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COVER CROPS, LIME AND GYPSUM INFLUENCE ON SOIL PHYSICAL ATTRIBUTES

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Abstract
Cover crops promote nutrient cycling, and lime and gypsum can alter the soil physical attributes. This study aimed to evaluate the effect of lime and gypsum rates applied to a no-tillage system with addition of residues of three cover crops on the soil physical attributes. This experiment was carried out in chapadão do sul-ms. The treatments were comprised of three cover crops (Urochloa ruziziensis, fallow, and Pennisetum glaucum), with gypsum (0, 2.3 and 4.6 Mg ha-1) and lime applied at a dose of 0, 2, 4, 6 Mg ha-1).The attributes evaluated were: soil density, macroporosity, microporosity, total porosity and penetration resistance. The soil of the experiment was classified an Oxisol. Cover crops and lime and gypsum improved macroporosity, microporosity and total porosity at all depths, 0-0.2 m. Millet presented lower values for penetration resistance with the lime application and without gypsum application. No residual effect on soil density was detected for lime and gypsum application or cover crops in the 0.1-0.2 m layer. Brazilian Cerrado producers will have a well-defined management system to follow aiming at improving the soil physical attributes.

Keywords: Bulk Density. Green Manuere. Liming. Macroporosity. Microporosity.

1. Introduction

Brazilian Cerrado soils are highly weathered and have been intensively used in agricultural production, thus leading to a high level of degradation (Ciotta et al. 2004). The use of amendments is fundamental to counteract the intensive that cultivation has decreased crop yields. With the intense use of the soil, crop residues should be allowed to remain in the field to avoid furthe degradation (Borges et al. 2016). The No-tillage (NT) crop production practice effective strategy to improve the sustainability of agriculture in tropical and subtropical regions No tillage minimizing nutrient losses due to erosion (Rodrighero et al. 2015).

The ability of NT to maintain crop yields is related to the quality and quantity of mulching on the soil surface. Thus, the use of cover crops with good dry matter yield is essential for NT maintenance and crop management. Several studies have reported challenge of maintaining the plant residues in Cerrado soils since the region presents low rainfall in half of the year, thus increasing the decomposition dose of residues

Establishment of crops can also be difficult/problematic (Kluthcouski et al. 2000; Silva et al. 2014; Horvathy Neto et al. 2014; Pacheco et al. 2008).

No-tillage increases the compaction of the surface and subsurface layers of the soil in the Cerrado region of Brazil, mainly due to the heavy use of machines and high tire pressures exerted on the ground (Muller 2014). Therefore, the search for systems that provide better soil physical conditions has increased. Areas that are under NT for several years present physical restrictions for in-depth root development (Silva et al. 2015).

The use of cover crops with high dry matter yield is recommended to improve soil attributes (Moraes et al. 2014; Pacheco et al. 2008). In the Cerrado biome, forage plants such as millet (Pennisetum glaucum) and brachiaria (Urochloa riziziensis), are known for their high organic matter yield, deep root growth, and soil preservation attributes (Kaufman et al. 2013). They improve soil structure, aggregation, permeability, and infiltration, besides promoting nutrients recycling.

An earlier study Caires et al. (2008) found that liming is the least costly and most effective practice to increase pH and base saturation as it provides calcium and magnesium and reduce toxic aluminum and manganese in the soil. However, the action of lime is usually limited to the application site. Moreover, the acidity reduction of the subsoil is slow due to its dependence on the leaching of carbonates in the soil profile to improve the physical and chemical attributes of the soil (Blum et al. 2013). Agricultural gypsum (CaSO4 H2O), another soil amendment acts as a soil conditioner owing to its high mobility in the soil profile. It provides calcium (Ca+2) and sulfur (SO4-2) in solution, which reduces the in-depth aluminum (Al+3) saturation and improves nutrient availability (calcium and magnesium) in subsurface layers (Caires et al. 2008).

Studies on the benefits of the joint application of lime and gypsum and the dynamics of soil acidity correction under NT without incorporation are still scarce in long-term experiments (> three years), especially in tropical regions. The hypothesize that different cover crops and the combined application of lime and agricultural gypsum will improve the soil physical attributes. This study evaluated the changes in and physical attributes of the soil, influenced by different cover crops associated with lime and gypsum application in a no-tillage system, in the Cerrado region.

2. Material and Methods

The experiment was carried out on Chapadão Fundation Research located in Chapadão do Sul, MS (18°41'33"S, 52°40'45" W, alt 810 m, in the 2016/2017 agricultural year

The region represents a tropical wet and dry climate (Aw), with well-defined seasons, characterized by dry winters (May-September) and rainy summers (October-April), according to the Köppen classification. The experimental area presents average annual temperature ranging from 13 °C to 28 °C, average annual rainfall of 1.850 mm, and average annual relative humidity of 64.8 % (Castro 2012). Rainfall and air temperature data were recorded during the experimental period (Figure 1).

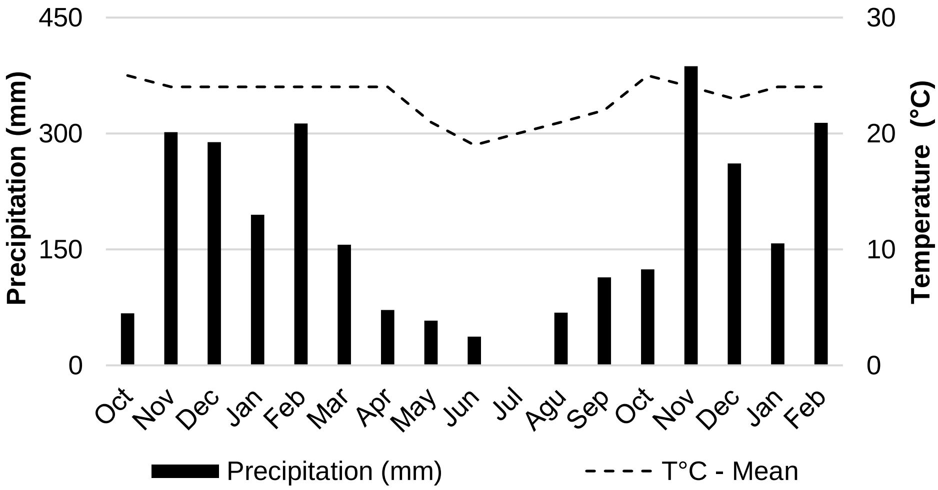

Figure 1. Rainfall (mm) and average monthly temperature (ºC) over the experiment period.

The soil of the experimental area was classified as Oxisol (EMBRAPA 2013). Soil texture was characterized using the densimeter method (Claessen et al. 1997). It contained 460, 51.5 and 2.5 g kg^{-1} of clay, sand and silt, respectively, in 0.0-0.2 m soil layer. Chemical analysis of soil samples (Table 1) was performed according to the Claessen method (1997). Samples were collected from the 0.-0.2 and 0.2-0.4 m layers in March 2011.

Table 1. Soil chemical analysis before the experiment installation.

Depth	pH	Ca	Mg	Al	H+Al	K	P(res)	S	OM	CEC	V	m
(m)	$CaCl_2$	--------cmol$_c$ dm^{-3}-----				------mg dm^{-3}----			g dm^{-3}	cmol$_c$ dm^{-3}	----%----	
0-0.20	4.2	2.0	0.3	0.3	5.5	157	37.3	7.7	36.9	8.3	33.5	11.6
0.20-0.40	4.3	1.3	0.2	0.2	5.2	94	5.70	15.8	24.0	6.9	25.1	9.8

Depth	B	Cu	Fe	Mn	Zn
(m)	---mg dm^{-3}--				
0-0.20	0.14	1.30	44.0	16.4	5.2

[1] Method of Raij and Quaggio (1983) – H+Al: Potential acidity; P(res): Phosphorus obtained by resin method; OM: Organic matter; CEC: Cation exchange capacity; V: base saturation; m: saturation by aluminium.

The preparation of the experimental area began in October 2010 with the application and incorporation of limestone in total area, with the working depth of 0.25 m scarifier. After one week, gypsum was applied in total area, followed by soil harrowing. For the chemical conditioning of the soil, dolomitic limestone with Relative Power of Total Neutralization (PRNT) of 95%, containing 32% of calcium, was used. and 17% magnesium and agricultural plaster with 18.63% calcium and 161 15.70% sulfur. The limestone dose adopted was to increase base saturation to 60% in the 0.0-0.20 m layer. The recommendations for liming and plastering followed the recommendations of Sousa and Lobato (2004).

In the 2011/2012 crop season, the first tillage system with soybean was started in the first crop, corn second crop and *U. ruziziensis* in the off season, the same sequence of crops was carried out in the subsequent crop (2012/2013). In the 2013/2014 crop season, in the season, cotton was cultivated and after its harvest was made a new application of limestone and plaster, without incorporation. Already in 2014/2015, in the season was cultivated bean and in the second crop corn. In 2015/2016 this experiment was implemented.

Sowing of cover crops was performed on October 28, 2015, using 5 and 15 kg ha^{-1} of seeds of *U. ruziziensis* and *P. glaucum* (cv ADR 300), respectively, using misaligned disc spacing and spacing. 0.17 m between lines. With a horizontal plant waste shredder (Triton) the cover plants were managed and desiccated in January 2016 were with glyphosate (1.98 kg ha^{-1} from i.a) and ethyl carfentrazone (20 g ha^{-1} from i.a). After desiccation, the cotton was implanted, obtaining a cycle of 190 days.

After the cotton harvest, in October 2016, soybean was cultivated with the cultivar NA 5909, with indeterminate growth habit, medium size, maturity group 5.9, with medium fertility requirement. The basic fertilization for soybean was 150 Kg ha^{-1} MAP, and its formulation was 11% N - 52% P_2O_5 - 00% K_2O. For this operation, a seeder-fertilizer with a front cutting disc and a stem-type fertilizer distribution system with row spacing of 0.45 m and sowing density of 22 seeds per meter was used. The soybean harvest was carried out in January 2017, and shortly afterwards the undisturbed soil samples were collected.

The experiment consisted of a completely randomized block design with four replications, in a split-plot scheme. The plots were 3.15 x 22 m and the subplots were 3.15 x 5.5 m. The main plot consisted of three cover crops (U ruziziensis, Pennisetum glaucum, fallow); the subplot consisted of agricultural gypsum (0, 2.3, and 4.6 Mg ha-1); and the sub-sub-plot consisted of different lime doses (0, 2, 4, and 6 Mg ha-1). For the analyzes, trenches of 0.5 m wide and 0.5 m deep were opened, and volumetric rings were collected at depths 0-0.10 and 0.10-0.20 m.

Bulk density (BD) was determined by the volumetric ring method. Total porosity (TP) was calculated by the soil water saturation percentage. The microporosity (Mi) and macroporosity (Ma) were determined using a tension table (Claessen et al. 1997). Soil penetration resistance (PR) was calculated using a digital electronic penetrometer (PenetroLOG, Falker). Penetration resistance data were classified (0.10m each) to a depth of 0.40 m and results reported in Megapascal (MPa). Soil moisture was measured at the same depths, on the same day of the penetration resistance test. Samples were randomly collected in each experimental plot at the end of the experiment.

Data were subject to analysis of variance considering all factors as fixed in the model, followed by means comparison of the levels of gypsum and cover crops by the Tukey's test (P ≤ 0.05). Polynomial regression analysis was used for the lime doses in the Sisvar software (Ferreira 2011).

3. Results

The analysis of variance (Table 2) for the evaluated variables showed no residual effect of lime and gypsum was observed in the soil for the variable microporosity (Mi) in the 0.0 – 0.10 m layer; and macroporosity (Ma), Bulk density (BD), and volumetric moisture (VM) in the 0.10 - 0.20 m layer.

Table 2. Summary of the analysis of variance for macroporosity (Ma), microporosity (Mi), total porosity (TP), Bulk density (BD), penetration resistance (PR) and volumetric moistures(VH) as a response to cover crops, lime and gypsum in the 0.0-0.10 and 0.10-0.20 m layers.

SV	DF	Ma (m^3 m^{-3})	Mi (m^3 m^{-3})	TP (m^3 m^{-3})	BD (Mg m^{-3})	PR (MPa)	VM (%)
		---------- 0,0 – 0,10 m ----------					
Block	2	0,0002	0,0001	0,0003	0,0522	0,0452	13,08
Cover (C)	2	0,0010*	0,1463*	0,0105*	0,0304*	3,1084*	142,32*
Gypsum (G)	2	0,0007*	$0,0043^{ns}$	$0,0051^{ns}$	0,0052*	0,4589*	$3,99^{ns}$
Lime (L)	3	0,0010*	$0,0073^{ns}$	0,0110*	0,0041*	0,8055*	$19,42^{ns}$
C x G	4	0,0008*	$0,0006^{ns}$	$0,0011^{ns}$	0,0041*	0,3373*	$14,61^{ns}$
C x L	6	0,0005*	$0,0015^{ns}$	$0,0018^{ns}$	0,0057*	0,5827*	$22,25^{ns}$
G x L	6	0,0004*	$0,0032^{ns}$	0,0065*	0,0293*	0,2515*	$62,88^{ns}$
Error 1	4	0,0002	0,0015	0,0008	0,0004	0,0091	13,16
Error 2	8	0,0001	0,0002	0,0006	0,0083	0,0078	3,24
Error 3	70	0,0002	0,0012	0,0017	0,0127	0,0972	19,51
CV 1 (%)	-	6,81	10,37	6,31	1,62	5,92	10,57
CV 2 (%)	-	14,22	4,10	5,64	7,44	5,46	5,24
CV 3 (%)	-	21,64	9,39	9,29	9,20	19,33	12,86
Mean	-	0,07	0,37	0,44	1,23	1,61	34,33
		Ma (m^3 m^{-3})	Mi (m^3 m^{-3})	TP (m^3 m^{-3})	BD (Mg m^{-3})	PR (MPa)	VM (%)
		---------- 0,10 – 0,20 m ----------					
Block	2	0,0000	0,0012	0,0004	0,0342	0,0029	43,98
Cover (C)	2	0,0010*	$0,0011^{ns}$	$0,0012^{ns}$	$0,2450^{ns}$	$3,8220^{ns}$	$16,59^{ns}$
Gypsum (G)	2	$0,0000^{ns}$	0,0034*	0,0032*	$0,0016^{ns}$	$0,3270^{ns}$	$13,15^{ns}$
Lime (L)	3	$0,0002^{ns}$	$0,0005^{ns}$	0,0030*	$0,0005^{ns}$	$0,4468^{ns}$	$18,74^{ns}$
C x G	4	$0,0002^{ns}$	$0,0004^{ns}$	$0,0019^{ns}$	$0,0010^{ns}$	0,8730*	$9,44^{ns}$
C x L	6	$0,0001^{ns}$	$0,0015^{ns}$	0,0026*	$0,0039^{ns}$	0,5031*	$2,34^{ns}$
G x L	6	0,0007*	$0,0010^{ns}$	$0,0012^{ns}$	$0,0016^{ns}$	0,2466*	$3,07^{ns}$
Error 1	4	0,00005	0,0004	0,0004	0,0082	0,0198	28,92
Error 2	8	0,0002	0,0007	0,0005	0,0029	0,0439	5,90
Error 3	70	0,0002	0,0007	0,0008	0,0040	0,1000	9,27
CV 1 (%)	-	7,02	5,42	4,17	7,00	4,95	15,31
CV 2 (%)	-	14,03	7,01	4,76	4,17	7,38	6,91
CV 3 (%)	-	12,82	7,08	6,32	4,88	11,13	8,66
Mean	-	0,10	0,37	0,46	1,29	2,84	35,13

*, ns: (P≤0.05) significant and not significant, respectively. C x G: interaction between cover and gypsum. C x L: interaction between cover and lime. G x L: interaction between gypsum and lime. CV: coefficient of variation.

Mi and TP (in the 0.0 - 0.10m layer) and Ma (in the 0.10 - 0.20m layer) were influenced by cover crops (Table 3). U ruziziensis provided a higher value of Mi and TP in the 0.0 - 0.10m layer, not differing from the fallow. Higher values of Ma were recorded in areas where U ruziziensis and millet were planted.

Table 3. Means comparison of microporosity (Mi), total porosity (TP), and volumetric moisture (VM) (in the 0.0-0.10 m layer) and macroporosity (Ma) (in the 0.10-0.20 m layer) as affected by cover crops.

Cover crop	Mi (m^3 m^{-3})	TP (m^3 m^{-3})	VM (%)	Ma (m^3 m^{-3})
	0.0 – 0.10 m		0.10 – 0.20 m	
U ruziziensis	0.39 a	0.45 a	36.62 a	0.10 a
Fallow	0.37 ab	0.45 a	33.16 b	0.09 b
Millet	0.35 b	0.42 b	33.19 b	0.10 a

Mean followed by lowercase letters in the column do not statistically differ from each other by the Tukey's test at 5%.

Gypsum doses influenced Mi and TP in the 0.10 - 0.20 m layer (Table 4). The highest values of Mi and TP were observed at the gypsum dose of 2.3 Mg ha^{-1}; however, these values did not differ from those of the treatment without gypsum. Lower values of Mi and TP were observed at the gypsum dose of 4.6 Mg ha^{-1}.

Table 4. Means comparison of microporosity (Mi) and total porosity (TP) in the 0.10 - 0.20 m layer, as affected by gypsum doses.

Gypsum Doses (Mg ha^{-1})	Mi (m^3 m^{-3})	TP (m^3 m^{-3})
	0.10 – 0.20 m	
0	0.36 ab	0.46 ab
2.3	0.38 a	0.47 a
4.6	0.36 b	0.45 b

Means followed by the same lowercase letters in the column do not statistically differ from each other by the Tukey's test at 5%.

Ma and BD, in the 0.0-0.10 m layer, and PR, in the 0.0-0.10 and 0.10-0.20 m layers, were significantly influenced by the cover crops and gypsum doses interaction (Table 5). U ruziziensis presented the highest Ma in the treatments using the gypsum dose of 2.3 Mg ha^{-1} and without gypsum. No significant difference was detected between cover crops at the gypsum dose of 4.6 Mg ha^{-1}.

Table 5. Unfolding of the cover crop x gypsum doses interaction obtained for macroporosity (Ma), Bulk density (BD), and penetration resistance (PR), according to the soil layer.

Cover crop	Gypsum doses (Mg ha^{-1})		
	0	2.3	4.6
	Ma (m^3 m^{-3})		
	0.0 – 0.10 m		
U ruziziensis	0.08 aB	0.09 aA	0.07 aC
Fallow	0.06 bB	0.08 bA	0.07 aA
Millet	0.06 bB	0.06 cB	0.07 aA
	BD (Mg m^{-3})		
	0.0 – 0.10 m		
U ruziziensis	1.27 aA	1.21 bB	1.24 aAB
Fallow	1.20 bA	1.20 bA	1.18 bA
Millet	1.25 aAB	1.26 aA	1.23 aB
	PR (MPa)		
	0.0 – 0.10 m		
U ruziziensis	1.65 bB	1.74aAB	1.87 aA
Fallow	1.34 cA	1.24 cA	1.25 bA
Millet	1.95 aA	1.49 bB	2.00 aA
	0.10 – 0.20 m		
U ruziziensis	3.39 aA	2.92 aB	2.82 bB
Fallow	2.38 cA	2.45 bA	2.56 cA
Millet	2.90 bB	2.82 aB	3.32 aA

Means followed by the same uppercase letters in the row and lowercase in the column do not statistically differ from each other by the Tukey's test at 5%.

The use of *U ruziziensis* as the cover crop combined with the gypsum dose of 2.3 Mg ha^{-1} resulted in highest Ma. Following the gypsum dose of 2.3 Mg ha^{-1} led to higher Ma; however, this result did not differ from that obtained with the gypsum dose of 4.6 Mg ha^{-1}. When using millet as a cover crop, the gypsum dose of 4.6 Mg ha^{-1} had better results when compared with the other doses.

Lower values of BD were observed with the use of fallow at the three gypsum doses (0, 2.3, and 4.6 Mg ha^{-1}). However, at the gypsum dose of 2.3 Mg ha^{-1}, the fallow did not differ statistically from *U ruziziensis*. The gypsum dose of 2.3 Mg ha^{-1} resulted in the lowest BD value when using *U ruziziensis*, not differing from the dose of 4.6 Mg ha^{-1}. For millet, the gypsum dose of 4.6 Mg ha^{-1} resulted in lower BD values, not differing from treatments without gypsum.

The fallow presented the lowest values of PR in the 0.0-0.10 and 0.10-0.20 m layers, at all gypsum doses. *U ruziziensis* presented a lower value of PR in the 0.0-0.10 m layer without gypsum application. However, no differences were observed for the gypsum dose of 2.3 Mg ha^{-1}. In the 0.10-0.20 m layer, the lowest PR value was detected at the gypsum dose of 2.3 Mg ha^{-1}, not differing from the gypsum dose of 4.6 Mg ha^{-1}. For millet, the gypsum dose of 2.3 Mg ha^{-1} had the best result in the 0.0-0.10 m layer. Conversely, in the 0.10-0.20m layer, the gypsum dose of 2.3 Mg ha^{-1} and no gypsum application resulted in a lower value of PR.

The variables Ma and BD, in the 0.0- 0.10 m layer; and RP, in the 0.0-0.10 and 0.10-0.20 m layers, were influenced by cover crops and lime doses (Table 6). At the lime dose of 2 and 6 Mg ha^{-1}, *U ruziziensis* provided better Ma values than the other cover crops. For the lime dose of 4 Mg ha^{-1}, an increase for Ma was observed during the fallow, but it did not differ from *U ruziziensis*. Areas where the lime dose was not increased presented no statistical difference between cover crops.

Table 6. Unfolding of the cover crops x lime doses interaction obtained for macroporosity (Ma), Bulk density (BD), and penetration resistance (PR), according to the soil layer.

Cover crop	Ma (m^3 m^{-3}) 0.0 – 0.10 m Lime Doses (Mg ha^{-1})				Equation	R^2
	0	2	4	6	---	--
U ruziziensis	0.06	0.08 a	0.07 ab	0.09 a	---	--
Fallow	0.07	0.06 c	0.08 a	0.07 b	---	--
Millet	0.06 a	0.07 b	0.07 b	0.06 c	---	--
	BD (Mg m^{-3})					
	0.0 – 0.10 m					
U ruziziensis	1.26 a	1.20 b	1.25 a	1.25 a	---	--
Fallow	1.22 b	1.19 b	1.16 b	1.20 b	---	--
Millet	1.23 b	1.26 a	1.23 a	1.25 a	---	--
	PR (MPa)					
	0.0 – 0.10 m					
U ruziziensis	1.72 a	2.12 a	1.24 b	1.93 a	---	--
Fallow	1.28 b	1.31 b	1.11 b	1.42 b	---	--
Millet	1.84 a	2.06 a	1.87 a	1.48 b	---	--
	0.10 – 0.20 m					
U ruziziensis	2.81 b	2.71 b	3.25 a	3.40 a	2.697333+0.000115x	0.80
Fallow	2.37 c	2.32 c	2.55 c	2.63 b	2.312778+0.000051x	0.79
Millet	3.23 a	2.99 a	3.00 b	2.82 b	3.196889-0.000061x	0.88

Means followed by the same lowercase letters in the column do not statistically differ from each other by the Tukey's test at 5%.

In relation to PR in the 0.0-0.10 m layer, at all lime doses, the fallow had a better result. Conversely, at the lime dose of 4 Mg ha^{-1}, it did not differ from *U ruziziensis,* and at the lime dose of 6 Mg ha^{-1}, it did not differ from millet. Results obtained for the 0.10-0.20 m layer are similar to those of the surface layer. Moreover, the fallow presented lower values of PR. A significant difference in lime doses within each cover crop was detected only for PR in the 0.10-0.20 m layer. *U ruziziensis* and fallow presented a linear increase of PR in function of lime doses. Millet showed no negative linear effect.

A significant gypsum dose x lime dose interaction was observed for Ma and PR (in the 0.0-0.10 and 0.10-0.20 m layers) and TP and BD (in the 0.0-0.10 m layer) (Table 7). The lime dose of 2 Mg ha^{-1} associated with the gypsum dose of 4.6 Mg ha^{-1} resulted in a higher value of Ma in the 0.0-0.10 layer. Conversely, lime doses of 4 and 6 Mg ha^{-1} combined with the gypsum dose of 2.3 Mg ha^{-1} provided higher values. No difference was detected in the treatment without lime application. In the 0.10-0.20m layer without lime application, the addition of the gypsum dose of 4.6 Mg ha^{-1} resulted in higher values of Ma, not differing from the gypsum dose of 2.3 Mg ha^{-1}. At the lime dose of 2 Mg ha^{-1}, the highest values were reported when combined with the gypsum dose of 2.3 Mg ha^{-1} and without gypsum application. No statistical difference was detected for lime doses of 4 and 6 Mg ha^{-1}.

BD presented interaction in all treatments. BD decreased in the treatment without lime and gypsum application. Lime doses of 2 and 6 Mg ha^{-1}combined with the gypsum dose of 2.3 Mg ha^{-1} reduced BD. The lime dose of 4 Mg ha^{-1} associated with the gypsum dose of 4.6 Mg ha^{-1} resulted in lower BD.

PR showed significant interaction between the two layers. Higher values of PR were obtained without the increment of lime and gypsum in the two layers. The treatment that combined 2 Mg ha^{-1} of lime and 4.6 Mg ha^{-1} of gypsum led to higher soil compaction in the 0.0-0.10m layer, which is a similar result to that of the 0.10-0.20m layer. However, higher values were also detected without gypsum application. The treatment that associated the lime dose of 4 Mg ha^{-1} with the gypsum dose of 2.3 Mg ha^{-1} (0.0-0.10m) resulted in a higher PR. In contrast, the lime dose of 6 Mg ha^{-1} combined with the gypsum dose of 4.6 Mg ha^{-1} led to higher values of PR.

Regarding the lime doses within each gypsum dose, a significant difference was observed only for Ma and PR in the two layers. The treatment without gypsum application to both layers, as well as the gypsum dose of 2.3 Mg ha^{-1}, applied to the 0.0-0.10 m layer presented a linear increase of Ma with the addition of lime doses.

For the treatment without gypsum, lime doses promoted a linear increase in the 0.0-0.10 m layer. A similar result was detected in the 0.10-0.20 m layer at the gypsum doses of 2.3 and 4.6 Mg ha^{-1}. The equations represent the effect of linear increase with the increase of lime doses. Soil penetration resistance has been widely used to evaluate soil compaction, in which the stem simulates the impediment imposed by the soil to the root development. Thus, it can be inferred that the 0.10-0.20 m layer is compacted.

4. Discussion

The mean values of Mi and TP levels in the 0.0-0.1 m layer (Table 3) are within range. The authors stated for that an ideal agricultural soil (Azevedo and Dalmolin 2006). There ideal levels for microporosity levels are 0.33 (m3 m^{-3}) and total porosity lower than 0.50 (m3 m^{-3}). Bonini et al. (2015) and Borges et al. (2016) reported that microporosity is associated with soil texture and little influenced by the management. They also stated that each soil has its support capacity; therefore, the changes depend on the soil structure, unlike macroporosity, which is directly affected by the management. Ma values lower than 0.10m^3 m^{-3} hinder root development due to low aeration (Vomocil and Folker 1961). In the present work, the treatment without cover crop resulted in Ma values higher than 0.10 m^3 m^{-3}, which could indicate soil degradation (Borges et al. 2016).

The recommended gypsum dose had better results for Mi and TP in the 0.10-0.20 m layer (Table 4). This fact may be related to the flocculent action of gypsum in transforming part of the macropores into micropores since the latter correspond to the intra-aggregate pores (Müller et al. 2012). The authors detected no significant effects of gypsum rates on Mi in the 0.075-0.150m layer.

The cover crops x gypsum interaction affected Ma in the 0.0-0.10 m layer (Table 5) at the recommended gypsum rate (2.3 Mg ha^{-1}) and without gypsum application when *U ruziziensis* was grown as cover crop. This result is a reflection of the root system of *U ruziziensis*, which is fasciculate and quite aggressive, responsible for increasing soil aeration and decreasing soil density (Andrade et al. 2009).

The Ma under plant residues of *U ruziziensis* associated with the recommended gypsum rate had better results (Table 5). This can be explained by the gypsum application, which causes chemical changes in the soil, such as the reduction of Al content and the increase of Ca content in all profile, allowing a better root development (Nora et al. 2014). Although the use of gypsum and cover crops increased Ma values, these values are lower than the minimum value of 10% (0.10m^3 m^{-3}), indicated as a critical limit to avoid soil aeration and gas exchanges restrictions (Lier 2010).

The use of *U ruziziensis* as cover crop combined with the recommended gypsum rates of 2.3 and 4.6 Mg ha^{-1} provided a lower BD value (Table 5). For millet, the gypsum dose of 4.6 Mg ha^{-1} resulted in a lower BD, not differing from the treatment without gypsum application. Gypsum promotes the dispersion of existing aggregates in Latosols due to the partial neutralization of aluminum ions (Rosa Junior et al. 2006). Another explanation may be the fact that Al runs off together with the gypsum during leaching (Pavan et al.

1984). Thus, BD can benefit from the formation of $AlSO_4^+$ complexes or ionic pairs. Similar results were reported Costa et al. (2007) the effects of agricultural gypsum for dystroferric Red Latosol cultivated with soybean under NT, where application of a gypsum dose of 2 Mg ha^{-1} increased soil density.

PR was affected in two layers (0.0-0.10, 0.10-0.20 m). All the doses applied to the fallow presented lower values (Table 5). Comparison of Penetration resistance in a Eutrophic Red-Yellow Argisol under fallow and velvet bean, millet, crotalaria, and jack bean. Showed lowest penetration resistance for millet (Horvathy Neto et al. 2014).

Recent studies (Moraes et al. 2014; Rós et al. 2013) have determined that the continuous use of NT results in higher compaction of the 0.10-0.20 m layer. PR values between 1 and 1.7 MPa affect root growth, whereas values higher than 3 MPa result in root growth interruption (Lipiec and Hatano 2003). However, PR values from 1.9 MPa influenced the height of soybean plants in a Dystrophic Red Argisol (De Lima et al. 2010). Thus, in the 0.10-0.20m layer, all values are higher than 2 MPa, which confirms the compaction of this layer and may indicate soil degradation (Horn et al. 2003).

The action of lime is directly related to the improvement of soil fertility (Table 6), which favors root growth and distribution. Although cover crops and lime application affect macropores and soil density, their values are still not considered as ideal. Thus, the use of management practices that increase macroporosity and improve soil aeration is crucial (Calonego and Rosolem 2010). The fallow showed lower values for PR, diverging from the results of Silva and Rosolem (2001), who evaluated the influence of the previous crop on soil compaction. Possibly most of the plants that developed in the fallow area had pivoting roots, or some auxiliary soil decompression.

A linear increase in PR was detected in the 0.10-0.20 m layer for *U ruziziensis* and fallow in function of lime doses (Table 6). This effect can be explained by an increase in the Ca content with the lime application, resulting in higher aggregation strength and formation of larger aggregates (Müller et al. 2012). Millet presented a negative linear effect. Although PR showed a difference between the treatments, all values are higher than 2 MPa, which is considered a limiting value for the development of soybean (Taylor et al. 1966). These high values are consequences of the use of NT for more than six years. Therefore, other management practices are recommended for the decompaction of soil, such as the use of plants with robust and deep root system (biological scarification) in rotation that are able to grow in compact layers (Abreu et al. 2004; Nicoloso et al. 2008).

The increase in macroporosity and total porosity with the use of lime and gypsum (Table 7) can be explained by the greater root development, which increases mechanical pressure and folds organomineral particles. Thus, a higher contribution of C, due to increases shoot. and roots growth. Intensifies microbial activity, which helps maintain aggregates stability, consequently increasing macroporosity and total porosity (Costa et al. 2007; De Lima et al. 2010). In addition, the increase of the negative loads of soil due to liming, when associated with the gypsum application, may increase the electrolyte concentration of the rainwater that infiltrates the soil (Serafim et al. 2012). This fact increases the Ca concentrations on the exchange sites and in solution, and promotes clay particles flocculation (Favaretto et al. 2006; Tirado-Corbalá et al. 2013), consequently favoring soil aggregation, TP, and Ma.

Bulk density reduction due to the combined lime and gypsum application has been attributed to the increase in the amount and activity of bivalent cations, such as Ca_2^+ and Mg_2^+, on the soil exchange sites. This occurs because these cations, under pH ($CaCl_2$) higher than 5.5, can form bonds between the polymers of the organic matter and the colloids surface, generating aggregates and consequently reducing soil density (Castro Filho 2002; Oliveira 2008). The flocculating action of liming is even more important in soils with the predominance of iron and aluminum oxides due to the increase of the concentration of negative charges promoted by the reaction of the lime in the soil. This theory was reinforced when an increase of Ca_2^+ was ensured the exchange sites of a Clayey Dystrophic Red Latosol, this reducing BD in an area under no-tillage system (Castro Filho 2002; Pessoni 2012).

Liming reduces BD as it favors the development of the crop's root system. The increase of pH and the reduction of Al lead to the higher development of thick and fine roots, which contribute to the aggregates formation and incorporate a large quantity of organic matter into the soil (Pessoni, 2012). No significant differences in BD in the deeper layers were detected, even though there might have been an increase in calcium and magnesium levels in these layers owing to lime and gypsum doses. This absence of significant differences might be due to the pH values of these layers, which are equal to or lower than 5.5 (Castro Filho 2002; Oliveira 2008). Thus, under these conditions, it is likely that the Al_3^+ ion still influences the soil aggregation. At these pH values, the Al_3^+ ion is still present in the soil solution. Moreover, owing to its higher valence and lower hydrated radius than Ca_2^+ and Mg_2^+, Al has the binding preference in the exchange complex, acting on the soil colloids aggregation.

The increase of PR with lime and gypsum application is explained by the increment of the calcium content in the subsoil, which increases the aggregation forces and forms larger aggregates. An increase in the size of the aggregate increases the force required for root penetration into the soil (Miska et al. 1986).

Thus, the PR measured by the penetrometer also increases with the lime and gypsum application. These results were different from those reported by Nogueira et al. (2016), who found no significant differences in PR in the 0.0-0.10, 0.10-0.20, and 0.20-0.30 m layers of a Clayey Dystrophic Red Latosol under the no-tillage system, after 30 months of alone and combined lime and gypsum application.

5. Conclusions

Lime and gypsum application and cover crops do not affect bulk density in the 0.1-0.2 m layer. The fallow provided lower bulk density in layer 0 - 0.1 m regardless of limestone dose. Cover crops and lime and gypsum doses improved the macroporosity, microporosity, total porosity, and soil density in all layers, except for the bulk density in 0.1-0.2 m layer. A millet cover crop together with lime doses, as well as the application of lime doses without gypsum, results in lower values of penetration resistance.

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