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Evaluation of aggregate distribution and selected soil physical properties under maize–jack bean intercropping and gypsum rates

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Adequate soil management can create favourable conditions to increase aggregation and porosity of the soil, resulting in better aeration of the soil and water infiltration. Consortia of maize and other species have been used in no-till systems to increase dry matter production, and consequently, the soil cover. This study aimed to evaluate the effects of consortia of maize and jack bean (*Canavalia ensiformis)* on aggregate stability and soil physical properties at different depths and with different rates of gypsum. The experiment was conducted in Paraná State, Brazil. The experimental design consisted of completely randomised blocks arranged in a split-plot design with four replications. The main plots consisted of maize intercropped with jack bean or not intercropped, and the subplots consisted of six rates of gypsum (0, 1, 2, 3, 4 and 5 t ha^{-1}). After maize cultivation, soil samples were collected for analysis of macroporosity, microporosity, total porosity, and soil bulk density at three depths. Monoliths were collected at 0-0.15 and 0.15-0.30-m depths for aggregate stability analysis. The application of gypsum promoted higher aggregate stability at the 0-0.15-m depths, but there was no effect on macroporosity, microporosity, total porosity, or soil bulk density. Maize intercropped with jack bean promoted more stable aggregates and increased macroporosity and total porosity. The use of gypsum in maize intercropped with jack bean promoted amelioration of the soil structure. The intercropping system increases the aggregate stability and macroporosity. The intercropping system also offers farmers the opportunity to improve the physical properties of the soil to benefit plant growth. In addition, intercropping maintains soil function, such as aeration, water infiltration and retention, and nutrient availability. In the long term, intercropping systems may be more stable than monocultures.

Key words: Bulk density, calcium sulphate, consortium, cover plants, cropping system, macroporosity, management system, soil sustainability, *Zea mays.*

INTRODUCTION

Inadequate soil management due to intensive machinery use, lack of crop rotation, and low input of organic matter cause the breakdown of soil structure and consequently lead to soil compaction. Soil compaction is characterised by the compression of soil aggregates, resulting in reduced pore volume (Batey, 2009), increased bulk density, decreased porosity (macroporosity), and reduced water infiltration into the soil (Meyles et al., 2006). Soil compaction also increases resistance to erosion, but soil compaction decreases the water storage capacity of the soil.

Soil aggregate stability represents an important attribute for evaluating the soil structure and its physical quality; the evaluation of soil aggregate stability can be performed using indirect measurements that assess the amount of water-stable aggregates (Salton et al., 2008). An enhanced aggregate stability decreases the losses of soil carbon, nitrogen, and phosphorus (Kasper et al., 2009). Soil aggregation occurs when soil particles approach one another due to the action of roots and fungal hyphae (Six et al., 2006), wetting cycles (Bastos et al., 2005), and electrostatic attraction between soil particles. These structures are then stabilised by cementing agents, such as clay, iron oxide, and aluminium (Salton et al., 2008); organic matter (Noellemeyer et al., 2008; Chieza et al., 2013); exudates; mucilage; roots; and polyvalent cations. The aggregation and stability directly affect the plant growth, since these properties regulate the supply of oxygen and water in the soil, in addition to being an important factor in controlling erosion in tropical acidic soils. A promising approach to increasing stability of soil aggregates is the use of polyvalent ions such as calcium (Becher, 2001).

The use of agricultural gypsum affects soil water characteristics (Escudero et al., 2015) by increasing surface soil water permeability, reducing soil compaction, and increasing hydraulic conductivity (Nan et al., 2016), particularly in soils with a high sodium content (Vasconcelos et al., 2013).

Most studies emphasise the indirect action of gypsum that improves soil chemical properties, favouring root growth in deeper soil layers (Serafim et al., 2011) and conditioning soil biological activity. This improved root growth favours greater absorption of water by plants and minimizes the effects of drought on the crops (Pauletti et al., 2014; Zandoná et al., 2015). However, studies conducted by Rosa Junior et al. (2006) showed that the use of gypsum increased the amount of aggregates larger than 1.0 mm in diameter and flocculation of clays, which increased the content of larger-diameter aggregates. Other physical soil properties such as soil bulk density and porosity can be affected by the combination of soil management and gypsum use (Bonini et al., 2012).

The soil management regime affects the aggregate stability, especially aggregates with significant organic carbon content. Therefore, establishing a management system aimed at producing and improving the physicalqualities of the soil is of great interest to the western region of Paraná. One of the alternatives is a consortium of species, and the maize crop is well adapted for this system. The consortium with maize can be with *Brachiaria* or with other species that initially experience reduced growth due to competition. The use of plants intercropped with maize can be an excellent option to increase soil organic content and sometimes to provide nitrogen to the crop (Corrêa et al., 2014). Among the plants of the Fabaceae family that are capable of fixing nitrogen, jack bean (*Canavalia ensiformis*) can be satisfactorily intercropped with maize (Paz et al., 2012) due to its rapid initial growth, even under diffuse light. This protects the soil from erosion and weeds.

In view of the aforementioned discussion, the present study aimed to assess the physical properties of an oxisol soil at different soil depths following intercropping maize with jack bean with additions of agricultural gypsum.

MATERIALS AND METHODS

Description of study site

The experiment was conducted at the "Núcleo de Estações Experimentais of UNIOESTE", Campus de Marechal Cândido Rondon, in southern Brazil. The average altitude of the site of the experiment is 420 m above sea level, and the geographic coordinates are 24°31'S latitude and 54°01'W longitude. The soil of the region was characterised as an oxisol (LVef), with clayey texture (Santos et al., 2013).The local climate was subtropical Cfa according to the Köppen climate classification, with rainfall distributed evenly throughout the year and with hot summers. The average temperatures ranged from 17 to 18°C during the coldest season of the year and from 28 to 29°C during the hottest season. Rainfall in the region ranged from 1600 to 1800 mm, with the wettest months (December to February) ranging from 400 to 500 mm (Caviglione et al., 2000) (Figure 1).

Treatments

The experimental design consisted of completely randomised blocks arranged in a split-plot design with four replications. The main plots consisted of maize intercropped with jack bean or not intercropped, and the subplots consisted of six rates of gypsum (0, 1, 2, 3, 4 and 5 t ha^{-1}). This experimental design was used to facilitate the mechanical sowing of maize (Figure 2). Each subplot

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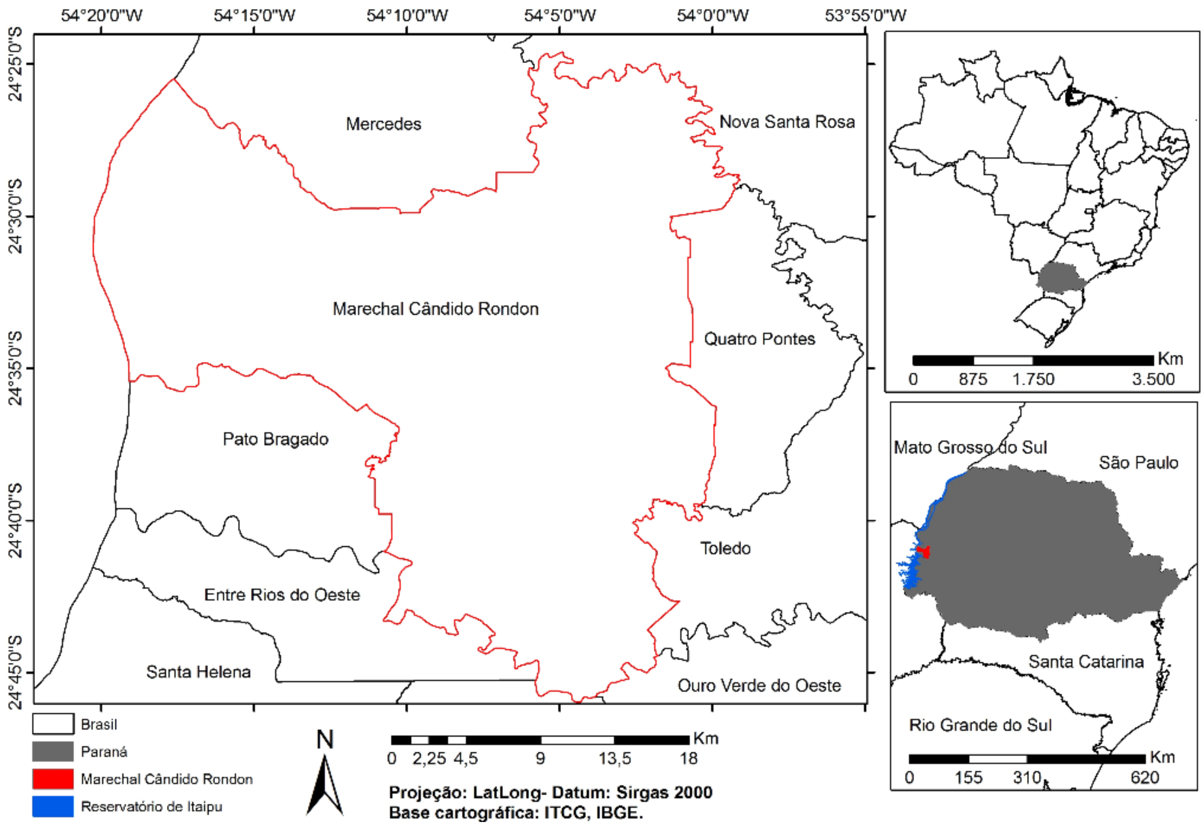

Figure 1. Location of Marechal Cândido Rondon/Paraná/Brazil.

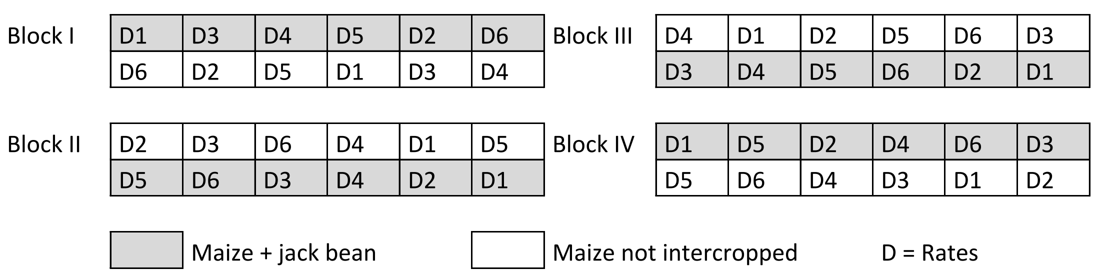

Figure 2. Experimental design.

had a total area of 31.5 m² (4.5 m wide by 7 m long). Thirty days before maize seeding, gypsum was manually applied to the soil surface. Maize hybrid 30F53 was mechanically seeded in a no-till system. The spacing was 0.70 m, with 4.2 seeds sown m^{-1}. The base fertiliser was 300 kg ha^{-1} of a 10-20-20 formulation of N, P_2O_5, and K_2O, respectively. Two days after sowing the maize, jack bean was seeded manually between the maize rows at a rate of 12 kg ha^{-1}.

Soil sampling and analyses of chemical properties

Before the implementation of the experiment, soil samples were collected at a 0.0-0.20-m depth for determination of the chemical properties and particle size characteristics. Chemical analyses were performed according to the methodology proposed by Raij et al. (2001). The results of chemical analysis of the soil are as follows: pH ($CaCl_2$) = 6.05; organic matter = 24.61 g dm^{-3}; P = 2.36 mg dm^{-3}; Ca^{2+} = 6.61 $cmol_c$ dm^{-3}; Mg^{2+} = 1.77 $cmol_c$ dm^{-3}; K^+ = 0.25 $cmol_c$ dm^{-3}; Al^{3+} = 0.00 $cmol_c$ dm^{-3}; $H^+ + Al^{3+}$ = 2.54 $cmol_c$ dm^{-3}; and base saturation (V%) = 77.26%.

Soil sampling and analyses of physical properties

After maize harvest, undisturbed soil samples were collected with

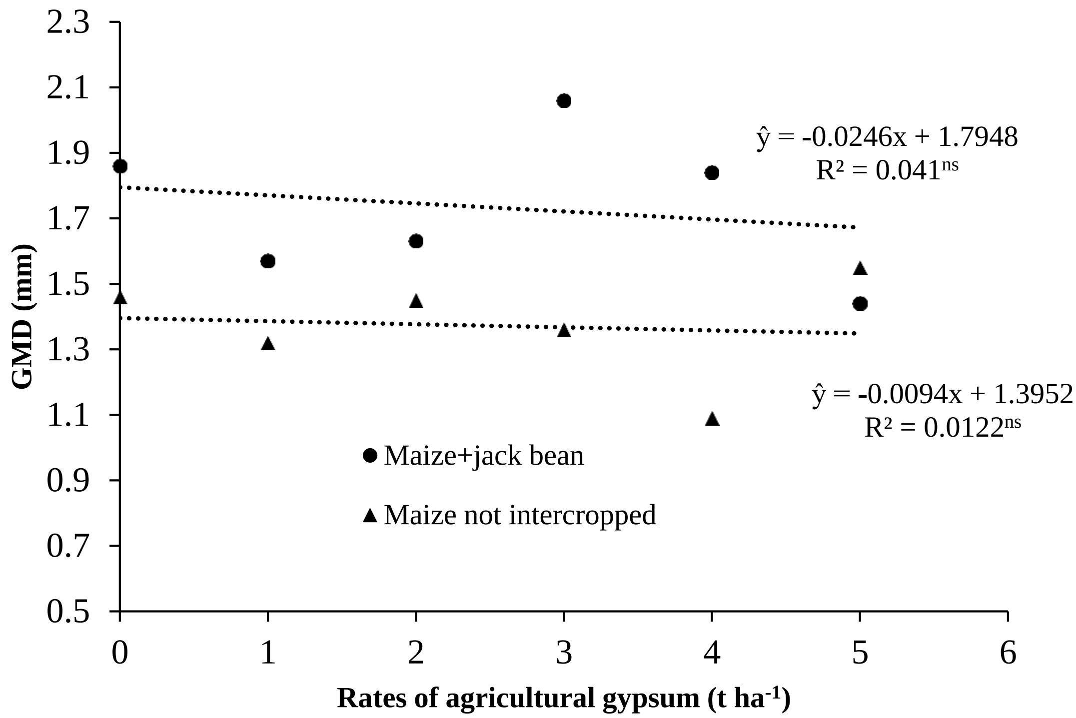

Figure 3. Geometric mean diameter (GMD) of aggregates in oxisol soils under different managements and rates of agricultural gypsum.

metal rings 0.047 m in diameter and 0.025 m in height at 0.0-0.10-, 0.10-0.20-, and 0.20-0.30-m depths for assessments of macroporosity, microporosity, total porosity, and soil bulk density. Initially, these samples were saturated by capillarity in trays until they reached about two-thirds the height of the samples, for 48 h. The total porosity was calculated as saturated soil water content. Quantification of macroporosity values (pores ≥ 50 μm) and microporosity (pores ≤ 50 μm) was obtained by subjecting all of the samples to a pressure of -0.006 MPa using a voltage table. The macropores were estimated as the difference between the saturated soil water content and the soil water content after application of -0.006 MPa of pressure. The soil bulk density was determined by the volumetric ring method, in which undisturbed soil samples were oven-dried at 105°C for 24 h (EMBRAPA, 1997).

Soil sampling and analyses of aggregate stability

Undisturbed soil samples (monoliths) were randomly collected at 0-0.15 and 0.15-0.30-m depths for analysis of aggregate stability. At the time of sampling, the soil consistency was friable. At the laboratory, the sample was passed through a #4 mesh (4.76 mm) sieve and retained on a 2-mm sieve. Plant fragments, other waste, stones, and gravel retained on the sieve were excluded. The analysis of aggregate stability was determined using the method described by Kemper and Chepil (1965), with three replications. In this method, soil aggregates are sieved in water with vertical oscillation for 15 min. Thirty grams of each sample were then placed on the top sieve of a set of sieves with mesh openings of 2.0, 1.0, 0.5, 0.25 and 0.10 mm. The water level of the apparatus was adjusted to the top level of the sieves so that water reached only the bottom of the 2-mm sieve.

Statistical analyses

The effects of treatments were analysed by analysis of variance (ANOVA) using the SAEG statistical program package (Saeg, 2007). For qualitative factors, the Tukey procedure was used where the ANOVA was significant, and regression analysis was used for quantitative variables. Differences were considered statistically significant at a p-value less than 0.05.

RESULTS

Soil aggregate stability

The results obtained from the ANOVA showed effects of the interaction of both gypsum rate and crop management system on the geometric mean diameter (GMD) of soil aggregates. A greater soil aggregate stability occurred in maize intercropped with jack bean. Based on the regression analysis of the rates of agricultural gypsum, there was no adjustment for either equation (Figure 3).

Analysis of the post-effects of the gypsum rates at the two soil depths assessed for aggregate stability showed a significant effect. More stable aggregates were observed at the 0-0.15-m depth with a rate 3 t ha^{-1} (2.06 mm). At this depth, the GMD was, on average, 1.73 mm, while at the 0.15-0.30-m depth the GMD was 1.37 mm; otherwise,

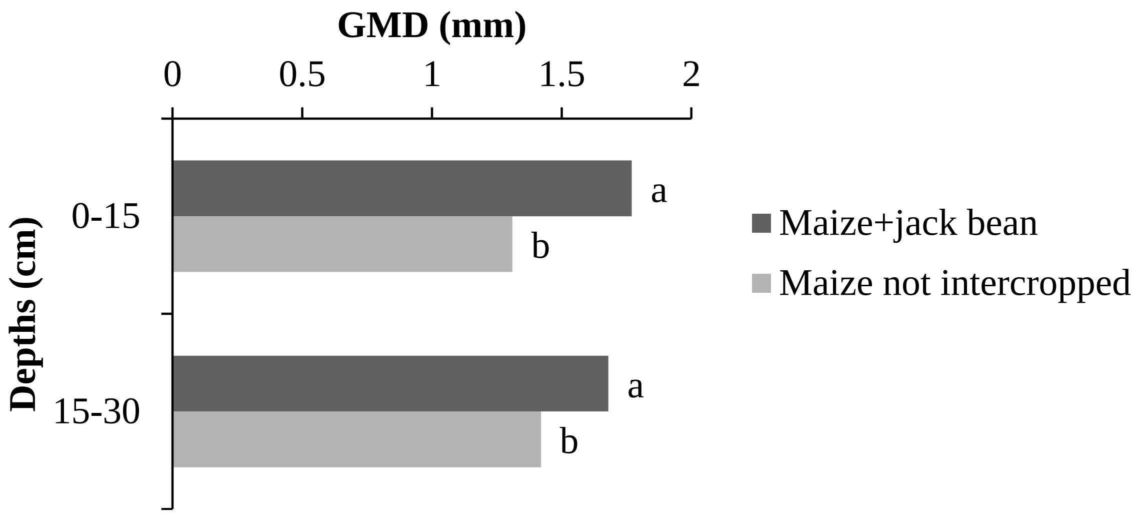

Figure 4. Geometric mean diameter (GMD) of aggregates in oxisol soils under two crop management systems. Bars followed by the same lowercase letter within a soil depth are not significantly different according to the Tukey test (P < 0.05).

Table 1. Average results for microporosity, macroporosity, total porosity, and soil bulk density at different soil depths after maize was intercropped and not intercropped with jack bean.

Depths (cm)	Macroporosity (m^3 m^{-3})			Microporosity (m^3 m^{-3})		
	Maize + Jack bean	Maize not intercropped	Average	Maize + Jack bean	Maize not intercropped	Average
0-0.10	0.130^{Aa}	0.053^{Ab}	0.09^{A}	0.445^{ns}	0.462^{ns}	0.45^{ns}
0.10-0.20	0.067^{Bb}	0.059^{Aa}	0.06^{B}	0.441	0.477	0.46
0.20-0.30	0.064^{Bb}	0.041^{Bb}	0.05^{B}	0.440	0.465	0.48
Average	**0.087^{a}**	**0.051^{b}**		**0.442^{a}**	**0.468^{a}**	
Depths	Total porosity (m^3m^{-3})			Bulk density (Mgm^{-3})		
0-0.10	0.575^{Aa}	0.515^{Ab}	0.54^{ns}	1.31^{ns}	1.34^{ns}	1.33^{ns}
0.10-0.20	0.508^{Bb}	0.536^{Aa}	0.52	1.36	1.43	1.40
0.20-0.30	0.504^{Bb}	0.506^{Ab}	0.53	1.40	1.39	1.40
Average	**0.53^{a}**	**0.52^{a}**		**1.36^{a}**	**1.39^{a}**	

Means followed by the same lowercase letters on the same line and the same uppercase

at the surface layer, aggregation increased by 21%. Regardless of the gypsum rate and crop management used, most organic matter accumulation occurred at the soil surface layer (Figure 3).

Figure 4 shows the average results for the GMD of the aggregates in the two crop management systems and depths. At the two assessed depths, there was greater aggregate stability in the crop system of maize intercropped with jack bean; the reported increase was 26% at the 0-0.15-m depth and 15% at the 0.15-0.30-m depth.

The greater root growth observed in maize intercropped with jack bean contributed to this result, as the two crops formed a tangled root system that involved soil particles, increasing the soil aggregation and stability.

Soil physical properties

Regarding macroporosity, microporosity, total porosity, and soil bulk density, the results obtained showed no effect of gypsum rate as well as of the interaction between gypsum rate and management system (Table 1). When the effect of the management alone was evaluated, without the interaction between management and depth, a significant effect was found for macroporosity and microporosity, but there were no effects on total porosity or soil bulk density (Table 1). The maize intercropped with jack bean showed higher macroporosity (0.087 m^3 m^{-3}) compared to maize not intercropped (0.051 m^3 m^{-3}); otherwise, in this system, macroporosity was 41% higher than in maize not intercropped. This result is related to the greater stability of the aggregates (GMD) found in this treatment, as shown in Figure 4.

Assessment of the interaction between the crop management system and depth showed that the average macroporosity (0.09 m^3 m^{-3}) and total porosity (0.57 m^3 m^{-3}) were higher at the 0-0.10-m depth. At this depth, the macroporosity was 63% higher than the average value of the other depths, and total porosity was higher, reaching 12% (Table 1).

DISCUSSION

Soil aggregate stability

The greater stability observed in the area planted with maize intercropped with jack bean, unique to the soil surface layer, occurred because in this system there was more input to the organic matter in the soil, such as leaves, plant roots, root exudates, dissolved organic matter, and bioturbation. In previous studies (Onweremadu et al., 2007; Shaoshan et al., 2010; Six and Paustian, 2014), it has been shown that organic matter influences the soil structure and stability by binding soil mineral particles.

The improved soil aggregation resulting from the accumulation of organic matter in the soil surface layer occurs due to the high specific surface area and cation exchange capacity of this layer. This allows more electrostatic bonds between soil particles, facilitating the formation of microaggregates (0.20 to 0.25 mm) and macroaggregates (> 0.25 mm) (Six et al., 2004). These findings corroborate the results obtained by Silva et al. (2013), who reported higher aggregation at the 0.15-m depth with gypsum rates of 28 and 56 t ha^{-1}. According to those authors, this higher aggregation was explained by the higher concentration of divalent cations (Ca^{+2}) that promoted flocculation of clays.

Root growth also affects soil structure. As roots grow, they compress the soil near the growth zone, which forces clay particles together, thus favouring aggregate formation (Brandão and Silva, 2012). The roots release exudates and mucilaginous materials near the rhizosphere, which directly or indirectly affect soil structure. In addition, fungal mycorrhizae is often associated with the root system, resulting in greater aggregation. Finally, when roots decay, the decomposition products contribute to the soil aggregation and aggregate stability.

Gypsum is the most commonly known and used calcium compound for studying the amelioration of soil structure (Gupta and Khan, 2015). However, in this study, only the use of gypsum did not promote amelioration of the stability of aggregates. These results are corroborated by Bennett et al. (2014), who found no effect of gypsum rates on the stability of soil aggregates.

When the agricultural gypsum was applied together in maize intercropped with jack beans, the aggregate stability increased. This increase occurred because the root systems promote an input of large amounts of organic matter in the soil, which increases the physico-chemical bonding between the organic colloids, calcium, and soil minerals (Norambuena et al., 2014).

The results concerning the use of agricultural gypsum are contradictory in this study. Sometimes the use of lower rate agricultural gypsum caused favourable effects on soil structure, while higher rates caused unfavourable effects. Therefore, in the regression analysis, there was no adjustment for any equation.

Soil physical properties

The previously mentioned finding was corroborated by Bertollo (2014), who found no significant differences in soil chemical properties in a study with gypsum and limestone rates in a no-till system. Results that diverged from the findings of this experiment were observed by Müller et al. (2012), who reported significant differences in macroporosity and microporosity at the 0-0.075-m depth with the use of agricultural gypsum at a rate up to 12 t ha^{-1}; however, these authors also did not find any effect on total porosity and soil bulk density.

This increase in macroporosity was related to the addition of organic matter by plants in the soil surface layer as well as the large surface area of the roots of most plants. The labile organic matter affects aggregation and therefore is the physical property most affected by soil management.

The average macroporosity values were found to be below the critical value of 0.10 m^3 m^{-3}. Soil macroporosity less than this value affects plant growth due to the decreased availability of oxygen, which reduces the supply of oxygen for respiration to the roots and thus the generation of energy for mineral nutrient absorption. The average values for soil bulk density were below the critical values for crop growth in clayey soils of 1.45 Mg m^{-3} (Reichert et al., 2009).

Corroborating these findings, Lanzanova et al. (2010), in a study of the physical properties of an Argisol soil following cultivation of different green fertilisers in rotation with soybean; did not find a significant difference in macroporosity, microporosity, total porosity, or soil bulk density. Before the 16 years of cultivation with green fertilisers in rotation, differences only in the macroporosity and soil bulk density in the area of uncovered soil were found.

Conclusions

The use of agricultural gypsum promoted greater aggregate stability at the 0–0.15-m depth and did not affect macroporosity, microporosity, porosity, or soil bulk density. More stable aggregates result in higher soil resistance to erosion and better aeration. The use of intercropping systems promotes improvements in aggregate stability, soil macroporosity, and total porosity, and intercropping optimises the use of land. The intercropping system offers farmers the opportunity to improve physical properties of the soil that promote plant growth and to maintain soil function, such as aeration, water infiltration and retention, and nutrient availability. In the long term, intercropping systems can be more stable than monocultures.

CONFLICTS OF INTERESTS

The authors have not declared any conflict of interests.

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