

# Effects of surface-applied and soil-incorporated lime on some physical attributes of a Dystrudept soil

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## Abstract

It is generally accepted that liming ameliorates soil acidity. However, the method of lime application is thought by many to influence its effectiveness in acid soils. In this study, we wanted to assess the degree of effectiveness of surface-applied lime and lime incorporated into the soil on soil structural attributes and water retention of a Dystrudept soil in the SE region of the State of Paraná, Brazil. Lime was added at the rate of 15 t/ha to soil through: (i) surface broadcasting, (ii) incorporation via ploughing and harrowing, (iii) incorporation via subsoiling and harrowing. A control treatment with zero lime application was included in the experiment. The addition of lime by surface broadcasting resulted in significant reductions in soil bulk density (BD) and macroporosity (Ma) and increases in total porosity (TP) and microporosity (Mi) of the top soil layer (0–0.10 m). The reverse was the case in the 0.10- to 0.20-m soil layer; where lime was incorporated via ploughing and harrowing, increases in BD and reductions in TP and Ma were observed. Addition of lime also significantly increased soil water retention, with maximum retention recorded from soil amended with surface broadcast lime. Changes in soil chemical attributes (increases in pH, Ca<sup>2+</sup> and Mg<sup>2+</sup> contents; reductions in potential acidity and Al<sup>3+</sup> content) were responsible for the changes observed in structural and physical attributes, and water retention. Bearing in mind the lower application costs, improvement in the soil chemical attributes for plant development and soil physical quality, surface broadcast lime can be considered a promising alternative for no-till farmers.

**Keywords:** Soil acidity, soil structure, water retention, cation exchangeable capacity

## Introduction

Tropical and subtropical soils can have high acidity due to their weathering processes; this reduces root growth, water and nutrient uptake, and crop yield (von Uexküll & Mutert, 1995). Degradation caused by soil acidity is commonly ameliorated through lime application, although soil acidity correction dynamics depend, to a large extent, on the mode of lime application (Caires *et al.*, 2008a,b, 2011).

With the emergence of no-tillage systems, lime application on the soil surface became widespread. However, as lime has low water solubility and the products of its reaction with the soil have limited mobility, the action of surface liming is

slow in reducing subsurface acidity in soils with variable charge predominance (Caires *et al.*, 1998, 2011).

In contrast under conventional tillage, the tilled layer acidity is neutralized through the mechanical incorporation of lime, and the reaction is favoured by mixing the corrective material with the soil. Disc ploughing to mix lime with the soil and then harrowing to level the soil are two common incorporation methods (Caires *et al.*, 2006). Many farmers, however, prefer methods that will not have a high energy demand or increase the time required to incorporate lime, such as scarification or subsoiling before harrowing.

Although incorporation favours the lime reaction, tillage alters soil structure, affecting thermodynamic processes that might occur (Auler *et al.*, 2014; Dal Ferro *et al.*, 2014). However, research on the influence of liming on soil physical attributes is scarce, contrasting and commonly limited to aggregation mechanisms. Some studies report on the

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negative effects of soil acidity correction, such as the increase in clay dispersion with reductions in flocculation and aggregate stability (Roth & Pavan, 1991; Haynes & Naidu, 1998; Six *et al.*, 2004). Others, however, highlight its positive effects, such as increases in water retention and aggregate stability (Castro Filho & Logan, 1991; Chan & Heenan, 1998; Six *et al.*, 2004). The differences in the literature depend on the corrective material, dose applied, reaction time, evaluated soil layer and intrinsic characteristics of each soil. Such variations hinder further understanding of the actual effects of liming on soil physical attributes (Paradelo *et al.*, 2015). Another aspect to be taken into consideration is that most previous studies have been carried out with Oxisols. Although Oxisols are predominant in Brazil, agrarian families in many regions base their agricultural systems on Inceptisols (Assis & Romeiro, 2005).

There is considerable concern about lime-induced soil acidity amelioration as it is not well understood which changes in soil physical properties may be influenced. Against the background of contradictory information in the literature and the socio-economic importance of Inceptisols, this study aimed to evaluate the effects of surface-applied and incorporated lime on soil physical structural attributes and water retention of a Dystrudept soil.

## Materials and methods

### Study location

The experiment was conducted on a family farming property in the city of Irati (25°28'S, 50°54'W, 821 m a.s.l), SE Paraná State, Brazil. Based on Köppen classification, the region has a humid subtropical climate (Cfb) (Iapar, 2009) with mean annual rainfall of 1600 mm. August and January are the driest and wettest months, respectively.

The area was converted (in the 1960s) from its natural vegetation (mixed ombrophilous forest) into a pasture

agroecosystem without any soil fertilizers or correction. The forage crop cultivated was giant missionary grass (*Axanopus catharinensis*) managed in continuous grazing systems at low stocking rate. The soil was classified as a Dystrudept (Soil Survey Staff, 2013), which had satisfactory soil physical quality. The pasture field was, however, severely degraded owing to the high soil acidity levels and low nutrient content (Table 1).

### Experiment design

The experiment (established in May 2012) was laid out in a completely randomized design with a factorial arrangement (3 × 2). The plot size was 150 m<sup>2</sup> (30 × 5 m – length and width), and each treatment was replicated four times (Table 2). Lime application treatments were as follows: surface broadcast, incorporated via ploughing and harrowing, and incorporated via subsoiling and harrowing, combined with treatments without (control) and with lime (15 t/ha) (Table 2). The lime rate was calculated to raise the base saturation in the topsoil (0–0.20 m) to 70%. The lime used had 285 and 200 g/kg of CaO and MgO, and 100.6, 74.7 and 75.1% neutralizing power, reactivity and total neutralizing relative power, respectively.

Ploughing was with a 28" disc reverse plough while subsoiling was with five parabolic stems spaced at 0.40 m. Both operations were performed to a depth of 0.25 m. Harrowing was with a levelling harrow using 32 discs of 20", spaced at 0.175 and 0.10 m depth.

After lime application, black oat (*Avena strigosa* S.) and hairy vetch (*Vicia villosa* R.) were intercropped on the field at a seed rate of 50 kg/ha each. The seeds were surface-sown during the autumn–winter 2012 season. In August 2012, crop desiccation was carried out using glyphosate. Thereafter, corn (*Zea mays* L.) was sown with a 0.90-m row spacing and at the rate of seven seeds per metre. There was no soil preparation at this stage, and a five-line sowing-fertilizing machine equipped with plane discs was used to open furrows,

**Table 1** Soil chemical and physical attributes in the 0–0.10 and 0.10–0.20 m layers ( $n = 4$ ) of the Dystrudept soil before the experiment

Layer m	pH	OC g/kg	H+Al	Al <sup>3+</sup>	Ca <sup>2+</sup> cmol <sub>c</sub> /dm <sup>3</sup>	Mg <sup>2+</sup>	K <sup>+</sup>	CEC	V %	m
0–0.10	3.7	27.46	16.33	6.8	1.0	1.3	0.61	19.24	15	70
0.10–0.20	3.6	19.46	19.63	9.00	0.40	0.50	0.41	20.94	6	87
	Sand	Silt g/kg	Clay	WDC	PD Mg/m <sup>3</sup>	BD	TP	Ma m <sup>3</sup> /m <sup>3</sup>	Mi	AC
0–0.10	46	474	480	238	2.50	1.19	0.51	0.05	0.46	0.07
0.10–0.20	54	469	477	248	2.53	1.21	0.51	0.06	0.45	0.08

pH, in Ca Cl<sub>2</sub>; OC, organic carbon content (Walkley-Black method); H+Al, potential acidity; Al<sup>3+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup> and K<sup>+</sup>, exchangeable aluminium, calcium, magnesium and potassium; CEC, cation exchange capacity; V and m, base and aluminium saturation; WDC, water-dispersed clay; PD and BD, particle and bulk density; TP, total porosity; Ma and Mi, macro- and microporosity (determined at –6 kPa); AC, aeration capacity (considering water content at –10 kPa).

**Table 2** Abbreviations and descriptions of the treatments

Abbreviation	Description <sup>a</sup>
Control	Without lime and without tillage
LS	Lime on the surface (in a single dosage)
PH	Ploughing and harrowing without lime
LPH	Lime incorporated via ploughing and harrowing
SH	Subsoiling and harrowing without lime
LSH	Lime incorporated via subsoiling and harrowing

<sup>a</sup>In the treatments that involved tillage with lime incorporation, 50% of the dosage was applied before ploughing or subsoiling, and 50% after this operation, but before levelling/harrowing, according to Caires *et al.* (2006).

and a double disc to deposit fertilizer and seed. All phytosanitary treatment and phytomass management were carried out with a backpack sprayer, to avoid machinery traffic on the area. In year 2013–2014, the same crop succession was employed with a few adaptations (e.g. phytosanitary treatments, nutrients sources) according to the crop needs.

#### Sampling, evaluations and analyses

Eighteen months after liming and around 30 days post-corn sowing, four soil samples were collected (considered as replications) per plot in the inter-rows of the crop, from the two soil layers (0–0.10 and 0.10–0.20 m). Undisturbed soil samples were collected into stainless steel volumetric rings of 0.05 cm external diameter × 0.05 - 0.03 m height using an Uhland sampler to optimize the time to obtain water retention curves (SWRC). Disturbed soil samples were collected using a shovel.

The undisturbed soil samples were saturated by the capillary rise method and submitted for matric potential assessment ( $\Psi_m$ ) at 0, -1, -2, -4, -6, -8 and -10 kPa (0.05 × 0.05 m) in a tension table (model M1-0801; Eijkelkamp<sup>®</sup>) and -33; -100 and -500 kPa (0.05 × 0.03 m) in a Richards chambers (model 1500, Soil Moisture Equip. Corp.<sup>®</sup>). Disturbed samples were used to determine soil volumetric water content ( $\theta$ ) for -1500 kPa  $\Psi_m$  (Dane *et al.*, 2002).

After equilibration, the undisturbed soil samples had their mass assessed and some physical structural attributes were determined (Table 3). The disturbed soil samples were dried in a forced air circulation oven (40 °C/24 h) and sieved in a 2-mm mesh sieve for determination of soil chemical properties using the methods shown in Table 3.

#### Mathematical models

The SWRCs were adjusted using the van Genuchten (1980) mathematical model, with the Mualem (1976) restriction. The data set of  $\theta$  and  $\Psi_m$  for all replications was used for the adjustments. All parameters of the SWRCs were determined using SWRC Fit software (Seki, 2007).

**Table 3** Description of the chemical<sup>a</sup> and structural physical<sup>b</sup> attributes in the undisturbed and disturbed soil samples

Measuring parameter	Method description
Undisturbed samples	
Bulk density (BD, kg/dm <sup>3</sup> )	Dried in a forced air circulation oven (105 °C/48 h)
Total porosity (TP, m <sup>3</sup> /m <sup>3</sup> )	Relation ship between BD and particle density
Microporosity (Mi, m <sup>3</sup> /m <sup>3</sup> )	At -6 kPa tension
Macroporosity (Ma, m <sup>3</sup> /m <sup>3</sup> )	Difference between TP and Mi
Disturbed samples	
Particle density	Helium gas pycnometer (model ACCUPYC 1330, Micromeritics Instrument Corp. <sup>®</sup> )
Sand, silt and clay (g/kg)	Densimeter method, with previous sample treatment (H <sub>2</sub> O <sub>2</sub> 30 v/v) and with the use of NaOH (1.0 mol/L)
Water-disperse clay (WDC, g/kg)	Densimeter, without previous sample treatment and chemical dispersion
Organic carbon (OC, g/kg)	Walkley-Black method
Active acidity (pH)	Potentiometry in CaCl <sub>2</sub> 0.01 mol/L
Potential acidity (H+Al, cmol <sub>c</sub> /dm <sup>3</sup> )	Potentiometry in SMP buffer
Exchangeable cations (Al <sup>3+</sup> , Ca <sup>2+</sup> and Mg <sup>2+</sup> , cmol <sub>c</sub> /dm <sup>3</sup> )	Extracted with KCl 1.0 mol/L, and NaOH 0.025 mol/L titration for Al <sup>3+</sup> , and EDTA 0.025 mol/L titration for Ca <sup>2+</sup> and Mg <sup>2+</sup>

<sup>a</sup>According to van Raij *et al.* (2001). <sup>b</sup>According to Dane *et al.* (2002).

From the adjusted data, the relative difference values (RD, %) were obtained between  $\theta$  for the different  $\Psi_m$  using Equation (1), to simplify the SWRCs analysis.

$$RD = \frac{\theta_{LS} - \theta_{LPH}}{\theta_{LS}} 100, \quad (1)$$

where  $\theta_{LS}$  and  $\theta_{LPH}$  are the soil volumetric water content in the treatments lime on the surface and lime incorporated via ploughing and harrowing, respectively.

#### Statistical analysis

The variance analysis statistical model was applied. Assumptions of residual normality and homoscedasticity were verified by the Shapiro–Wilk and Bartlett tests, and the *F*-test was employed. Decomposition analyses were carried out, and, whenever necessary, the Tukey test was applied for multiple comparisons to identify significant interactions. For the significant interactions, simple linear correlation analyses were carried out between the  $\theta$  values for -10, -33, -100,

–500 and –1500 kPa, and the soil physical and chemical attributes. Statistical analyses were performed using the R software, version 3.3.1 (R Core Team, 2016).

## Results

### Soil chemical attributes

Liming, lime application method and their interaction all influenced soil pH, exchangeable calcium ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), potential acidity (H+Al) and exchangeable aluminium ( $\text{Al}^{3+}$ ) contents, in both soil layers (Table 4). Liming increased soil pH,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  and reduced H+Al and  $\text{Al}^{3+}$  for all modes of application in the 0- to 0.10-m soil layer. In the 0.10- to 0.20-m soil layer, these effects only occurred when lime was incorporated, and the two incorporation treatments did not differ from each other (Table 4).

### Soil structural attributes

Liming, lime application method and their interaction also influenced soil bulk density (BD), total porosity (TP),

macroporosity (Ma) and microporosity (Mi) in both soil layers, except for Mi in the 0.10- to 0.20-m layer (Figures 1 and 2). In the 0- to 0.10-m layer, both without and with liming, tillage reduced BD and increased TP (Figure 1a and b). Surface application of lime only influenced soil structural attributes in the 0- to 0.10-m soil layer, reducing BD and Ma and increasing TP (especially Mi) (Figure 1).

In the 0.10- to 0.20-m soil layer, the control and SH treatments had higher BD and lower TP and Ma relative to the PH treatment. The BD value for SH was the same as the control and PH treatments (Figure 2). Surface application of lime had higher BD and lower TP than the LSH treatment, while LPH had a similar BD value to those of the other application methods in this layer (Figures 2a, b). Liming increased BD and reduced TP in the LPH treatment and increased Ma in the LSH treatment in this layer (Figure 2).

Changes in BD and TP with liming and the different application methods did not influence Ma, in any of the soil layers (Figures 1 and 2). In the 0- to 0.10-m layer, the control treatment had higher Ma than the incorporation treatments, and the two incorporation treatments did not differ from each other. With liming,

**Table 4** Soil physical and chemical attributes in the 0.0–0.10 and 0.10–0.20 m layers of a Dystrudept soil due to liming and application method

Soil attributes	Treatments					
	Control	LS	PH	LPH	SH	LSH
0–0.10 m layer						
Sand (g/kg)	46 Aa	48 Aa	51 Aa	57 Aa	30 Aa	32 Aa
Silt (g/kg)	460 Aa	461 Aa	494 Aa	464 Aa	443 Aa	449 Aa
Clay (g/kg)	494 Aa	491 Aa	455 Ab	479 Aa	527 Aa	519 Aa
WDC (g/kg)	204 Bc	244 Ab	249 Ab	257 Aab	292 Aa	282 Aa
OC (g/kg)	29.53 Aab	30.98 Aa	26.73 Ab	31.08 Aa	30.25 Aa	30.67 Aa
pH (CaCl <sub>2</sub> 1:2.5)	3.7 Ba	4.8 Aa	4.1 Ba	5.2 Aa	3.7 Ba	5.2 Aa
H+Al (cmol <sub>c</sub> /dm <sup>3</sup> )	17.28 Aa	7.03 Ba	15.79 Aa	6.65 Ba	17.15 Aa	6.59 Ba
Al <sup>3+</sup> (cmol <sub>c</sub> /dm <sup>3</sup> )	4.60 Aa	0.15 Ba	3.68 Ab	0.05 Ba	3.83 Aab	0.13 Ba
Ca <sup>2+</sup> (cmol <sub>c</sub> /dm <sup>3</sup> )	1.48 Ba	7.43 Aa	2.10 Ba	7.40 Aa	1.63 Ba	7.50 Aa
Mg <sup>2+</sup> (cmol <sub>c</sub> /dm <sup>3</sup> )	1.25 Ba	3.83 Ac	1.38 Ba	5.15 Ab	1.25 Ba	6.18 Aa
0.10–0.20 m layer						
Sand (g/kg)	54 Aa	37 Bab	43 Aa	43 Aa	21 Ab	24 Ab
Silt (g/kg)	449 Aa	418 Aa	496 Aa	483 Aa	504 Aa	464 Aa
Clay (g/kg)	497 Aa	545 Aa	461 Aa	474 Aa	475 Aa	512 Aa
WDC (g/kg)	274 Ab	294 Aa	259 Bb	310 Aa	328 Aa	332 Aa
OC (g/kg)	20.29 Ab	19.26 Aa	25.17 Aa	19.67 Ba	21.75 Aab	21.43 Aa
pH (CaCl <sub>2</sub> 1:2.5)	3.7 Aa	3.7 Ab	4.0 Ba	4.5 Aa	3.6 Ba	4.2 Aab
H+Al (cmol <sub>c</sub> /dm <sup>3</sup> )	18.99 Aa	17.94 Aa	17.72 Aa	11.03 Bb	19.87 Aa	10.24 Bb
Al <sup>3+</sup> (cmol <sub>c</sub> /dm <sup>3</sup> )	6.53 Aa	5.48 Aa	4.83 Aa	2.30 Bb	6.30 Aa	2.65 Bab
Ca <sup>2+</sup> (cmol <sub>c</sub> /dm <sup>3</sup> )	0.58 Aa	1.13 Ab	1.38 Ba	4.35 Aa	0.88 Ba	4.10 Aa
Mg <sup>2+</sup> (cmol <sub>c</sub> /dm <sup>3</sup> )	0.55 Aa	1.20 Ab	1.35 Ba	3.65 Aa	0.73 Ba	3.38 Aa

Control = treatment without liming; LS, liming on the soil surface; PH, ploughing and harrowing without lime; LPH, lime incorporated via ploughing and harrowing; SH, subsoiling and harrowing without lime; LSH, lime incorporated via subsoiling and harrowing; WDC, water-dispersed clay; OC, organic carbon content (Walkley-Black method); pH, in Ca Cl<sub>2</sub>; H+Al, potential acidity; Al<sup>3+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>, exchangeable aluminium, calcium and magnesium. Averages ( $n = 4$ ) followed by the same capital letter for liming and small letter for the modes of lime application did not differ from each other by the Tukey test ( $P \leq 0.05$ ).

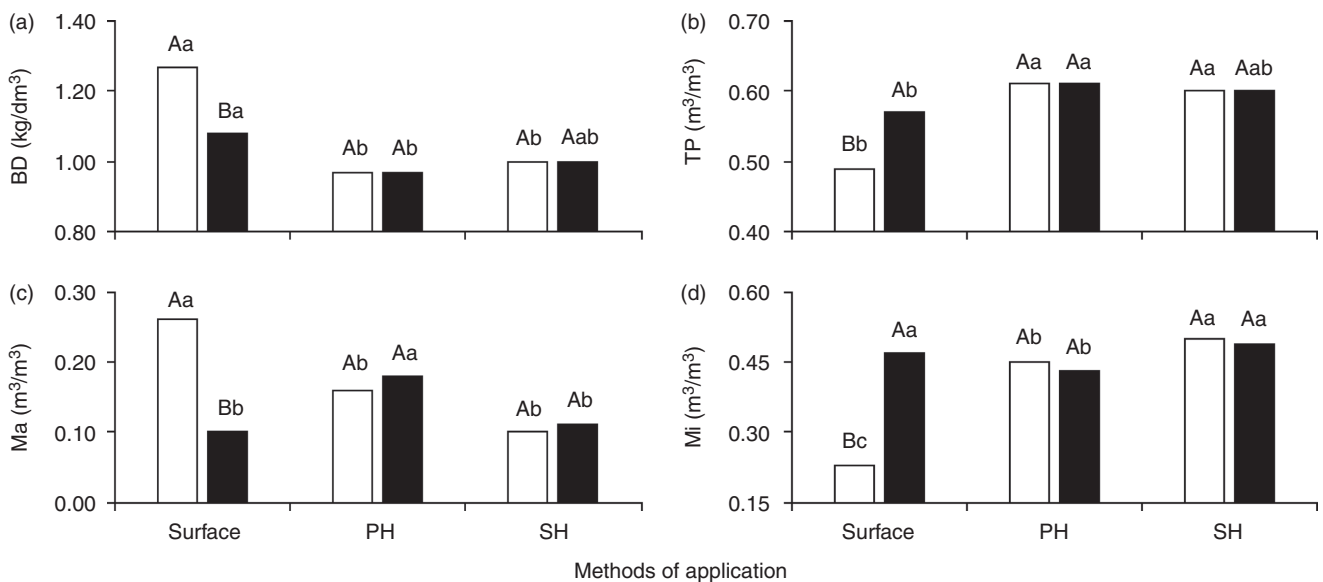
the LPH treatment had higher Ma in this layer than LS and LSH treatments, which did not differ from each other (Figure 1c).

In the unlimed treatments, Mi differed in all soil tillage methods in the 0- to 0.10-m layer, following the order: SH > PH > control (Figure 1d); Mi had contrary behaviour to Ma in all the liming treatments within this layer (Figure 1c). In the 0.10- 0.20-m layer, however, isolated effects occurred in values of Mi which were affected by application method and liming. In this case, liming reduced Mi and the treatments with ploughing and harrowing had lower Mi than the treatments without soil disturbance or

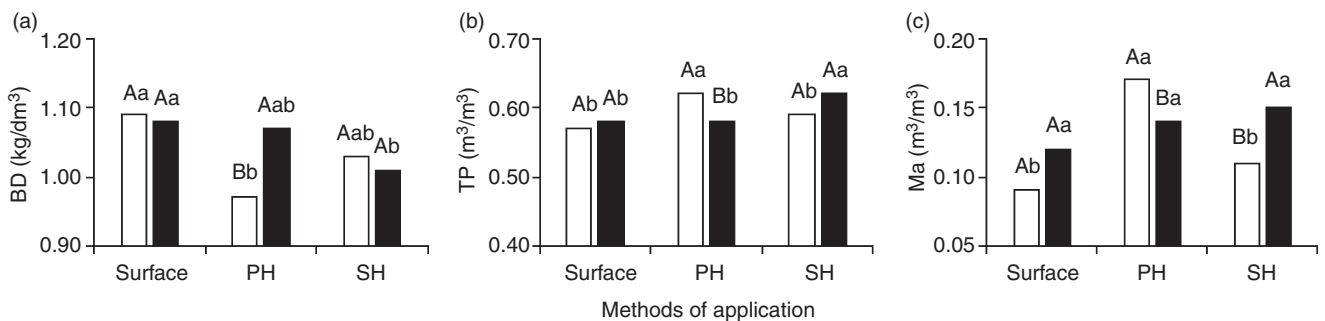
with subsoiling and harrowing, which did not differ from each other (Figure 3).

The linear correlation analysis for LS and control treatments in the 0- to 0.10-m layer (significant interaction) revealed that the increase in soil pH, water-dispersible clay (WDC),  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  promoted lower BD and Ma values and increased the values of TP and Mi. The H+Al and  $\text{Al}^{3+}$  were positively correlated with BD and Ma and negatively correlated with TP and Mi (Table 5).

In the 0.10- to 0.20-m layer, in the LPH and PH treatments WDC was positively correlated with BD negatively correlated with TP. The increase in Ma with liming on the LSH



**Figure 1** Bulk density (BD) (a), total porosity (TP) (b), macroporosity (Ma) (c) and microporosity (Mi) (d) in the 0- to 0.10-m layer of a Dystrudept soil due to liming [without (□) or with lime (■)] and methods of lime application [on the surface, via ploughing and harrowing (PH) and via subsoiling and harrowing (SH)]. Averages ( $n = 4$ ) followed by the same capital letter for liming and small letter for methods of lime application did not differ from each other by the Tukey test ( $P \leq 0.05$ ).



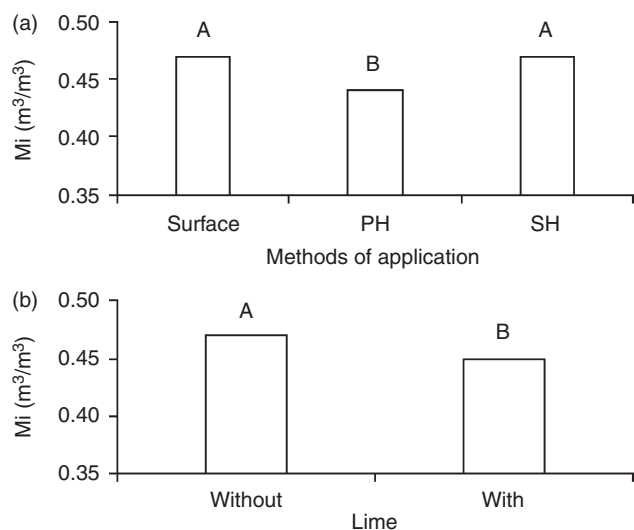
**Figure 2** Bulk density (BD) (a), total porosity (TP) (b) and macroporosity (Ma) (c) in the 0.10- to 0.20-m layer of a Dystrudept soil due to liming [without (□) or with lime (■)] and methods of lime application [on the surface, via ploughing and harrowing (PH) and via subsoiling and harrowing (SH)]. Averages ( $n = 4$ ) followed by the same capital letter for liming and small letter for methods of lime application did not differ from each other by the Tukey test ( $P \leq 0.05$ ).



treatment compared with the SH treatment was positively correlated with sand content (Table 5).

#### Soil water retention in the 0- to 0.10-m layer

In the 0- to 0.10-m layer with and without liming, the treatments with ploughing and harrowing and subsoiling and harrowing had a higher  $\theta$  compared with the treatments without soil disturbance, mainly between  $-10$  and  $-100$  kPa (Figure 4a, b). For the PH and SH treatments, the RD values were  $< 10\%$  along the SWRCs. However, these



**Figure 3** Microporosity (Mi) in the 0.10- to 0.20-m layer of a Dystrudept soil due to the methods of application (a) [on the surface, ploughing and harrowing (PH) and subsoiling and harrowing (SH)] and liming (b). Averages ( $n = 4$ ) followed by the same letter did not differ from each other by Tukey test ( $P \leq 0.05$ ).

treatments had higher RD (70–130%) compared with the control treatment in the 0- to 0.10-m layer (Figure 5a).

Water retention on the liming treatments (LS and LSH) was similar. The LPH treatment had lower water retention in relation to the other application methods (Figure 6a), possibly due to Mi reduction in the LPH treatment compared with LS and LSH (Figure 1d).

Surface application increased water retention at high and low potentials. Liming had an effect on water retention ( $\text{RD} < 20\%$ ), particularly when lime was incorporated (Figure 7a). When lime was applied on the surface,  $\theta$  at different potentials had strong positive correlations with the WDC, TP, Mi, soil pH,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , and strong negative correlations with BD, Ma, H+Al and  $\text{Al}^{3+}$  (Table 6). In this case, the effects for WDC and the chemical attributes on  $\theta$  were dependent upon the water matric potential in the soil and can be explained by different processes.

For lime incorporation, few significant correlations were observed between the soil physical and chemical attributes and  $\theta$  in saturation and at  $-10$ ,  $-33$ ,  $-100$  and  $-500$  kPa. However, at  $-1500$  kPa the correlations were strong and restricted to the soil chemical attributes (Table 6).

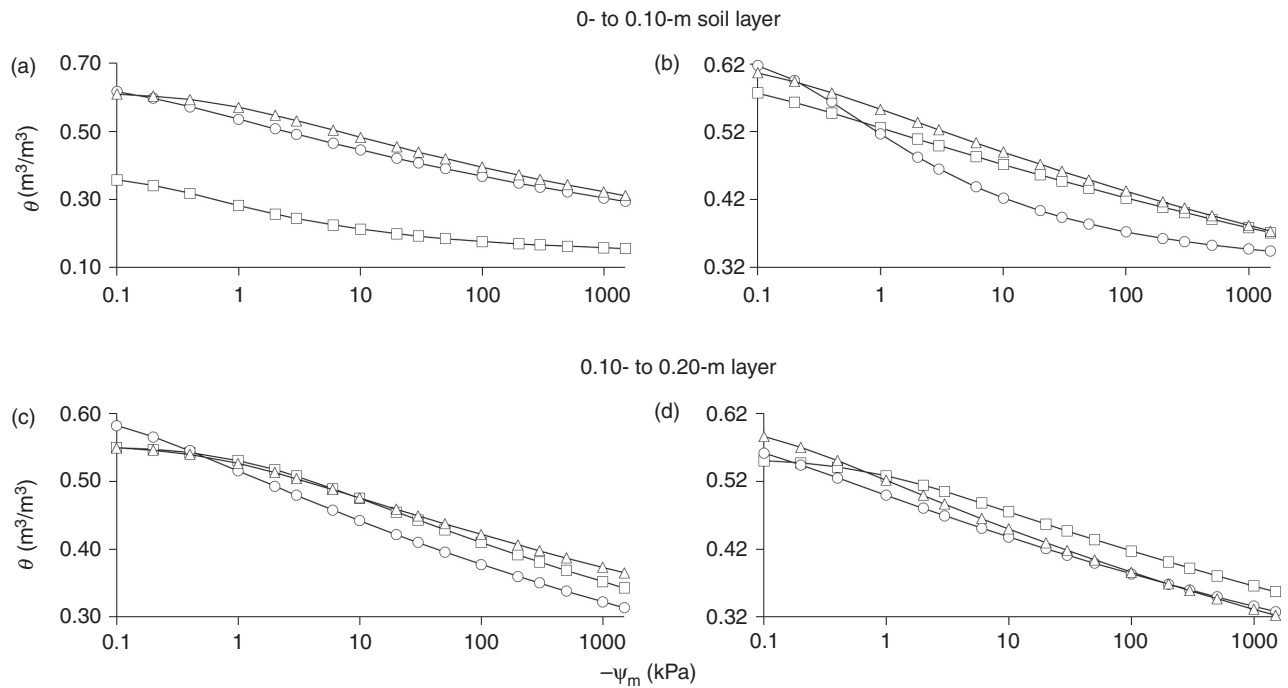
#### Soil water retention in the 0.10- to 0.20-m layer

In the 0.10- to 0.20-m layer, the SWRCs and its RD were lower than those observed in the 0- to 0.10-m layer (Figures 4c, d, 5b, 6b and 7b). In the 0.10- to 0.20-m layer, the PH treatment had a distinct behaviour with respect to soil water retention relative to control and SH treatments (Figure 5b). The PH treatment increased water retention between saturation up to  $-10$  kPa in relation to the control treatment, but from this potential on, the SWRC of these treatments was not significantly different ( $\text{RD} < 2\%$ ). However, the PH treatment had higher water retention closer

**Table 5** Pearson correlation coefficients ( $n = 8$ ) between physical structural properties and granulometry, and chemical properties in the 0–0.10 or 0.10–0.20 m layers of a Dystrudept soil due to liming and application method

Soil attributes	Sand	Silt	Clay	WDC	OC	pH	H+Al	$\text{Al}^{3+}$	$\text{Ca}^{2+}$	$\text{Mg}^{2+}$
Lime on the surface – 0- to 0.10-m layer										
BD	-0.07	-0.02	0.05	-0.84*	-0.40	-0.96*	0.96*	0.96*	-0.95*	-0.89*
TP	0.06	0.02	-0.04	0.85*	0.42	0.96*	-0.96*	-0.96*	0.95*	0.89*
Ma	-0.24	0.16	-0.08	-0.76*	-0.31	-0.93*	0.95*	0.94*	-0.94*	-0.91*
Mi	0.21	-0.13	0.05	0.81*	0.36	0.97*	-0.99*	-0.98*	0.98*	0.93*
Lime incorporated with ploughing and harrowing – 0.10- to 0.20-m layer										
BD	0.12	0.13	-0.14	0.70*	-0.44	0.18	-0.33	-0.21	0.34	0.41
TP	-0.12	-0.10	0.12	-0.73*	0.48	-0.26	0.40	0.29	-0.41	-0.48
Lime incorporated with subsoiling and harrowing – 0.10- to 0.20-m layer										
Ma	0.78*	-0.44	0.42	0.25	-0.49	0.58	-0.48	-0.60	0.58	0.68

\*Significant to the  $F$ -test ( $P \leq 0.05$ ). WDC, water-dispersed clay; OC, organic carbon content (Walkley-Black method); pH, in  $\text{CaCl}_2$ ; H+Al, potential acidity;  $\text{Al}^{3+}$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , exchangeable aluminium, calcium and magnesium; BD, particle and bulk density; TP, total porosity; Ma and Mi, macro- and microporosity.



**Figure 4** Soil water retention curves (SWRCs) without (a and c) and with liming (b and d) in the 0- to 0.10-m and 0.10- to 0.20-m layers of a Dystrudept soil comparing methods of lime application [on the surface ( $\square$ ), via ploughing and harrowing ( $\circ$ ) and via subsoiling and harrowing ( $\Delta$ )].

to saturation and lower retention from  $-1$  kPa than the SH treatment. In this layer, the SH treatment also showed an increase in water retention at low potentials ( $< -10$  kPa) compared with the control treatment (Figure 5b).

The SWRCs on the LPH and LSH treatments were similar ( $RD < 5\%$ ). However, the LS treatment showed different behaviour compared with the other application methods, with a reduction in water retention in relation to the LPH treatment and an increase in relation to the LSH treatment (Figures 4d and 6b).

Liming had little influence on SWRCs with respect to surface application and lime incorporated via ploughing and harrowing ( $RD < 5\%$ ), while in treatments with subsoiling and harrowing, liming reduced water retention (Figure 7b). The correlation analyses in the 0.10- to 0.20-m layer were similar to in the 0- to 0.10-m layer. For lime applied on the surface at lower potentials,  $\theta$  values were positively correlated with soil pH,  $Ca^{2+}$  and  $Mg^{2+}$  and negatively correlated with H+Al and  $Al^{3+}$  (Table 6).

## Discussion

### *Effects of tillage and chemical attributes on the soil structure*

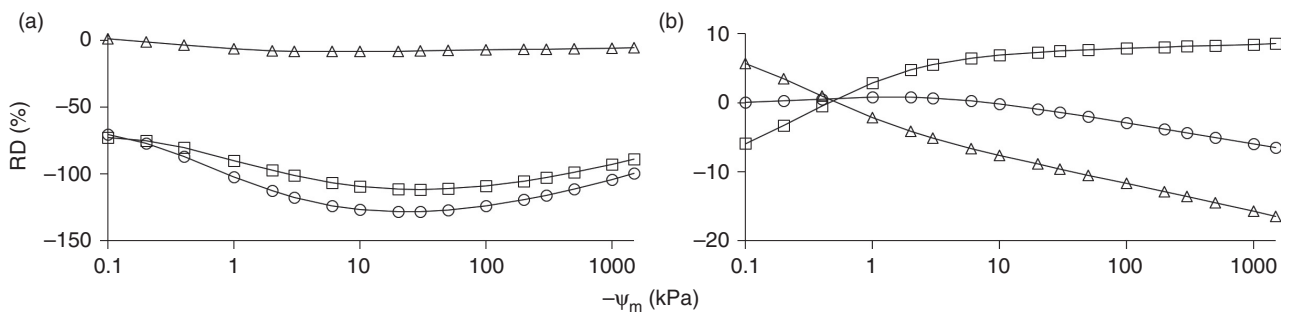
Similarities in BD and TP for the PH, LPH, SH and LSH treatments in the 0- to 0.10-m soil layer can be ascribed to the

secondary operation to incorporate the lime (harrowing, levelling) carried out for both modes of application. This secondary operation tends to make the soil upper layers more uniform, as the primary operations of ploughing and subsoiling have shown differences in soil mobilization intensity (Auler *et al.*, 2014; Moraes *et al.*, 2016).

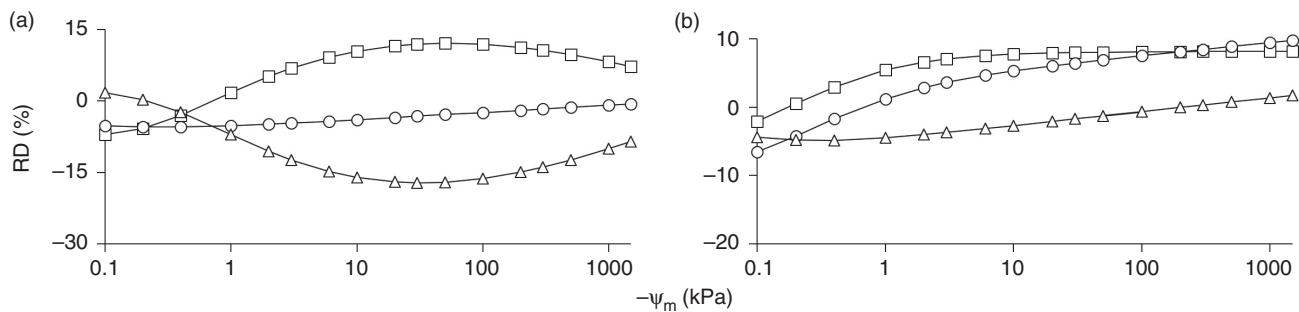
The surface liming influence on BD, TP and Ma might be related to biopore formation in the soil through (i) the slow and gradual decomposition of the fasciculate roots and stolons of the forage which covered the area prior to the experiment installation (Six *et al.*, 2004); (ii) crop root growth increases (Caires *et al.*, 2008a); and (iii) higher density and activity of the soil macrofauna (Giracca *et al.*, 2008; Han *et al.*, 2015).

Due to the formation of biopores, in this study the increase in BD on the control treatment in the 0- to 0.10-m soil layer and for all application methods in the 0.10- to 0.20-m soil layer did not reduce Ma, as it is usually observed (Alaoui *et al.*, 2011; Auler *et al.*, 2014; Moraes *et al.*, 2016).

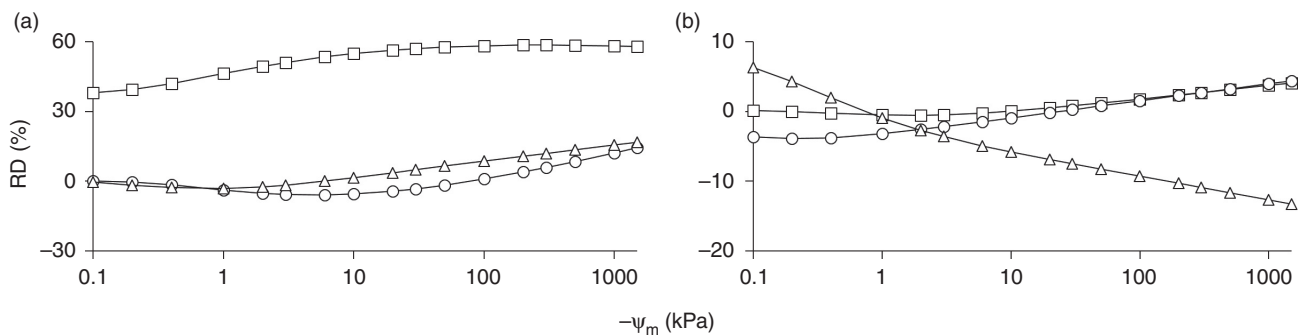
However, the correlation of Mi with WDC (Table 6) in the 0- to 0.10-m soil layer, by the surface liming, suggests that there could be obstruction of macropores by the dispersed particles (Baldock *et al.*, 1994). Considering that clay dispersion is dependent on the soil pH increase and lower valence ion exchange, the Ma and Mi on the LS treatment might also be related to the WDC and soil



**Figure 5** Soil water retention curve (SWRC) relative differences in the 0- to 0.10-m (a) and 0.10- to 0.20-m (b) layers of a Dystrudept soil of the treatments without liming: Control compared with PH (□), Control compared with SH (○) and PH compared with SH (Δ).



**Figure 6** Soil water retention curve (SWRC) relative differences in the 0- to 0.10-m (a) and 0.10- to 0.20-m (b) layers of a Dystrudept soil of the treatments with liming: LS compared with LPH (□); LS compared with LSH (○), and LPH compared with LSH (Δ).



**Figure 7** Soil water retention curve (SWRC) relative differences in the 0- to 0.10-m (a) and 0.10- to 0.20-m (b) layers of a Dystrudept soil of the liming in each mode of application: on the surface (□), via ploughing and harrowing (○) and via subsoiling and harrowing (Δ), taking liming as a reference.

chemical alterations (Baldock *et al.*, 1994; Haynes & Naidu, 1998; Six *et al.*, 2004).

The absence of a liming effect on Ma in the LPH treatment in the 0- to 0.10-m soil layer (Figure 1c) might be explained by soil tillage, which provided higher Ma compared with the LS treatment (Auler *et al.*, 2014; Moraes *et al.*, 2016). Although the LSH treatment also had soil disturbance similar to the LPH treatment, Ma in the LSH

treatment was lower than the LPH treatment (Figure 1c). The Ma reduction in the LSH treatment might be ascribed to the higher WDC (Table 4), as the dispersed particles might cause obstruction of macropores (Baldock *et al.*, 1994).

The results for Mi on the LPH and LSH treatments in the 0- to 0.10-m soil layer were the opposite of the observed Ma increase in relation to the TP (Figures 1b–d), with the higher



**Table 6** Pearson correlation coefficients ( $n = 8$ ) of the water content ( $\theta$ ) at different matric potentials ( $\Psi_m$ ) with physical and chemical properties, in the 0–0.10 and 0.10–0.20 m layers of a Dystrudept soil due liming and application method

Soil attributes	$\theta_s$	$\theta_{-10}$	$\theta_{-33}$	$\theta_{-100}$	$\theta_{-500}$	$\theta_{-1500}$	$\theta_s$	$\theta_{-10}$	$\theta_{-33}$	$\theta_{-100}$	$\theta_{-500}$	$\theta_{-1500}$
	0– to 0.10–m layer						0.10– to 0.20–m layer					
Lime on the surface												
Sand	0.19	0.23	0.09	–0.01	–0.10	0.12	0.01	0.20	0.58	–0.41	–0.68	–0.18
Silt	–0.15	–0.11	–0.01	0.01	0.10	–0.03	0.12	0.57	0.15	–0.31	–0.19	–0.30
Clay	0.09	0.03	–0.02	–0.01	–0.07	–0.01	–0.12	–0.59	–0.33	0.43	0.41	0.35
WDC	0.85*	0.80*	0.85*	0.80*	0.72*	0.83*	0.68	–0.38	–0.27	0.58	0.46	0.57
BD	–0.94*	–0.92*	–0.92*	–0.75*	–0.74*	–0.91*	–0.02	0.04	0.36	–0.18	–0.44	–0.12
TP	0.94*	0.93*	0.92*	0.77*	0.66*	0.91*	0.15	–0.04	–0.38	0.26	–0.51	0.19
Ma	–0.97*	–0.98*	–0.97*	–0.94*	–0.85*	–0.98*	0.07	–0.86*	–0.57	0.56	–0.77*	0.26
Mi	0.99*	0.99*	0.98*	0.90*	0.80*	0.99*	–0.11	0.95*	0.43	–0.50	0.62	–0.24
OC	0.41	0.33	0.33	0.26	0.18	0.31	0.28	0.62	0.50	–0.19	0.33	0.28
pH	0.97*	0.97*	0.97*	0.86*	0.77*	0.96*	0.39	–0.14	–0.01	0.72*	–0.43	0.83*
H+Al	–0.98*	–0.98*	–0.99*	–0.90*	–0.81*	–0.98*	0.22	0.12	0.29	–0.81*	0.57	–0.71*
Al <sup>3+</sup>	–0.98*	–0.98*	–0.98*	–0.88*	–0.78*	–0.98*	0.15	0.28	0.49	–0.83*	–0.75*	–0.75*
Ca <sup>2+</sup>	0.97*	0.97*	0.99*	0.91*	0.83*	0.98*	0.19	–0.24	–0.28	0.91*	0.73*	0.88*
Mg <sup>2+</sup>	0.92*	0.93*	0.94*	0.85*	0.79*	0.93*	0.49	–0.22	–0.24	0.80*	0.72*	0.78*
Lime incorporated with ploughing and harrowing												
Sand	–0.42	–0.36	–0.21	–0.13	–0.09	–0.01	–0.19	0.43	0.19	0.18	0.07	0.01
Silt	0.32	0.66	0.4	0.31	0.24	–0.01	0.12	0.35	0.70	0.53	0.36	–0.63
Clay	–0.23	–0.76*	–0.49	–0.37	–0.29	0.04	–0.09	–0.38	–0.70	–0.54	–0.36	0.61
WDC	0.09	–0.58	–0.03	0.05	0.11	0.50	0.14	–0.06	0.50	0.53	0.48	0.19
BD	–0.27	0.52	0.52	0.51	0.41	0.51	0.09	0.12	0.39	0.48	0.58	0.25
TP	0.28	–0.52	–0.53	–0.53	–0.43	–0.53	–0.11	–0.11	–0.39	–0.48	–0.57	–0.28
Ma	0.02	–0.60	–0.31	–0.28	–0.16	–0.27	–0.37	–0.53	–0.57	–0.63	–0.69	–0.08
Mi	0.19	0.58	0.09	0.04	–0.08	0.02	0.67	0.97*	0.37	0.37	0.39	–0.30
OC	–0.05	–0.72*	–0.02	0.09	0.14	0.56	0.22	0.45	–0.17	–0.23	–0.22	–0.38
pH	–0.35	–0.50	0.28	0.41	0.44	0.81*	0.25	–0.13	0.04	–0.01	–0.14	0.36
H+Al	0.39	0.51	–0.25	–0.38	–0.40	–0.79*	–0.19	0.07	–0.14	–0.12	0.01	–0.38
Al <sup>3+</sup>	0.43	0.51	–0.22	–0.36	–0.36	–0.80*	–0.29	–0.03	–0.17	–0.12	0.04	–0.26
Ca <sup>2+</sup>	–0.43	–0.46	0.27	0.40	0.40	0.82*	0.20	–0.10	0.04	0.04	–0.06	0.48
Mg <sup>2+</sup>	–0.36	–0.59	0.18	0.32	0.34	0.77*	0.18	–0.04	0.08	0.07	–0.03	0.51
Lime incorporated with subsoiling and harrowing												
Sand	–0.76*	0.66	0.37	0.34	0.26	0.37	0.27	–0.65	–0.49	0.23	–0.50	–0.15
Silt	–0.45	0.83*	0.57	0.49	0.54	0.11	–0.40	0.17	0.17	–0.06	0.34	0.18
Clay	0.50	–0.84*	–0.58	–0.50	–0.53	–0.14	0.40	–0.14	–0.16	0.05	–0.33	–0.17
WDC	0.76*	–0.64	–0.14	–0.02	0.05	–0.21	–0.19	0.09	0.08	–0.21	0.10	0.30
BD	–0.54	0.64	0.31	0.06	0.09	0.07	–0.51	0.03	0.58	0.10	0.69	0.12
TP	0.50	–0.60	–0.32	–0.08	–0.11	–0.04	0.35	–0.13	–0.67	0.02	–0.72*	0.02
Ma	0.45	–0.91*	–0.28	–0.01	–0.06	0.03	–0.10	–0.84*	–0.30	0.30	–0.33	0.04
Mi	–0.22	0.95*	0.10	–0.11	–0.06	–0.17	0.44	0.94*	0.01	–0.40	–0.03	–0.15
OC	–0.21	0.08	–0.27	–0.12	–0.22	0.04	0.01	0.54	–0.65	–0.37	–0.31	0.38
pH	–0.60	0.08	0.42	0.62	0.54	0.92*	–0.04	–0.32	–0.54	–0.05	–0.50	0.20
H+Al	0.63	–0.14	–0.46	–0.64	–0.55	–0.95*	0.52	0.50	0.43	–0.28	0.23	–0.55
Al <sup>3+</sup>	0.66	–0.16	–0.46	–0.61	–0.50	–0.97*	0.24	0.48	0.54	–0.16	0.41	–0.38
Ca <sup>2+</sup>	–0.71*	0.13	0.49	0.66	0.57	0.91*	–0.30	–0.45	–0.55	0.16	–0.41	0.45
Mg <sup>2+</sup>	–0.62	0.03	0.47	0.63	0.53	0.97*	–0.15	–0.48	–0.62	0.08	–0.50	0.35

\*Significant to the  $F$ -test ( $P \leq 0.05$ ).  $\theta_s$ ,  $\theta_{-10}$ ,  $\theta_{-33}$ ,  $\theta_{-100}$ ,  $\theta_{-500}$  and  $\theta_{-1500}$ , water content in saturation and at  $-10$ ,  $-33$ ,  $-100$ ,  $-500$  and  $-1500$  kPa; WDC, water-dispersed clay; PD and BD, particle and bulk density; TP, total porosity; Ma and Mi, macro- and microporosity; OC, organic carbon content (Walkley-Black method); pH, in  $\text{CaCl}_2$ ; H+Al, potential acidity; Al<sup>3+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>, exchangeable aluminium, calcium and magnesium.

Mi in the SH treatment probably ascribed to higher OC and clay contents compared to the PH treatment (Table 4) which tends to promote the flocculation of soil particles (Ehlers *et al.*, 1995).

Also, in the 0.10- to 0.20-m soil layer, the similarity between the control and SH treatments compared to the PH treatment might be ascribed to the absence and lower intensity of soil tillage, respectively (Cássaro *et al.*, 2011; Dal Ferro *et al.*, 2014; Pires *et al.*, 2017); the results for the LS treatment were the same as those obtained in the absence soil tillage. However, in this case, considering the intense soil disturbance in LPH, BD in this treatment was expected to be lower and TP higher. As this did not occur, the results for BD and TP in LPH might be the result of higher lime reaction in this layer (Table 4), which, along with the WDC, might have altered macroaggregate organization and formation (Rajaram & Erbach, 1999; Six *et al.*, 2004).

The linear correlation of BD and TP in the 0.10- to 0.20-m soil layer of the LPH treatment with WDC content reinforces the hypothesis of comparable changes in soil macroaggregate formation, possibly due to macropore obstruction by the dispersed clays, considering that ploughing promotes rupture of soil macroaggregates (Baldock *et al.*, 1994; Rajaram & Erbach, 1999). The correlation of the Ma of the LSH treatment with sand content in this layer might be ascribed to the presence of lime particles with a diameter larger than 53  $\mu\text{m}$ , as there was not a complete reaction in this layer (Table 4). Thus, coarser lime particles might have behaved as sand particles to form the soil macropores.

#### *Effects of tillage and chemical attributes on the soil water retention*

In the 0- to 0.10-m soil layer, the PH and SH treatments (Figure 5a) had a BD reduction and, consequently, TP increase, which did not differ from each other, but which were different from the control treatment (Figures 1a, b) as a result of soil tillage (Auler *et al.*, 2014; Moraes *et al.*, 2016). In this case, the TP increases favoured high water retention potential (Dane *et al.*, 2002). Also, TP increase can be followed by increases in smaller diameter pores, which results in higher  $\theta$  at low potential (Dal Ferro *et al.*, 2014; Moraes *et al.*, 2016).

In the 0.10- to 0.20-m soil layer, the increase in Ma on the control treatment in relation to the PH treatment (Figure 2c) was probably because at high potentials there is also water in the macropores and their reduction reduces water retention at high potentials (from 0 to  $-10$  kPa) (Alaoui *et al.*, 2011). Similarly the higher Mi of the SH treatment (Figure 3a) leads to higher retention at lower potentials (Ogunwole *et al.*, 2015; Moraes *et al.*, 2016).

Water-dispersible clay correlations with  $\theta$  (Table 6) depending on the soil water matric potential were explained by

different processes. Because WDC reduces soil structural stability and alters its porous space (Roth & Pavan, 1991; Haynes & Naidu, 1998; Six *et al.*, 2004), the highest  $\theta$  at saturation and at the highest potentials (Figure 7a) might be an indirect effect of the highest WDC, which led to TP and Mi increases with surface application (Table 4 and Figures 1b, d).

At low potentials ( $-1000$  to  $-1500$  kPa, e.g.), water retention is governed by water molecules adsorption on the clay particle surfaces (Libardi *et al.*, 2012). As dispersed particles manifest all their specific surface in comparison with aggregate particles (Kay & Dexter, 1990), the positive correlation between  $\theta$  and WDC might be ascribed to the higher capacity of water molecule adsorption by dispersed particles.

The chemical attribute effects on  $\theta$  were also dependent upon the soil water matric potential and can be explained by different processes (Pires *et al.*, 2011). At saturation and at  $-10$  and  $-33$  kPa, the increase in soil pH,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  and reduction in H+Al and  $\text{Al}^{3+}$  are consequences of alterations in the soil structure (BD and Ma reduction, and TP and Mi increase) provided by liming (Table 4).

On the other hand, at low potentials, water retention was also dependent upon the soil electrochemistry and the characteristics of predominant cations. With pH increased by liming, there was an increase in negative charges,  $\text{Al}^{3+}$  precipitation and an increase in  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , which might be adsorbed on the clay particle surface and promote ionic exchange with  $\text{Al}^{3+}$ . Therefore, a predominance of negative charges, higher cation adsorption and higher  $\text{Al}^{3+}$  substitution in the soil solid phase were observed (Sparks, 2003; Caires *et al.*, 2011).

Positive  $\theta$  correlations at  $-1500$  kPa with  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  (Table 6) possibly resulted from the formation of outer sphere adsorption complexes and these ions' reduced ionic radius. In this kind of adsorption the bond between cations and clay particles is mediated by water molecules, thus the higher the cation adsorption, the higher the  $\theta$  value. Also,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions have a small ionic radius and, therefore a large hydrated radius, which also contributes to higher  $\theta$  due to the higher number of water molecules solvating these ions (Sparks, 2003).

#### **Conclusion**

This study has shown that lime application method influences its effect on soil physical attributes. Lime applied on the soil surface reduced soil bulk density and increased total porosity (especially microporosity). Incorporation of lime via ploughing and harrowing or subsoiling and harrowing had similar results, with no significant effects on the physical attributes evaluated. Increases in soil water retention were also observed, regardless of the application method, but this effect was more pronounced when lime was

applied on the soil surface; the changes in the soil physical attributes were more pronounced in the surface soil (0–0.10 m) layer. The alterations caused by the surface liming were strongly correlated with soil chemical attributes being mediated by soil pH increase, and  $\text{Al}^{3+}$  precipitation in the soil solution and substitution in the exchange complex by  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ . Bearing in mind the lower application costs, and the improvements in soil chemical attributes for plant development and soil physical quality, surface liming can be considered a promising alternative for farmers using no-till systems.

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### References

- Alaoui, A., Lipiec, J. & Gerke, H.H. 2011. A review of the changes in the soil pore system due to soil deformation: a hydrodynamic perspective. *Soil and Tillage Research*, **115–116**, 1–15.
- Assis, R.L. & Romeiro, A.R. 2005. Agroecologia e agricultura familiar na região centro-sul do estado do Paraná. *Revista de Economia e Sociologia Rural*, **43**, 155–177.
- Auler, A.C., Miara, S., Pires, L.F., Fonseca, A.F. & Barth, G. 2014. Soil physico-hydrical properties resulting from the management in integrated production systems. *Revista Ciência Agrônômica*, **45**, 976–989.
- Baldock, J.A., Aoyama, M., Oades, J.M., Susanto, O. & Grant, C.D. 1994. Structural amelioration of a South Australian red-brown earth using calcium and organic amendments. *Australian Journal of Soil Research*, **32**, 571–594.
- Caires, E.F., Chueiri, W.A., Madruga, E.F. & Figueiredo, A. 1998. Alterações de características químicas do solo e resposta da soja ao calcário e gesso aplicado na superfície em sistema de cultivo sem preparo do solo. *Revista Brasileira de Ciência do Solo*, **22**, 27–34.
- Caires, E.F., Barth, G. & Garbuio, F.J. 2006. Lime application in the establishment of a no-till system for grain crop production in Southern Brazil. *Soil and Tillage Research*, **89**, 3–12.
- Caires, E.F., Garbuio, F.J., Churka, S., Barth, G. & Corrêa, J.C.L. 2008a. Effects of soil acidity amelioration by surface liming on no-till corn, soybean, and wheat root growth and yield. *European Journal of Agronomy*, **28**, 57–64.
- Caires, E.F., Pereira Filho, P.R.S., Zardo Filho, R. & Feldhaus, I.C. 2008b. Soil acidity and aluminium toxicity as affected by surface liming and cover oat residues under a no-till system. *Soil Use and Management*, **24**, 302–309.
- Caires, E.F., Joris, H.A.W. & Churka, S. 2011. Long-term effects of lime and gypsum additions on no-till corn and soybean yield and soil chemical properties in southern Brazil. *Soil Use and Management*, **27**, 45–53.
- Cássaro, F.A.M., Borkowski, A.K., Pires, L.F., Saab, S.C. & Rosa, J.A. 2011. Characterization of a Brazilian clayey soil submitted to conventional and no-tillage management practices using pore size distribution analysis. *Soil and Tillage Research*, **111**, 175–179.
- Castro Filho, C. & Logan, T.J. 1991. Liming effects on the stability and erodibility of some Brazilian Oxisols. *Soil Science Society of American Journal*, **55**, 1407–1413.
- Chan, K.Y. & Heenan, D.P. 1998. Effect of lime ( $\text{CaCO}_3$ ) application on soil structural stability of a red earth. *Australian Journal of Soil Research*, **36**, 73–86.
- Dal Ferro, N., Sartori, L., Simonetti, G., Berti, A. & Morari, F. 2014. Soil macro- and microstructure as affected by different tillage systems and their effects on maize root growth. *Soil and Tillage Research*, **140**, 55–65.
- Dane, J.H., Topp, C.G. & Campbell, G.S. (eds) 2002. *Methods of soil analysis: Part 4 – Physical methods*. Soil Science Society of America, Madison, WI, USA.
- Ehlers, W., Wendroth, O. & Mol, F. 1995. Characterizing pore organization by soil physical parameters. In: *Soil structure – its development and function* (eds K.H. Hartge & B.A. Stewart), pp. 257–275. *Advances in Soil Science*. CRC Press, Boca Raton, FL, USA.
- Giracca, E.M.N., Antonioli, Z.I., Steffen, R.B., Steffen, G.P.K., Schirmer, G.K. & Eltz, F.L.F. 2008. Influência da aplicação de calcário na população da meso e macrofauna do solo sob sistema plantio direto. *Ciência e Agrotecnologia*, **32**, 1794–1801.
- Han, E., Kautz, T., Perkons, U., Lüsebrink, M., Pude, R. & Köpke, U. 2015. Quantification of soil biopore density after perennial fodder cropping. *Plant and Soil*, **394**, 73–85.
- Haynes, R.J. & Naidu, R. 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems*, **51**, 123–137.
- Instituto Agrônômico do Paraná – Iapar. 2009. *Cartas climáticas do Paraná: classificação climática – segundo Köppen*. Iapar, Londrina, BR. CD-ROM.
- Kay, B.D. & Dexter, A.R. 1990. Influence of aggregate diameter, surface area and antecedent water content on the dispersibility of clay. *Canadian Journal of Soil Science*, **70**, 655–671.
- Libardi, P.L. 2012. *Dinâmica da água no solo*, 2nd edn. EDUSP, São Paulo, SP, Brazil.
- Moraes, M.T., Debiasi, H., Carlesso, R., Franchini, J.C., Silva, V.R. & Luz, F.B. 2016. Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil. *Soil and Tillage Research*, **155**, 351–362.
- Mualem, Y. 1976. Hydraulic conductivity of unsaturated soils: prediction and formulas. In: *Methods of soil analysis: I. physical*

- and mineralogical methods, 2nd edn (ed. A. Klute), pp. 799–823. Soil Science Society of America, Madison, WI, USA.
- Ogunwale, J.O., Pires, L.F. & Shehu, M.B. 2015. Changes in the structure of a Nigerian soil under different land management practices. *Revista Brasileira de Ciência do Solo*, **39**, 830–840.
- Paradelo, R., Virto, I. & Chenu, C. 2015. Net effect of liming on soil organic carbon stocks: a review. *Agriculture, Ecosystems and Environment*, **202**, 98–107.
- Pires, L.F., Villanueva, F.C.A., Dias, N.M.P., Bacchi, O.O.S. & Reichardt, K. 2011. Soil chemical migration during soil water retention curve evaluation. *Anais da Academia Brasileira de Ciências*, **83**, 1097–1107.
- Pires, L.F., Borges, J.A.R., Rosa, J.A., Cooper, M., Heck, R.J., Passoni, S. & Roque, W.L. 2017. Soil structure changes induced by tillage systems. *Soil and Tillage Research*, **165**, 66–79.
- R Core Team. 2016. *R: a language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Áustria.
- van Genuchten, M. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, **44**, 892–898.
- van Raij, B., Andrade, J.C., Cantarella, H. & Quaggio, J.A. 2001. *Análise química para avaliação da fertilidade de solo tropicais*. Instituto Agronômico de Campinas, Campinas, BR.
- Rajaram, G. & Erbach, D.C. 1999. Effect of wetting and drying on soil physical properties. *Journal of Terramechanics*, **36**, 39–49.
- Roth, C. & Pavan, M. 1991. Effects of lime and gypsum on clay dispersion and infiltration in samples of a Brazilian Oxisol. *Geoderma*, **48**, 351–361.
- Seki, K. 2007. SWRC fit - a nonlinear fitting program with a water retention curve for soils having unimodal and bimodal pore structure. *Hydrology and Earth System Sciences Discussions*, **4**, 407–437.
- Six, J., Bossuyt, H., Degryze, S. & Denef, K. 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, **79**, 7–31.
- Soil Survey Staff. 2013. *Simplified guide to soil taxonomy*. USDA-Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE, USA.
- Sparks, D.L. 2003. *Environmental soil chemistry*, 2nd edn. Elsevier Science, San Diego, USA.
- von Uexküll, H.R. & Mutert, E. 1995. Global extent, development and economic impact of acid soils. *Plant and Soil*, **171**, 1–15.