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The no-tillage, with crop rotation or succession, can increase the degree of clay dispersion in the superficial layer of highly weathered soils after 24 years

O plantio direto, com rotação ou sucessão, pode aumentar o grau de argila dispersa na camada superficial de solos altamente intemperizados depois de 24 anos

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Highlights

No-tillage was the soil management system with the highest cay dispersion values.
Crop rotation did not reduce clay dispersion when compared to succession.
The agricultural implements provided the same values of clay dispersion.
H+Al was the only chemical attribute that affected clay dispersion.

Abstract

Clay dispersion is directly related to water erosion, especially during detaching and dragging of particles. No-till is one of the most important strategies for soil and water conservation in tropical and sub-tropical regions, and when associated with crop rotation, may reduce the degree of clay dispersion. The study aimed to evaluate, after 24 years, the effect of different soil management systems and crop systems on the degree of clay dispersion of a Rhodic Ferralsol. The experimental design was completely randomized in a 4x2 factorial scheme, with four soil managements (continuous no-tillage, no-tillage with chiseling every three years, disk plowing followed by light harrowing and heavy disking followed by light harrowing) and with two crop systems (crop succession and rotation). The degree of clay dispersion was evaluated and associated with soil chemical attributes from layer 0.00-0.10 m. The degree of clay dispersion is affected by the soil

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management systems with no effect of crop systems. The soil management system with the lowest soil disturbance (continuous no-tillage) has a higher degree of clay dispersion than the ones that disturb the soil, regardless of the agricultural implement used or soil disturbance intensity. The soil electrochemical imbalance, primarily caused by soil potential acidity, is positively correlated to the increase in the degree of clay dispersion of the superficial soil layer under continuum no-tillage.

Key words: Rhodic Ferralsol. Soil management. Crop systems. Conventional tillage.

Resumo

A argila dispersa está diretamente relacionada com a erosão hídrica, especialmente durante o desprendimento e arraste de partículas. O plantio direto é uma das mais importantes estratégias para conservação do solo e da água nas regiões tropical e sub-tropical, e quando associado com a rotação de culturas, pode reduzir o grau de dispersão de argila. O objetivo desse estudo foi avaliar, após 24 anos, o efeito de diferentes sistemas de manejo e de culturas no grau de dispersão de argila de um Latossolo Vermelho. O delineamento experimental foi inteiramente casualizado em um esquema fatorial 4x2, com quatro manejos do solo (plantio direto contínuo, plantio direto com escarificação a cada três anos, aração de discos seguida de gradagem leve e gradagem pesada seguida de gradagem leve) e dois sistemas de cultivo (sucessão de cultura e rotação). O grau de dispersão da argila foi avaliado e associado aos atributos químicos do solo da camada 0,00-0,10 m. O grau de dispersão da argila é afetado pelos sistemas de manejo do solo sem efeito dos sistemas de cultivo. O sistema de manejo de solo com menor perturbação do solo (plantio direto contínuo) possui o maior grau de dispersão de argila do que os que perturbam o solo, independentemente do implemento agrícola utilizado ou da intensidade do distúrbio do solo. O desequilíbrio eletroquímico do solo, causado principalmente pela acidez potencial do solo, está positivamente correlacionado ao aumento do grau de dispersão de argila da camada superficial do solo sob plantio direto contínuo.

Palavras-chave: Latossolo Vermelho. Manejo do solo. Sistemas de culturas. Plantio convencional.

Introduction

Conservation agriculture is practiced at around 100 Mha of land in the world (Federação Brasileira de Plantio Direto e Irrigação [FEBRAPD], 2020), which represents just over 6% of the 1,500 Mha of arable land in the world (Food and Agriculture Organization of the United Nations [FAO], 2001). Most areas which operate in the conservation system are in North and South America (FAO, 2001). It makes grain production viable and reduces the need for agricultural inputs and the climatic risks caused by agriculture (Findlater, Kandlikar, & Satterfield, 2019). In this context, no-till is one of the most important strategies for soil and water conservation in tropical and sub-tropical regions (Derpsch, Friedrich, Kassam, & Hongwen, 2010).

In Brazil, more than 32 Mha of soil are managed under a no-tillage system, which corresponds to more than 85% of the temporary crop areas in the country (Kassam, Friedrich, & Derpsch, 2019). The benefits of no-till to the chemical, physical and biological qualities of the soil have been extensively documented in the literature (Singh, Phogat, Dahiya, & Batra, 2014; Pittelkow et al., 2015; Munkholm, Heck, Deen, & Zidar, 2016), especially when associated with crop rotation (Palm, Blanco-Canqui, De Clerck, Gatere, & Grace, 2014), thus significantly reducing the production of sediments and soil erosion (Merten & Minella 2013). However, this conservationist system involves a continuous and complex process of agricultural technologies that are partially adopted by farmers or extension agents (FAO, 2001; Merten, Araújo, Biscaia, Barbosa, & Conte, 2015). The partiality in the adoption of no-till can be observed in the farmers that have adopted a poor crop diversity for straw management (Merten et al., 2015) and increased the frequency of agricultural implements use such as the chisel and the disc harrow to incorporate fertilizers (Auler et al., 2019) and to destroy superficial crusts caused by the absence of soil revolvement (Camara & Klein, 2005).

Clay dispersion has been used to evaluate the effects of different uses and management systems in Oxisols (Tavares, Barbosa, & Ribon, 2010; Barbosa, Oliveira, Miyazawa, Ruiz, & Tavares; 2015; Melo, Telles, Machado, & Tavares, 2016; Machado, Melo, & Tavares, 2017) or other soil types (Abdollahi, Schjonning, Elmholt, & Munkholm, 2014; Lipiec, Czyżb, Dexter, & Siczeka, 2018; Rengasamy, Tavakkoli, & Mcdonald, 2016; Getahun, Munkholm, & Schjonning, 2016). Clay dispersion is directly related to the stability of the microstructure, and the erosive processes (Igwe & Udegbunam, 2008; Igwe & Obalum, 2013). The increase in clay dispersion potentiates the formation of surface crusts, reducing infiltration capacity and hydraulic conductivity of the soil, and can still be easily transported to water bodies (Nguetnkam & Dultz, 2014; Didoné, Minella, & Merten, 2015).

Increased levels of dispersed clay and problems of soil degradation and erosion in no-till areas have recently been reported in the literature (Merten et al., 2015; Didoné et al., 2014, 2015; Telles, Righetto, Costa, Volsi, & Oliveira, 2019). Hence, the hypothesis presented is that a conservationist no-tillage system should associate crop rotation and the absence of soil revolving to reduce the dispersed clay content of the surface layer and, consequently, the potential for degradation of these areas, compared to other systems with soil revolving and low crop diversity.

This study aimed to evaluate, after 24 years, the effect of different soil management and crop systems on the degree of clay dispersion of a Rhodic Ferralsol.

Material and Methods

Experimental area

Before the installation of the experiment, the area was planted with coffee (*Coffea arabica L.*) for approximately 40 years. The experiment was installed in the 1988/1989 crop year, at the experimental station of the Brazilian Agricultural Research Corporation (*Empresa Brasileira de Pesquisa Agropecuária* - EMBRAPA) - National Soybean Research Center (*Centro Nacional de Pesquisa de Soja* - CNPS), located (23°11′ S, 51°11′ W) in the municipality of Londrina (PR). The area has an average altitude of 620 m, the regional climate is mesothermal humid subtropical (Cfa) according to the Köppen-Geiger climate classification, with an average annual rainfall of 1,651 mm. The average precipitation is 217 mm in January, the wettest month, and 60 mm in August, the driest month. The experiment was installed on a Latossolo Vermelho distroférrico (Santos et al., 2013) (Rhodic Ferralsol (IUSS Working Group WRB, 2015)), with 760 g kg^{-1} clay, 170 g kg^{-1} silt, and 70 g kg^{-1} sand.

Experimental design and treatments

To install the experiment, the area was divided into experimental units 7.5 m wide by 30 m long (225 m^2). The experimental design was completely randomized, with four replicates, in a 4x2 factorial design, with four soil managements and two crop systems.

The following soil managements were used: Continuous no-tillage (NT), in which sowing is performed over residues of the previous crop, opening only a furrow in the sowing row; No-tillage with chiseling (NTC), in which the soil is chiseled every 3 years in the winter, using a chisel plow with five shanks 0.35 m apart, working at a depth of 0.25 m, without soil leveling operations; Conventional tillage with disk plowing (DP) with 6-inch disc blades at a mean depth of 0.20 m, followed by light harrowing, working at a depth of 0.08 m; Conventional tillage with heavy disking (HD) with 24-inch blades working at a mean depth of 0.15 m followed by light harrowing at 0.08 m of depth. In DP and HD, tillage is performed every year before the summer crops and before the winter crops with heavy disking, at approximately 0.15 m, followed by light harrowing, at a depth of 0.08 m. In the NTC treatment, chiseling was performed for the last time three years before sampling the soil for the study.

The following crop systems were evaluated: Succession, with common wheat (*Triticum aestivum L.*) in the winter and soybean (*Glycine max L. Merr.*) in the summer; Rotation, in 4-year cycles, with the following species in the winter-summer: white lupin (*Lupinus albus L.*) - corn (*Zea mays L.*); black oat (*Avena strigosa Schreb.*) - soybean; common wheat - soybean; common wheat - soybean.

Experiment

Since the installation of the experiment, every three years, limestone has been applied to reach 60% base saturation and to adjust the pH in water to 5.5, applying limestone for the last time in the 2012/2013 crop year. The fertilizers were applied simultaneously at 0.05 m below and beside the seeds, during sowing.

Throughout the experiment, soybean seeds have been inoculated with *Bradyrhizobium japonicum* and *B. elkanii*, adding, on average, 47 kg ha^{-1} P (triple superphosphate) and 41.2 kg ha^{-1} K^+ (potassium chloride), without mineral nitrogen fertilization. After growing soybean for 10 years, 20 g ha^{-1} Mo (sodium molybdate) and 2 g ha^{-1} Co (cobalt chloride) have been added to the soil annually. In the 1998/1999 and 2000/2001 crop years, the soybean crop was not fertilized. For the corn and common wheat crops, an average of 19.2 and 16.4 kg ha^{-1} N (urea), 51.5 and 57.5 kg ha^{-1} P (triple superphosphate), and 47 and 32.3 kg ha^{-1} K^+ (potassium chloride) were added, respectively, each year. For cover crops, no fertilizer was added.

Since the beginning of the experiment, plots grown with common wheat and winter cover crops (white lupin or black oat) were sown in April. Conversely, summer crops (soybean and corn) were sown in November.

Sowing, crop management, and weed, pest, and disease control were performed according to the technical recommendations for growing soybean, corn, and common wheat and were the same for all treatments. In the NT system, before sowing, the weeds were desiccated using glyphosate. After sowing, other herbicides were applied in the DP treatment as needed.

Sample and laboratory procedures

Disturbed soil samples were collected from the 0.00-0.10 m layer, in the 2012/2013 crop year, after the soybean harvest, 24 years after starting the experiment. Until the collection period, six cycles of 4 years of crop rotation were performed. The samples were air-dried and sieved through a 2-mm mesh (air-dried fine earth - ADFE) for chemical and physical analysis.

The chemical analyses were performed according to the methods described by (Pavan, Bloch, Zemoulski, Miyazawa, & Zocoler, 1992), determining the following parameters: pH($CaCl_2$) 1 mol L^{-1}; pH(H_2O); pH(KCl) 1 mol L^{-1}; exchangeable acidity (Al^{3+}) in KCl (1 mol L^{-1}) assessed by titration with NaOH (0.01 mol L^{-1}); soil potential acidity (H+Al) using the Shoemaker-McLean-Pratt (SMP) buffer test; exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) extracted with 1 mol L^{-1} KCl and titrated with EDTA; available phosphorus (P) and exchangeable potassium (K^+) assessed by Mehlich-1 extraction and reading on a spectrophotometer at 630 nm and a flame photometer, respectively; total organic carbon (TOC) determined by Walkley-Black, with oxidation by $Cr_2H_2O_7$ and titration with $FeSO_4$. The total cation exchange capacity (CEC) and ΔpH (ΔpH= (pH(KCl) (1 mol L^{-1}) - pH(H_2O) were also calculated in this study.

The physical analyses were performed according to the methods described by (Claessen, Barreto, Paula, & Duarte, 1997). The granulometry was determined using 20 g of ADFE and the pipette method with slow stirring, at 180 rpm for 16 hours as mechanical dispersant and with NaOH 1 mol L^{-1} as chemical dispersant. The degree of clay dispersion (DCD) was calculated after determining the disperse clay using the same method, albeit without adding sodium hydroxide, that is, only using mechanical dispersion, based on the following equation: DCD (%) = disperse clay * 100 / total clay.

Statistical procedures

After determining the homogeneity of variance and normality of the residuals using the Bartlett and Shapiro - Wilk tests, respectively, the data were subjected to factorial analysis (four soil managements x two crop systems), and when presenting a significant p-value ($P < 0.05$), the data were subjected to the least significant difference (LSD) test with 5% probability to observe differences between the means of treatments and DCD. Multiple regression analysis was also performed between the chemical attributes (TOC, Ca^{2+}, Mg^{2+}, Al^{3+}, P, K^+, H+Al, CEC, pH($CaCl_2$) and ΔpH) and the DCD, using the Stepwise method to identify those that effectively affected the DD.

All statistical tests were performed using the software R and the packages “mass”, “agricolae”, “ExCNTs.pt” and “rcmdr”.

Results

Factorial analysis between crop systems (crop rotation and succession), soil management (HD, DP, NTC, and NT), and the interaction of both variables (Table 1) shows that DCD was only affected by the different soil management.

Table 1
Factorial analysis of the degree of clay dispersion (DCD), for crop systems and soil management in the 0.00-0.10 m layer

	DF	MS	F	Sig.
Soil management (SM)	3	123.66	11.2	<0.01*
Crop systems (CS)	1	0.36	0.03	0.86
SM * CS	3	24.74	2.24	0.11
Error	24	11.04		

*Significant at 5%.

The mean comparison test between soil management (Table 2) showed that NT had a higher DCD than soil management with soil disturbance (NTC, DP, and HD), with no significant differences between these soil management.

Similarly to DCD, the chemical attributes were influenced only by soil management, without influence from either crop systems or interaction of these factors (Table 3). The soil chemical analyses showed that, after 24 years of management, the values of TOC, CEC macronutrients (Ca^{2+}, Mg^{2+} e K^{+}), and pH($CaCl_2$) were higher in the NT. Furthermore, the system presented the lowest value of H+Al (Table 3). The CEC values decreased with the increase in soil disturbance (Table 3).

Multiple regression analyses between these chemical properties and DCD resulted in the following function: $\hat{y}$ =120.259** - (7.703**H+Al), with R^2 = 0.55 (Eq. 1), where the increase of H+Al decreased the values of DCD.

Table 2
Degree of clay dispersion (DCD, %), in the 0.00-0.10 m layer in rotation and succession crop systems, and soil managements: heavy disking (HD), disk plowing (DP), no-tillage with chiseling (CNT), and continuous no-tillage (NT)

Soil management	Crop systems					
	Rotation	C.V.	Succession	C.V.	Mean	C.V.
DP	80.66	3.20	84.21	3.05	82.43 B	3.80
HD	84.44	3.49	83.88	4.52	84.16 B	4.05
NTC	84.21	2.39	79.81	3.37	82.01 B	3.95
NT	89.38	2.40	91.63	4.08	90.51 A	3.59
Mean	84.67 a	-	84.88 a	-	-	-

Different letters, uppercase in columns and lowercase in rows, indicate significant differences according to the LSD test at a 5% probability level.

Table 3
Soil chemical properties in the rotation and succession crop systems and in the soil managements: heavy disking (HD), disk plowing (DP), no-tillage with chiseling (CNT) and continuous no-tillage (NT). in the 0.00-0.10m layer

Soil management	Crop system	Ca^{2+}	K^{+}	Mg^{2+}	Al^{3+}	H+Al	CEC	TOC	pH $CaCl_2$	ΔpH
		------------------------------cmol$_c$ dm^{-3}------------------------------						g kg^{-1}		
DP	Rotation	4.48	0.65	1.97	0.03	4.87	11.87	12.01	4.85	-0.80
	Succession	3.82	0.66	1.72	0.11	4.98	11.18	12.07	4.68	-1.05
	Mean	4.15 B	0.66 B	1.85 B	0.07 AB	4.92 BC	11.52 B	12.04 B	4.76 B	-0.93 B
HD	Rotation	3.54	0.58	1.67	0.18	5.86	11.65	11.81	4.53	-1.37
	Succession	4.30	0.54	1.30	0.05	5.07	11.20	11.59	4.75	-1.10
	Mean	3.92 B	0.56 B	1.49 B	0.12 A	5.46 AB	11.42 B	11.70 B	4.64 B	-1.24 A
NTC	Rotation	3.96	0.90	1.68	0.11	5.49	12.90	13.90	4.90	-0.95
	Succession	4.26	0.59	2.03	0.08	5.67	12.54	11.31	4.57	-1.00
	Mean	4.11 B	0.75 A	1.85 B	0.10 AB	5.58 A	12.72 AB	12.60 B	4.74 B	-0.98 B
NT	Rotation	4.80	0.97	2.51	0.07	4.55	12.82	17.19	5.17	-0.67
	Succession	5.93	0.91	2.62	0.00	3.90	13.36	16.05	5.35	-0.90
	Mean	5.37 A	0.94 A	2.56 A	0.04 B	4.22 C	13.09 A	16.62 A	5.26 A	-0.79 B

Different uppercase letters in the columns indicate significant differences according to the LSD test at a 5% probability level.

The H+Al is inversely correlated to the attributes related to the balance of charges in the soils (ΔpH and pH) and the Ca^{2+} content, without a significant correlation with the TOC, CEC, $Mg^{2+,}$ and K^{+} (Table 4). In contrast, the TOC is directly correlated to pH($CaCl_2$), Ca^{2+}, Mg^{2+}, $K^{+,}$ and soil CEC (Table 4).

Table 4

Correlation between soil potential acidity (H+Al) and total organic carbon (TOC) with the ΔpH, pH($CaCl_2$), Ca^{2+}, Al^{3+}, Mg^{2+}, K^{+} and CEC in 0.00-0.10 m layer of a Rhodic Ferralsol, under different soil managements and crop systems (n=32)

	TOC	H+Al	ΔpH	pH($CaCl_2$)	Ca^{2+}	Al^{3+}	Mg^{2+}	K^{+}	**CEC**
TOC	1	-0.23	0.32	0.46**	0.52**	-0.26	0.50**	0.65**	0.60**
H+Al	-0.23	1	-0.44*	-0.72**	-0.61**	0.43*	-0.23	-0.27	0.09

**Significant at 5%; and, *Significant at 1%.

Discussion

The hypothesis that soil management under NT with crop rotation would show the lowest values of DCD was not validated. Crop systems did not affect DCD, and the soil management system NT had the highest values of DCD. Because TOC lowers the DCD values (Carvalho, Fontes, & Costa, 1998; Melo, Rengasamy, Figueiredo, Barbosa, & Tavares, 2019), NT with crop rotation, by increasing the TOC values (Table 3), was expected to reduce the DCD. However, DCD was only correlated with H+Al (Eq. 1), showing no correlation with TOC (Table 4).

Maintaining soil cover with crop residues while increasing the TOC content in NT may have had the opposite effect to that expected, indirectly promoting clay dispersion. Liming every three years combined with maintaining soil cover with crop residues, releasing alkaline plant extracts and organic acids with acid-base character, may have enhanced clay dispersion in the topsoil layer. The neutralization of the reactivity of clay minerals (oxides and kaolinite) may have overridden the flocculation effect caused by the increase in ionic strength of the soil solution and by the decrease in the diffuse double layer, promoted by cations such as Al^{3+}, $Ca^{2+,}$ and Mg^{2+}.

Higher H+Al values in soil management with soil disturbance provided lower DCD values, overriding the flocculation effect of the TOC. Liming decreased H+Al, thereby possibly neutralizing the positive charges of the iron and aluminum oxides and kaolinite aluminol groups, increasing the repulsion between these minerals (Castro & Logan, 1991). In addition, the decreased values of exchangeable hydrogen (H^{+}) and Al^{3+} neutralization, cations that stabilize the soil structure, have a dispersing action (Morelli & Ferreira, 1987; Pavan & Roth, 1992). Increasing the net charge of the particle surfaces increases the thickness of the diffuse double layer of the soil, increasing the repulsion force between particles (Albuquerque, Bayer, Ernani, & Fontana, 2000; Albuquerque, Bayer, Ernani, Mafra, & Fontana, 2003; Sposito, 2008).

The lowest H+Al values on the soil surface under NT most likely resulted from the accumulation of limestone and organic matter (OM) on the soil surface. The surface application of limestone without incorporation causes the accumulation of this corrective on the soil surface (Leite, Galvão, Holanda, Araújo, & Iwata, 2010), neutralizing the acidity. Furthermore, because this soil management shows higher TOC values (Table 3), the release of alkaline plant extracts, by decomposition of crop residues, and the amphoteric character of the OM may have helped to increase the pH (Diehl, Miyazawa, & Takahashi, 2008), thus explaining the lowest values of H+Al. The highest TOC values, which were found in NT, are related to the minimum soil disturbance that occurs under this soil management, which increases the accumulation of crop residues on the surface and reduces OM exposure, thereby reducing its decomposition (Bayer, Mielniczuk, Amado, Martin, & Fernandes, 2000).

In the crop rotation system, six cycles were repeated, suggesting that these cycles of crop rotation would suffice to increase the diversity of OM, concerning succession, and that they would promote differences in DCD between crop systems due to the effects of mechanical preparation on the soil structure, which depend on the management of crop residues. In addition, the use of black oat in rotation, whose basic plant extract is alkaline (pH 7.2), and higher K^+ content in solution than in soybean and common wheat extracts used in crop succession (Diehl et al., 2008) could alter interactions between clay particles because of the increases in the K^+ content and pH increase the DCD (Ferreira, Tavares, Ferreira, & Ralisch, 2010; Homem, Almeida, Condé, Silva, & Ferreira, 2014). However, in this study, no significant differences in DCD were found between the different crop systems.

NT brings benefits to the soil, such as improved aggregate stability (Singh et al., 2014; Munkholm et al., 2016), attributed to TOC accumulation, which allows the formation of organic bridges between mineral particles (Lee, Schlautman, Toorman, & Fettweis, 2012), in addition to reducing its wettability (Chenu, Bissonnais, & Arrouays, 2000). Liming increase the soil pH, neutralizes Al^{3+} and adds Ca^{2+} and Mg^{2+} to the soil surface under NT, improving their chemical fertility (Zandoná, Beutler, Burg, Farias Barreto, & Schmidt, 2015). However, these changes in soil chemical properties also intensify the charge imbalance in the clay fraction, which, after the impact of raindrops, favors repulsion between particles, thus hindering reflocculation. These findings highlight the importance of not disturbing and of protecting the soil surface in NT to enhance its conservation.

Conclusion

The degree of clay dispersion is affected by soil management systems with no effect on crop systems. The soil management system with the lowest soil disturbance (continuous no-till) has a higher degree of clay dispersion than the management systems that disturb the soil, regardless of the agricultural implement used or soil disturbance intensity.

The degree of clay dispersion is affected by the soil electrochemical imbalance, primarily caused by the potential soil acidity (H+Al).

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