻¹)	73.3 ± 10.4	118.2 ± 10.5	96.0 ± 10.3	126.1 ± 11.3	107.3 ± 10.6	117.8 ± 10.9	108.8 ± 10.8	115.8 ± 12.0	88.8 ± 10.1	109.2 ± 10.3	91.2 ± 10.7	111.8 ± 10.9
TiO ₂ (g kg ⁻¹)	30.9 ± 5.1	56.6 ± 6.4	50.4 ± 5.5	52.1 ± 5.0	45.0 ± 4.9	50.8 ± 5.3	48.3 ± 4.7	49.9 ± 4.9	39.8 ± 4.2	43.1 ± 4.4	41.1 ± 4.0	45.5 ± 4.2
MnO (g kg ⁻¹)	0.3 ± 0.0	0.7 ± 0.1	0.3 ± 0.0	0.8 ± 0.1	0.5 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.5 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.1 ± 0.0
K _f	1.91 ± 0.2	1.63 ± 0.2	1.66 ± 0.2	1.65 ± 0.2	2.16 ± 0.3	2.20 ± 0.3	1.89 ± 0.2	2.0 ± 0.2	0.77 ± 0.1	0.97 ± 0.2	0.84 ± 0.1	0.93 ± 0.1
K _r	1.37 ± 0.1	0.98 ± 0.1	1.16 ± 0.1	1.01 ± 0.1	1.62 ± 0.2	1.43 ± 0.1	1.43 ± 0.1	1.37 ± 0.1	0.67 ± 0.1	0.78 ± 0.1	0.74 ± 0.1	0.76 ± 0.1

^AClay and silt (hydrometer method); sand (sieving). ΣB (base sum) = K⁺ + Ca²⁺ + Mg²⁺. CEC (cation exchange capacity) = (H⁺ + Al³⁺) + ΣB. %BS (base saturation) = ΣB/CEC. %Al (saturation by aluminium) = Al³⁺/(ΣB + Al³⁺). OC, organic carbon (Walkley-Black method). K_f and K_r are defined as the molar ratios SiO₂/Al₂O₃ and SiO₂/(Al₂O₃ + Fe₂O₃) respectively.

between the groups respectively. For both layers, the third canonical pair was not found to be significant. Since only the first two canonical pairs were significant for both layers, and together they were sufficient to explain 98% of the total covariance between the groups, the subsequent evaluations were limited to the first two canonical pairs.

The canonical coefficients of the variables within the first two canonical pairs estimated by applying a maximisation of covariance model (canonical weights) are presented in Table 4. The values of the canonical coefficients for the variables of Group II permit the identification of the chemical attributes that are most important in relating linear combinations of the Group I variables that generate the canonical variables of

structural stability of the soil to the variables of Group II. In the case of the surface layer, the most important Group II variables were pH, K^+ , Al^{3+} , OC, and Fe_2O_3 , showing that the structural stability of the three studied Oxisols was principally influenced by the levels of these attributes. For the subsurface layer, Ca^{2+} , Al^{3+} , %Al, OC, and Fe_2O_3 emerged as the most important Group II variables for the prediction of the Group I canonical variables. However, the weight for OC in the first canonical pair and for %Al in the second pair were much greater than for the other Group II variables. These results indicate that for the subsurface layer of Oxisols cultivated under NT the structural stability was influenced most strongly by the content of OC and the Al^{3+} saturation of the soil (%Al).

With the most important soil attributes for the prediction of the structural stability of the soil in the two layers identified, the next objective in the analysis was to establish the functional relationships between the three indicator variables and the soil attributes, obtained by stepwise multiple regression, with RDC, MDC, and WP treated as dependent variables. For the surface layer, the initial set of explanatory variables was pH, K^+ , OC, and Fe_2O_3 ; Al^{3+} was excluded because of its very high correlation with soil pH. For the subsurface layer, the initial set of explanatory variables was Ca^{2+} , %Al, OC, and Fe_2O_3 ; in this case, Al^{3+} was excluded because of its collinearity with %Al. Finally, multiple regression was performed for the combined dataset from the two layers, with pH, K^+ , Ca^{2+} , %Al, OC, and Fe_2O_3 as the initial set of explanatory variables.

Table 5 shows the linear equations with optimised parameter values obtained from model adjustment. With the exception of the equations for RDC and MDC for the surface layer, all included OC as a term, proving the influence of organic carbon on soil structural stability, independent of the layer under evaluation. In addition to OC, the structural stability of the NT soil in the surface layer depends on the concentrations of K^+ and Fe_2O_3 , and pH, whereas for the subsurface layer Al^{3+} saturation (%Al) is an additional important factor.

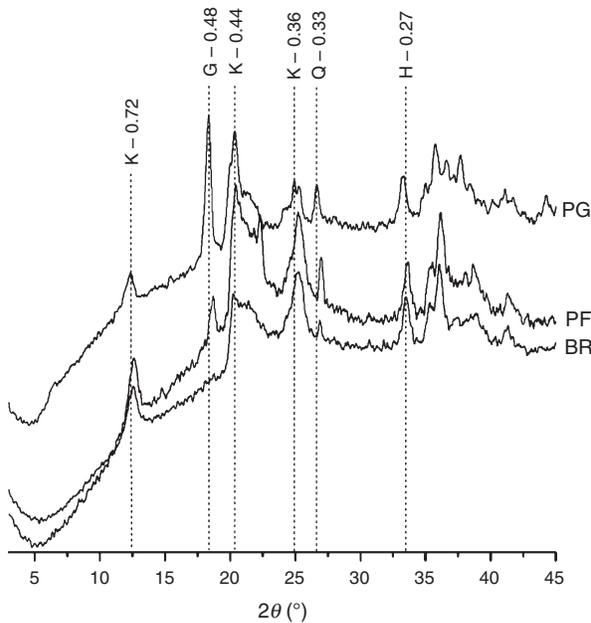


Fig. 2. Powder X-ray diffraction patterns of the clay fraction isolated from soil samples collected from the 0–0.20 m layer in a non-cultivated area of each of the three sites. BR: Haplorthox from Bom Recreio (RS); PF: Hapludox from Passo Fundo (RS); and PG: Acrorthox from Ponta Grossa (PR). The identified peaks are from the minerals kaolinite (K), gibbsite (G), quartz (Q), and hematite (H).

Discussion

Chemical factors in the structural stability of Oxisols managed under NT

The mineralogical composition of the Oxisols investigated in this study is predominantly kaolinite together with oxides

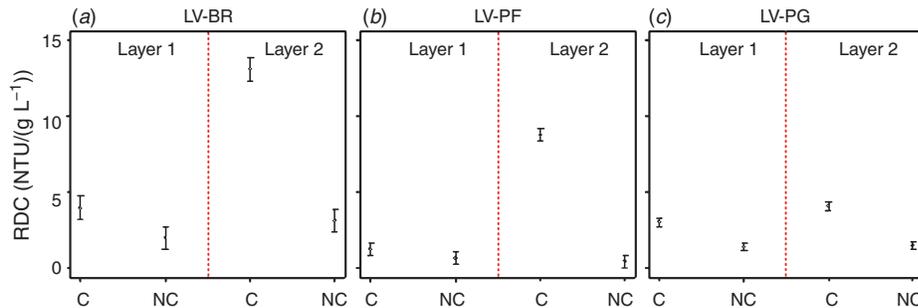


Fig. 3. Readily dispersible clay in water (RDC) for the soils collected from the three sites. (a) LV-BR: Haplorthox, (b) LV-PF: Hapludox; and (c) LV-PG: Acrorthox. Samples were collected from areas cultivated under no-till (C) and non-cultivated areas (NC). Layer 1: 0.0–0.05 m; Layer 2: 0.10–0.15 m. Vertical bars indicate the confidence intervals ($P < 0.15$) for the mean RDC values.

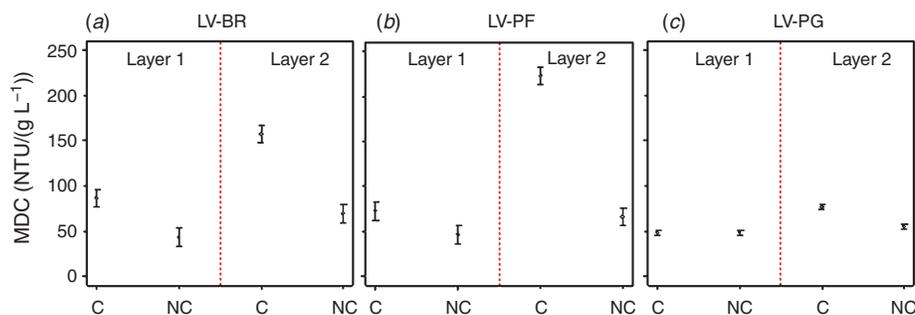


Fig. 4. Mechanically dispersible clay in water (MDC) for the soils collected from the three sites. (a) LV-BR: Haplorthox, (b) LV-PF: Hapludox; and (c) LV-PG: Acrorthox. Samples were collected from areas cultivated under no-till (C) and non-cultivated areas (NC). Layer 1: 0.0–0.05 m; Layer 2: 0.10–0.15 m. Vertical bars indicate the confidence intervals ($P < 0.15$) for the mean MDC values.

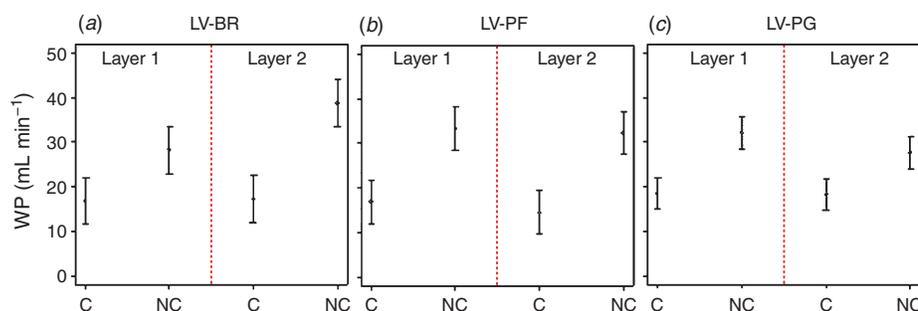


Fig. 5. Water percolation (WP) through the soils collected from the three sites. (a) LV-BR: Haplorthox, (b) LV-PF: Hapludox, and (c) LV-PG: Acrorthox. Samples were collected from areas cultivated under no-till (C) and non-cultivated areas (NC). Layer 1: 0–0.05 m; Layer 2: 0.10–0.15 m. Vertical bars indicate the confidence intervals ($P < 0.15$) for the mean WP values.

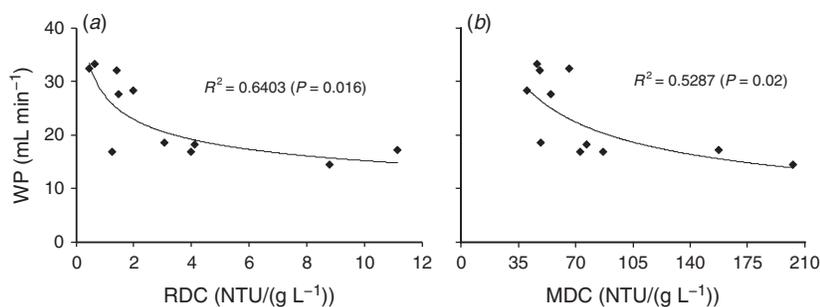


Fig. 6. Water percolation (WP) plotted as a function of (a) the readily dispersible clay in water (RDC) and (b) the mechanically dispersible clay in water (MDC). Data points are from the complete group of sampled Red Latosols: all three sites, cultivated under no-till and non-cultivated (under native vegetation), in Layer 1 (0–0.05 m) and Layer 2 (0.10–0.15 m).

of Fe and Al (Fig. 2), which possess variable surface charge (Uehara and Gillman 1980). The greater structural stability of non-cultivated soils than NT-cultivated soils (Figs 3–5) may be viewed as a consequence of the physical and chemical equilibria at play in these soil systems. Of particular importance are the OC and Al^{3+} concentrations and the pH (Table 2); concentrations of OC and Al^{3+} were higher for the non-cultivated soils, which also had a lower pH. At a pH below the PZC of the oxides, the soil becomes electropositive, which

makes it possible for the electronegative functional groups of soluble organic anions to bind to the electropositive domains of soil particles. The adsorption of the organic anions reduces the positive surface charges on the oxides (Coleman *et al.* 1989), allowing the oxides to link together through Al^{3+} bridges (Ramos and McBride 1996; Vrdoljak and Sposito 2002). Thus, the tendency of the soil particles to flocculate is increased by an increased concentration of organic matter and a greater abundance of Al^{3+} in the non-cultivated soils, coupled

Table 3. Canonical correlation analysis between the variables of Group I (indicators of soil structural stability) and the variables of Groups II (selected explanatory chemical attributes of the soil)

Canonical pair	Canonical correlation	Proportion of covariance explained		<i>p</i> -value
		by canonical pair	cumulative sum	
<i>Layer 1 (0–0.05 m) surface</i>				
First	0.99	0.94	0.94	0.0000
Second	0.87	0.04	0.98	0.0498
Third	0.76	0.02	1.00	0.1637
<i>Layer 2 (0.10–0.15 m) subsurface</i>				
First	0.99	0.82	0.82	0.0000
Second	0.94	0.16	0.98	0.0051
Third	0.71	0.02	1.00	0.2628

Table 4. Estimated canonical coefficients of the structural stability variables (Group I) and the selected soil chemical variables (Group II) in the first two canonical pairs, for the surface and subsurface layers RDC, readily dispersible clay; MDC, mechanically dispersible clay; WP, water percolation; OC, organic carbon

Variable	Surface (0–0.05 m) Canonical pair		Subsurface (0.10–0.15 m) Canonical pair	
	First	Second	First	Second
Group I				
RDC	0.211	1.171	0.358	0.575
MDC	0.380	0.719	0.006	1.541
WP	–0.605	–0.312	–0.768	–0.708
Group II				
pH	0.212	1.247	0.046	–0.489
K ⁺	0.204	0.886	0.078	0.206
Ca ²⁺	–0.240	0.139	0.611	0.621
Mg ²⁺	0.236	0.494	0.569	0.194
Al ³⁺	–0.611	0.056	–0.671	–0.532
%Al	0.332	0.038	–0.380	2.518
OC	–0.415	–0.318	–1.378	0.434
Fe ₂ O ₃	–0.418	–1.163	–0.287	–1.432

with the lower pH of the medium (Parks and Bruyn 1962; Ramos and McBride 1996), thereby increasing the stability of the aggregates in the soil from non-cultivated areas (Figs 3–5).

The reduction of Oxisols structural stability under NT, compared with the non-cultivated Oxisols, can result in environmental and agricultural problems. The water-dispersible clay is directly linked to the soil erosion (Castro and Logan 1991; Igwe 2005). Denardin *et al.* (2008) reported the erosion occurrence in Oxisols under NT in farms from South of Brazil and stressed that the soil erosion process promoted the loading of limestone, fertilisers and organic matter from the uppermost layer of these soils, resulting in both economic damage to the agricultural system and environmental pollution. The transport of fertilisers, soil particles, organic matter and water out of the crop field promotes pollution of surface water sources, reduction of the volume of water stored in the soil, and reduction of the recharge of groundwater aquifers (Schick *et al.* 2000; Dalla Costa 2004). In addition, water-dispersible clay can promote surface crusting and decreases soil permeability to water and gases (Bolan *et al.* 1996), influencing the capability of the soil to provide water and oxygen to plants.

The decrease in the structural stability of the Oxisols managed under NT (Figs 3–5) is in part due to the surface application of limestone and fertilisers, which consequently concentrate in the soil surface layer. The lower quantity and lesser quality of the organic matter added to the cultivated soil compared with the non-cultivated soil may also have contributed (Tivet *et al.* 2013; Sá *et al.* 2014). These factors lead to physicochemical alterations in the cultivated system (Haynes and Naidu 1998; Li and Zhang 2007) in both the surface layer (where fertilisers and ameliorants accumulate; Costa and Rosolem 2007; Nunes *et al.* 2014; Dang *et al.* 2015) and in the subsurface layer (where there is minimal addition of organic matter). In tropical and subtropical soils, the negative effects of limestone and fertiliser on saturated hydraulic conductivity, physical properties, water infiltration, and water erosion have previously been reported (Castro and Logan 1991; Roth and Pavan 1991; Fontes *et al.* 1995; Fontes *et al.* 2001; Soprano 2002; Spera *et al.* 2008). Comparison of an Oxisol under

Table 5. Results of multiple regression, with stepwise elimination of explanatory variables, to obtain linear expressions for the prediction of the three indicators of soil structural stability from the chemical attributes of the sampled Oxisols

RDC, readily dispersible clay; MDC, mechanically dispersible clay; WP, water percolation; NTU, nephelometric turbidity units; OC, organic carbon

Equation	<i>R</i> ²	<i>p</i> -value	Equation no.
Surface layer (0–0.05 m)			
[RDC/NTU (g L ^{–1}) ^{–1}]=5.748+0.571 pH–0.661 [Fe ₂ O ₃ (g kg ^{–1})]	0.65	0.0009	2
[MDC/NTU (g L ^{–1}) ^{–1}]=5.493+16.641 pH–3.737 [Fe ₂ O ₃ (g kg ^{–1})]	0.67	0.0008	3
[WP/mL (10 min) ^{–1}]=69.758–18.08 [K ⁺ (g kg ^{–1})]+1.582 [OC (g kg ^{–1})]+1.783 [Fe ₂ O ₃ (g kg ^{–1})]	0.60	0.0026	4
Subsurface layer (0.10–0.15 m)			
[RDC/NTU (g L ^{–1}) ^{–1}]=25.411–0.107 ×%Al–0.831 [OC (g kg ^{–1})]	0.70	0.0008	5
[MDC/NTU (g L ^{–1}) ^{–1}]=254.000–0.331 ×%Al–6.431 [OC (g kg ^{–1})]	0.51	0.0051	6
[WP/mL (10 min) ^{–1}]=6.913–0.410 ×%Al–0.524 [OC (g kg ^{–1})]	0.70	0.0001	7
Combined data from the two layers			
[RDC/NTU (g L ^{–1}) ^{–1}]=23.949+1.941 pH–0.570 [OC (g kg ^{–1})]–1.711 [Fe ₂ O ₃ (g kg ^{–1})]	0.43	0.0005	8
[MDC/NTU (g L ^{–1}) ^{–1}]=122.139+0.972 ×%Al–0.849 [OC (g L ^{–1}) ^{–1}]–0.763 [Fe ₂ O ₃ (g kg ^{–1})]	0.53	0.0004	9
[WP/mL (10 min) ^{–1}]=9.129–0.401 ×%Al–0.411 [OC (g kg ^{–1})]	0.51	0.0005	10

cultivation with the same soil under forest cover revealed greater clay dispersion and lower aggregate stability, which were attributed to liming and a reduction in the level of OC in the cultivated soil (Roth and Pavan 1991; Castro and Logan 1991). The results obtained in this study confirm OC as one of the principal soil attributes that influences the structural stability of the soils. Also, identified as important for the surface layer were pH, K^+ , Al^{3+} , and Fe_2O_3 (Table 4; Table 5: Eqns 2–4), and the content of Al^{3+} in the subsurface layer (Table 4; Table 5: Eqns 5–7).

For soil particles in contact with solutions of electrolytes, the charge on the surface of the particles is altered by the pH, the valence of the ions, and the concentration of electrolytes in the solution (Arora and Coleman 1979; Itami and Kyuma 1995; Ramos and McBride 1996). Limestone applied to Oxisols managed under NT, which is concentrated in the surface layer, raises the pH of the medium and increases the negative charge of soil particles. The presence of more cations of lower valence with a greater radius of hydration reduce the electrostatic forces between kaolinite and the oxides, increasing the content of dispersible clay in the soil (Figs 3 and 4) and decreasing the rate of WP (Fig. 5).

High correlations between the structural stability of Oxisols and their Al^{3+} content and pH, such as those found in the present study, have previously been reported by Roth and Pavan (1991), Castro and Logan (1991), and Fontes *et al.* (1995). The pH is one of the principal factors affecting the dispersion of the particles in soils with a variable charge (Suarez *et al.* 1984; Bolan *et al.* 1996), which can be carried by percolating water and deposited in the subsurface layer, thereby obstructing the natural porosity of the soil (Haridasan and Chibber 1971). Due to the concentration of roots and crop residues close to the surface of the soil, the OC inputs into the subsurface layer is minimal for soils cultivated under NT (Nunes *et al.* 2015b), so that the eluviated clay remains dispersed.

The non-cultivated soil guarantees greater quantities of organic matter (Table 2) of superior quality (Leite *et al.* 2003). The conversion of native forest into farmland substantially diminishes the formation of organo-mineral complexes and the structural stability of the soil, in comparison to the non-cultivated soil (Dal Ferro *et al.* 2012; Tivet *et al.* 2013). Derpsch *et al.* (2014) have argued that the efficiency of NT agricultural production depends upon the presence of crop residues on the soil and can benefit from crop diversification. The positive effect of OC on the structural stability of the soil (Etana *et al.* 2009; Udom *et al.* 2016), seen in the surface and subsurface layers (Figs 3 and 4), serves to reinforce this view.

The greater structural stability of the soil managed under NT at site LV-PG in comparison to sites LV-BR and LV-PF (Figs 3–5) can be related to the higher levels of OC and Fe_2O_3 (Table 2), attributes which are known to influence the structural stability of a soil (Regelink *et al.* 2015). There were also mineralogical differences between the soils. Both the indices K_i and K_r (Table 2) were smaller for the LV-PG soils than for the soils from LV-BR and LV-PF. Furthermore, the qualitative mineralogical analysis (Fig. 2) revealed the presence of gibbsite in the LV-PG, and, possibly, a lower kaolinite concentration. The kaolinite is formed of two basal faces that are, in principle, electrically neutral. However, it is estimated

that this mineral presents ~10% of its total surface covered by external faces and broken edges, where reactive OH groups are found. Since the kaolinite PZC (~4) is much lower than the gibbsite PZC (~9; Essington 2004), an increase in the pH of Oxisols under NT has supported surface deprotonation of surface edges of kaolinite, increasing the liquid negative electric charge of soil (Tan 1998; Alkan *et al.* 2005). Considering the electrostatic potential increase, attraction forces between kaolinite and both Fe and Al oxides were reduced as the repulsion forces between colloids enhanced (Ramos and McBride 1996). As a result, colloidal suspension stability decreased (Tan 1998), influencing the soil structural stability. The PZC of the studied soil was not quantified, and further research is important to improve our knowledge of the physicochemical properties of these soils under different agricultural practices. Nonetheless, the results from the present research and the data from previously studies suggest that kaolinitic Oxisols are more susceptible to soil chemical degradation than gibbsite Oxisols.

Moreover, the higher levels of OC in the NT-managed soil from LV-PG is a reflection of greater diversification in the species cultivated (Martins *et al.* 2012), both in summer and winter, and the maintenance of plant cover throughout the year. In the LV-BR and LV-BR farms, in the winter season, the land is left fallow and occasionally cultivated with wheat; and in the LV-PG, besides corn and soybean, the crop rotation system includes a wide range of green manures species (*Crotalaria breviflora*, *Crotalaria juncea*, *Cajanus cajan*, *Mucuna deeringiana* and *Pennisetum glaucum*, in the summer, and wheat, black oats, rye and vetch, in the winter). This diversification of species can improve OC stocks (Blanco-Canqui *et al.* 2017) and the microbial biomass in soils (Babujia *et al.* 2010), thus improving the structural stability of Oxisols (Tivet *et al.* 2013). In contrast, at sites LV-BR and LV-PF the production model is predominantly soybean monoculture in the summer and a fallow period in the winter, which has led to reduced levels of OC (Table 2) and greater soil dispersion in the subsurface layer (Figs 3 and 4), as reported by Etana *et al.* (2009). This in turn increases the vulnerability of the soil to structural degradation in subsequent seasons (Watts and Dexter 1997).

Current chemical management of soils cultivated under NT and soil conservation

We determined that the NT farming systems can still be improved to ensure that this technique of the soil and crop management is further aligned with conservation objectives. Productivity and conservation diverge when optimisation of the former is founded upon current models of soil fertility that are expressed exclusively in terms of chemical indicators and neglect the biological and physical aspects of soil fertility. Without tillage, the conditioning of the soil for plant development becomes a function of the soil structure created by the biota and the delivery of fertilisers, which enter through the soil surface (Nunes *et al.* 2014). The soil layer in which the crops are raised develops physical differences from other layers (Reichert *et al.* 2009; Nunes *et al.* 2015a; Dang *et al.* 2015) and becomes chemically distinct (Costa and Rosolem 2007; Nunes *et al.* 2014). Under these conditions, the traditional

models for the evaluation of soil fertility, which are built on the assumption of soil homogeneity, cease to be sufficient.

In contrast to conventional management systems, in NT, storage and availability of water, storage and diffusion of heat, oxygen flow, permeability to air, and resistance to root penetration are soil properties that are inextricably linked to soil fertility (Denardin and Denardin 2015). Since soil structure determines these processes, it must be considered alongside biological and chemical factors in the evaluation of fertility (Magdoff and van Es 2009; Iqbal *et al.* 2014). Additionally, soil sampling requires examination as our results have demonstrated vertical heterogeneity in the chemical and physical properties of Oxisols cultivated under NT (Denardin and Denardin 2015), and recommendations for lime and fertilisers based on conventional sampling may be upwardly biased. Excess nutrients may then accumulate at or close to the surface of the soil (Costa and Rosolem 2007; Nunes *et al.* 2014; Dang *et al.* 2015), aggravate physical and chemical stratification (Table 2; Figs 3–5), compromise structural stability (Figs 3–5), and create problems with erosion (Derpsch *et al.* 2014).

To improve chemical management in NT, we must change the way we sample soils to evaluate their fertility. First, before soil sampling in areas under NT for at least 5 years, verify whether physical and chemical stratification has occurred within the 0–0.2 m layer of soil. It is important to avoid mixing stratified layers from the collected soil samples into a heterogeneous sample. Chemical fertility analysis from heterogeneous samples that were originally stratified by sufficient or insufficient fertility levels will result in inaccurate or non-existent data. The second step is to consider that a compacted layer may interfere with hydrologic dynamics, plant-water and nutrient availability, air and heat diffusion, and plant and root development from both resistance to penetration and in the soil reaction solution itself. Therefore, the soil fertility under NT must be interpreted based on the soil biological characteristics, which can indicate an agronomically desirable soil to promote nutrient use efficiency. If soil stratification is found in the 0–0.2 m layer there are management practices to address the issue such as chiseling and use of seeders equipped with fixed shanks in deeper action to the inferior limit of the compact layer. This kind of seeder can break the compact soil layer and, at the same time, promote the chemical soil fertility in profundity depositing fertilisers into the soil subsurface layer, which can stimulate root development of the plants at this layer (Nunes *et al.* 2014, 2015a). To prevent an increase in clay dispersal at the soil surface and to minimise the increase of soil bulk density in the subsurface layer, it is necessary to reduce lime application in the soil surface and to diversify the production systems through crop rotations to produce high amount of biomass, increase organic carbon storage and maintain soil stability (Conceição *et al.* 2013; Tivet *et al.* 2013; Derpsch *et al.* 2014; Corbeels *et al.* 2016; Miranda *et al.* 2016).

Conclusion

Oxisols under NT were investigated and showed a reduction in stability, greater clay dispersion and slower percolation of water than equivalent non-cultivated soil. These negative

effects were traced to a reduction in the supply of organic material to the soil and inappropriate chemical management underpinned by erroneous soil fertility diagnostics, without considering structural and biological attributes and the vertical heterogeneity in the chemical and physical properties of soils under NT to recommend lime and fertilisers. For the surface layer of these soils, the principal explanatory variables for alterations in stability were changes in the pH of the soil, and the content of K^+ , Al^{3+} , and OC, whereas for the subsurface layer the most important variables were the levels of Al^{3+} and OC in the soil.

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