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Actual and Relative Soil Air Permeability as Soil Physical Quality Index

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Abstract

Developing indices to evaluate soil physical quality can facilitate diagnosis and decision-making. In this context, intrinsic soil air permeability (K_{air}) is a physical parameter very sensitive to structural changes due to soil management. However, it is important to establish a standard K_{air}, considering a reference soil physical state. Thus, the present study proposes to create an index called relative soil air permeability (K_{airr}), taking as reference the physical state of maximum bulk density, obtained by normal Proctor test. K_{airr} is the ratio between compacted soil air permeability (K_{airc}) and actual soil air permeability (K_{air}). K_{airr} was evaluated using disturbed and undisturbed samples of a *Latossolo* and a *Planossolo*. The experimental design was completely randomized, with four treatments (T_1-*Latossolo* 0-0.1 m; T_2-*Latossolo* 0.1-0.2 m; T_3-*Planossolo* 0-0.1 m and T_4-*Planossolo* 0.1-0.2 m) and eight replicates. K_{airr} was equal to 0.1032 and 0.3547 in the *Latossolo* and to 0.4115 and 0.1923 in the *Planossolo*, in the 0-0.1 and 0.1-0.2 m layers, respectively. These characteristic values observed in both soils and layers are due to the management adopted in the area. In *Latossolo*, the use of medium harrow has made the 0.1-0.2 m layer more restrictive to air movement, whereas the *Planossolo* showed lower values of relative soil air permeability in the 0-0.1 m layer due to animal grazing, which has greater impact on the superficial portion of the soil.

Keywords: aeration, degradation, structure

1. Introduction

Anthropic actions in agricultural production systems can cause alterations in soil physical characteristics, which may vary in magnitude depending on the adopted management, causing positive or negative effects on the agroecosystem in which the activity is being conducted. Nevertheless, most agricultural activities developed by mankind have high potential for degradation of soil structure, which in the long term may cause deleterious effect on the maintenance of its productive viability.

Aiming at safe management of natural resources, quantitative analyses and interpretation of physical and physical-hydraulic attributes, which in turn allow measuring the main changes caused in soil quality, are fundamental (Stefanoski, Santos, Marchão, Petter, & Pacheco, 2013). In this perspective, the importance of quantifying soil air permeability (K_{air}) is due to the need for characterizing the porous space and identifying changes in soil structure, caused by management practices (Blackwell et al., 1990; Cavalieri et al., 2009; Schjonning & Koppelgaard, 2017).

Soil air permeability is a parameter that allows establishing correlations with other soil attributes which are difficult to determine, such as hydraulic conductivity (Loll, Moldrup, Schjonning, & Riley, 1999; Rahmati & Neyshaboury, 2016), which indicates its versatility in terms of capacity to provide information on soil structural state, so as to allow reviewing actions, evaluating management strategies and correcting possible mistakes during the production process. Additionally, it allows obtaining data for environmental studies on the extraction of vapor of contaminants present in porous media of this nature (Fahran, Holsen, & Budiman, 2001; Shi, Wu, Ai, & Zhang, 2018).

Pore-size distribution, tortuosity and connectivity are the characteristics of the porous space geometry that most influence the transport of fluids in soil (Iversen, Moldrup, Schjønning, & Loll, 2001; Tuli, Hopmans, Rolston, & Moldrup, 2005; Chief, Ferré, & Nijssen, 2006), whereas viscosity is the relevant attribute which characterizes the studied fluid (Libardi, 2012). Thus, soils with high K_{air} have greater capacity to exchange gases with the atmosphere, *i.e.*, they have better aeration (Menezes et al., 2018). This is important because higher relative concentration of CO_2 in soil, to the detriment of O_2, due to metabolic activities of roots and soil biota, may compromise the yields of agricultural crops, when air renewal in soil is limited.

Soil structural degradation, in general, reduces water and air flows so that agricultural crops are not able to express their genetic potential. In this context, intrinsic permeability is the inherent soil attribute (Libardi, 2012) which translates the capacity to transport air through the interconnected air-filled pores (Chief et al., 2006). However, in Brazil, there is scarce information on K_{air}, particularly for methodological reasons, associated with both measurement methods and equipment availability (Silva, Leão, Tormena, & Gonçalves, 2009; Rodrigues, Silva, Giarola, & Rosa, 2011; Silveira, Brito, Mota, Moraes, & Libardi, 2011; Guedes Filho, Silva, Giarola, & Tormena, 2015; Jesus, Brito, Silva, Teixeira, & Carvalho, 2017).

Different indicators of soil physical quality have been used to measure management effects on soil structural aspects (Klein, Baseggion, & Madalosso, 2009; Loss, Pereira, Giacomo, Perin, & Anjos, 2011; Moreira et al., 2014; Martínez et al., 2016; Brown, Barbosa, Bertoll, Mafral, & Muzekal, 2018). Nonetheless, a common characteristic among these indicators is that, in general, they are direct or indirect expressions of pore volume and/or function of soil porous space (Reynolds, Drury, Tan, Fox, & Yang, 2009).

Some indices have been created to establish correlations with other soil attributes, such as the index based on the ratio between soil air conductivity and aeration porosity, determined with samples equilibrated at 5.0 kPa tension (Groenevelt, Kay, & Grant, 1984), the index of structural organization, which is similar to the one previously mentioned, but uses soil air permeability instead of soil air conductivity (Blackwell et al., 1990) and the pore continuity index, which relates K_{air} with aeration porosity, using the Kozeny-Carman model (Ahuja, Naney, Green, & Nielsen, 1984).

The existing soil physical quality indicators are generated for specific situations, requiring higher number of studies for validation and reliable application, which constitutes an opportunity to develop new soil physical quality indicators (Stefanoski et al., 2013). Thus, creating an index which allows more efficient distinction of soil physical quality is fundamental for decision-making regarding soil management.

The present study aimed to develop a soil physical quality index, which is based on intrinsic soil air permeability at two physical states, in order to allow a more efficient distinction of soil physical quality. This index has been called relative soil air permeability.

2. Methods

2.1 Location of Soils

The *Latossolo* and *Planossolo* evaluated are located in the experimental area of the Federal Institute of Education, Science and Technology (IFBAIANO), Guanambi Campus (geographic coordinates: 14º13′30″ S, 42º46′53″ W and altitude of 525 m), which is used for cultivation of vegetables, annual crops, fruit crops and grasses, besides scientific experiments. Soil samples were collected in the areas with agricultural systems, in order to assess their structural physical quality and validate the proposed index.

2.2 Soil Air Permeability

Air movement in soil was assessed according to the methodology developed by Kirkham (1946), using undisturbed soil sample to measure the intrinsic soil air permeability, which will be referred to herein only as soil air permeability (Silveira et al., 2011).

Air pressure in the cylinder at the beginning of each measurement was equilibrated at 1 kPa (1 kPa above local atmospheric pressure), causing air flow to be laminar and not lead to significant modifications in the water films on the surface of soil aggregates.

The K_{air} determination model, through the decreasing pressure method, was based on the Darcy's model, which requires laminar flow regime and, in the case of gas flow, an isothermal process. Thus, the reduction of internal pressure (manometric pressure) in the air cylinder was given by the following Equation (1):

$$\ln P_{a1} - \ln P_{a2} = \frac{K_{air} A P_{atm}}{LnV} \left(t_2 - t_1\right) \quad (1)$$

where P_{a1} and P_{a2} are the manometric pressures (above atmospheric pressure) at times t_1 and t_2, respectively; K_{air} is soil air permeability; A is the cross-section area of the undisturbed soil sample; P_{atm} is the local atmospheric pressure; L is soil sample height; n is air viscosity; and V is the air cylinder volume.

By referring to K_{air}APatm/LnV as S and knowing that this term represents the angular coefficient of the linear regression of pressure (Ln pressure) as a function of time, Equation (1) can be rewritten as:

$$\ln P_{a2} = -St + \ln P_{a1} \quad (2)$$

Hence, the permeability (K_{air}) can be calculated from the regression $LnP_a\ x\ t$, which allows obtaining the angular coefficient (*S*), and from it the soil air permeability:

$$K_{air} = \left(\frac{LnV}{AP_{atm}}\right) \times S \quad (3)$$

Soil air permeability was measured in undisturbed soil samples collected in the 0-0.1 m and 0.1-0.2 m layers, for both soils evaluated, in eight replicates. These samples were collected (soil pits) using Uhland-type sampler and volumetric cylinder with the following dimensions: 0.047 m diameter and 0.05 m height. For transportation to the laboratory, these undisturbed samples were wrapped in non-porous plastic film and placed in plastic box, covered on the inside with bubble wrap to avoid alterations during the transportation.

In the laboratory, the samples were properly prepared by removing excess soil, to make soil volume equal to cylinder volume, and placing the bottom part of the volumetric cylinder on a piece of blotting paper with the same diameter, to avoid soil losses and improve the contact between the sample and the porous surface of the tension table, during the process of stabilization at the tensions. After preparation, the samples were saturated using a container of greater height than the cylinders, gradually filled with deionized water up to ¾ of cylinder height, in order to expel all the air from soil pores. The samples were left under the saturation process for 24 h.

The samples were equilibrated at 6.0 kPa tension on a tension table. As soil air permeability is hampered by excess water or by degraded or even massive soil structure, which may result from a process of compaction, the choice of each tension becomes more important for the evaluation of this soil attribute. After equilibrium, the samples were weighed on precision scale, the blotting paper was removed with a stiletto, and the side of the soil sample in contact with the porous surface was slightly scarified.

The sample was then attached to the permeameter to determine soil air permeability. The permeameter consists of three parts: 1) injection compartment; 2) pressurized air cylinder (0.031 m^3 volume) and 3) data acquisition and processing system. The acquisition system is composed of an electronic module and the computer program PermeAR 1.0. The electronic module of the acquisition system consists of a differential pressure transducer (MPXV5004DP model, Freescale) with operating range from 0 to 3.92 kPa, sensitivity of 1.0 mV Pa^{-1} and accuracy of ±1.5 % of its full scale voltage. All sensors were connected to a microcomputer by a microcontroller (Basic Step M8 model, Tato ind.), which has a 10-bit (eight channels) internal A/D converter and internal voltage reference (Silveira et al., 2011).

2.3 Relative Soil Air Permeability

Relative soil air permeability (K_{airr}) was measured in soil samples in the worst physical condition. Disturbed soil samples were collected in the same layers where air permeability was determined and sieved through 4-mm-mesh sieve for the Proctor normal test (Klein, Madalosso, & Baseggio, 2013), which aimed to produce soil samples at maximum compaction.

In samples with maximum bulk density (sample compacted in normal Proctor cylinder), subsamples were collected with the aid of a hydraulic press, using volumetric cylinders with the same dimensions as those used to measure soil air permeability.

The saturation process of these samples ended when a film of water was observed on the surface. After that, the samples were equilibrated in Haines funnels (6 kPa tension) and used in the determination of soil air permeability. After equilibrium, the samples were weighed and attached to the permeameter, where compacted soil air permeability (K_{airc}) was determined.

With the values of soil air permeability for both physical condition (actual and compacted soil), the relative soil air permeability was calculated according to Equation (4):

$$K_{airr} = \frac{K_{airc}}{K_{air}} \quad (4)$$

Regarding the interpretation of results, after calculating the relationship between compacted soil air permeability (K_{airc}) and actual soil air permeability (K_{air}), the relative soil air permeability is calculated (K_{airr}): if the value is close to one, the soil is degraded; if K_{airr} is closer to zero, the soil is in good physical quality.

2.4 Particle size, Bulk Density and Pore-Size Distribution of the Soils

Particle-size analysis was carried out by the pipette method (Gee & Or, 2002) in the layers of 0-0.1 m and 0.1-0.2 m. However, a few variations recommended by the Soil Physics Laboratory of the IFBAIANO/Guanambi Campus were adopted in the procedure, such as the use of a dispersant composed of sodium hydroxide (4 g L^{-1}) and sodium hexametaphosphate (10 g L^{-1}) solutions, according to the methodology of IAC (Camargo, Moniz, Jorge, & Valadares, 1986).

Bulk density was determined by the volumetric cylinder method. Soil samples used for permeability determination were also used for bulk density determination. For that, the heights and diameters of all rings were previously measured, in three replicates, using a digital caliper. The masses of the piece of blotting paper and volumetric cylinder were also estimated, in order to be subtracted during the soil sample mass calculation.

For soil dry mass determination, the samples were placed in the oven (105 °C, for 24 h) and weighed on precision scale. Bulk density was then calculated based on the mean volume of the volumetric cylinder, obtained from its mean height and diameter, and mass of dry soil.

2.5 Data Analysis

The experimental design was completely randomized, with four treatments (T_1-*Latossolo Vermelho Amarelo* in the 0-0.1 m layer; T_2-*Latossolo Vermelho Amarelo* in the 0.1-0.2 m layer; T_3-*Planossolo* in the 0-0.1 m layer; T_4-*Planossolo* in the 0.1-0.2 m layer) and eight replicates, totaling 32 undisturbed soil samples. Four soil samples, with mass around 20 kg, were also collected to construct compaction curves and particle-size graphs.

The data were initially subjected to exploratory analysis in R environment (R development core team, 2018), through the package Mass (Brian et al., 2018). Then, analysis of variance was carried out and means were compared by Tukey and Duncan tests, at 5% probability level, through the package ExpDes.pt (Ferreira, Cavalcanti & Nogueira, 2018).

3. Results and Discussion

In the compaction curves for the two soils analyzed in the 0-0.1 m layer (Figure 1), maximum density was equal to 1,955 kg m^{-3} in the *Latossolo* (Figure 1A), whereas a lower maximum density (1,845 kg m^{-3}) was found in the *Planossolo* (Figure 1B). This is due to the pedogenetic phenomenon of clay illuviation, which leads to higher presence of clay in the subsurface layers of the *Planossolo* (Oliveira, Ribeiro, Ferraz, Ferreira, & Mermut, 2004), and this can be noted in the higher clay content in the 0-0.2 m layer, about 18 % (Figure 2), especially in the B horizon, originated from the surface layer. Similar results were observed in a *Planossolo* located in the semi-arid region of Bahia, where particle-size analyses showed high sand contents in the entire profile, with increase in clay content in subsurface (Santos, Santos, Souza, Bahia, & Rodrigues, 2013).

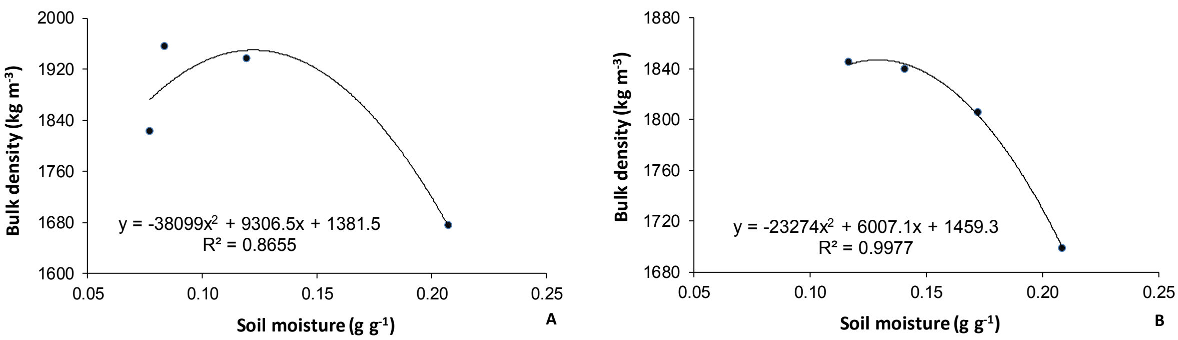

Figure 1. Compaction curves of the *Latossolo Vermelho Amarelo* (A) and *Planossolo* (B) in the 0-0.1 m layer

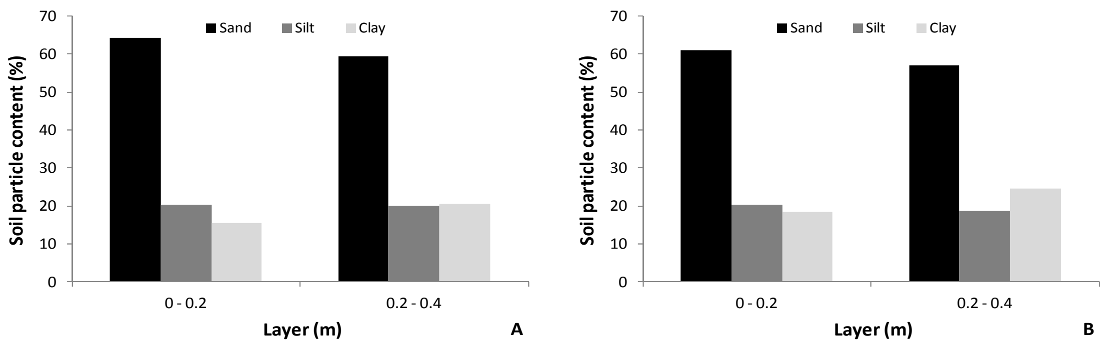

Figure 2. Percentages of sand, silt and clay in the *Latossolo Vermelho Amarelo* (A) and *Planossolo* (B)

The differences between the compaction curves of the two soils analyzed demonstrate that each type of soil has a maximum bulk density and a specific optimal moisture of compaction. Using these values for other soil classes may lead to errors in the determination of ideal moisture for management or evaluation of the current compaction state of an area. However, studying different types of soil allows obtaining reference values (Luciano, Albuquerque, Costa, Batistella, & Armling, 2012).

There was an accentuated reduction of macroporosity in the 0.1-0.2 m layer of the *Latossolo* (Figure 3A), which differed statistically from the other layers analyzed. This considerably affects bulk density when the soil is compacted, due to a more cohesive arrangement, caused by the presence of an intermediate silt content and increase in clay concentration, which may become a limiting factor for crop development.

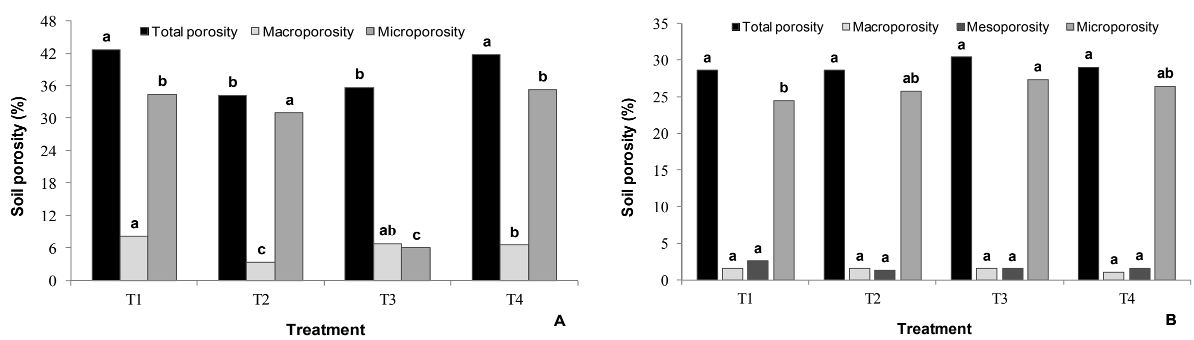

Figure 3. Porosity of the *Latossolo* in the layers of 0-0.1 m (T1) and 0.1-0.2 m (T2) and *Planossolo* in the layers of 0-0.1 m (T3) and 0.1-0.2 m (T4) in their natural state (A) and in the worst state of compaction (B). Means were compared by Tukey test at 5% probability level

The pressure exerted by the normal Proctor test drastically affects the porous space geometry (Figure 3B), modifying pore-size distribution. Macropores and mesopores were the ones which decreased the most, whereas micropores increased considerably, causing restrictions to air flow.

Reduction in aeration porosity, combined with other parameters, has direct impact on soil air permeability, causing its reduction (Tang, Cui, Richard, & Défossez, 2011). Thus, the *Planossolo* in the 0-0.1 m layer showed the highest quantity of micropores, differing only from the *Latossolo* in the 0-0.1 m layer, which can be explained by the low clay content in this layer, since soil texture has influence on porosity (Dexter, 2004). In relation to total porosity, there was no statistical difference for any of the layers in the soils evaluated, as also observed for macroporosity and mesoporosity.

Therefore, when the soil is subjected to a pressure there is a change in the state of its pores, and macroporosity is the first parameter to undergo alterations, decreasing linearly as the pressure increases (Stone, Guimarães, & Moreira, 2002; Silva, Albuquerque, & Costa, 2014).

The percentage of micropores was statistically equal in both layers of the *Latossolo*, due to its uniformity, and of the *Planossolo*, despite the small increment in micropore percentage in the 0.1-0.2 m layer, compared to 0-0.1 m (Figure 3B).

Regarding the bulk density of the soils in their natural state, the 0.1-0.2 m layer of the *Latossolo* had the highest value (Figure 4). This is particularly due to the soil management adopted in the area, where medium harrow has been used at the same depth, which allowed the formation of "harrow pan". Such increase of density due to management is directly linked to the reduction of macroporosity in subsurface layers (Viana, Batista, Tormena, Costa, & Inoue, 2011), which corroborates the fact that the reduction in macroporosity is inversely proportional to the increase in soil density.

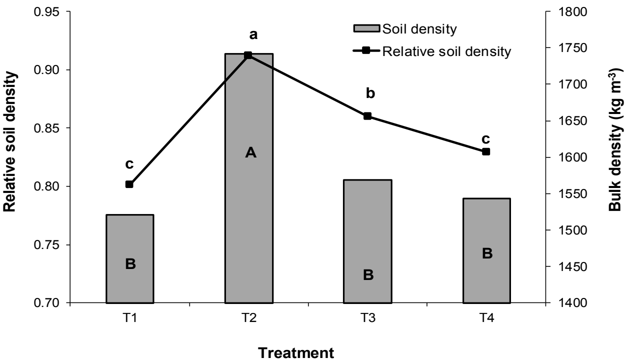

Figure 4. Relative soil density and bulk density in the natural state of the *Latossolo* in the layers of 0-0.1 m (T1) and 0.1-0.2 m (T2) and of the *Planossolo* in the layers of 0-0.1 m (T3) and 0.1-0.2 m (T4). Means were compared by Tukey test at 5% probability level

The relative soil density (Figure 4), for being a ratio between soil density in the worst state of compaction and soil density in the natural state, clearly reflects the variations of soil density in the natural state (Marcolin & Klein, 2011). It can be noted that soil density in the natural state, when high, may limit root development and the more degraded the soil structure, the more the relative soil density will approach the value 1, which reflects the worst density possible. Thus, it can be noted that the *Latossolo* in the 0.1-0.2 m layer, due to the high density caused by soil tillage management, had also a high relative density, above 0.9, statistically differing from the other layers, hence reflecting a critical state of its structure.

The increase in soil density to high levels may lead to reduction in crop development and yield due to the restriction to root system growth. In a study with jatropha, its shoots were limited from the density of 1,260 kg m^{-3} in a clay-textured *Latossolo*, with reduction in the number of leaves, leaf area and shoot dry matter production (Ohland et al., 2014).

The relative density, therefore, serves as a parameter to assist in the decision-making regarding the intervention on soil physical structure. For that, measures of control of soil physical quality must be taken considering the warning values of soil density and critical soil density, based on either least limiting water range (Guimarães, Tormena, Blainski, & Fidalski, 2013) or air permeability (Jesus et al., 2017).

Although the *Latossolo* in the 0-0.1 m layer was statistically equal to the *Planossolo* in the 0-0.1 m and 0.1-0.2 m layers with respect to density, their values of permeability differed, both in the natural state. In the *Latossolo*, the use of medium harrow improved soil density in the surface layer, but compacted the 0.1-0.2 m layer and this influenced air permeability (Figure 5).

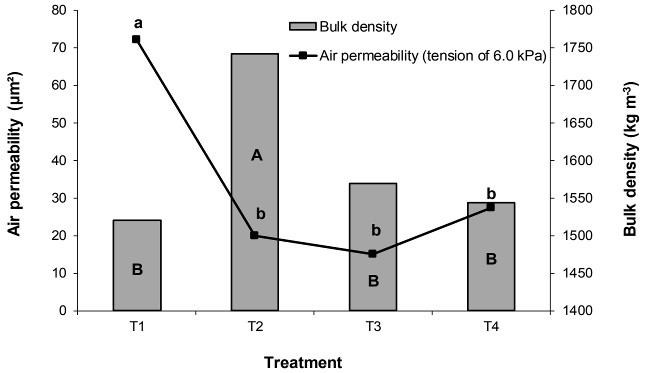

Figure 5. Bulk density and air permeability in the natural state of the *Latossolo* in the layers of 0-0.1 m (T1) and 0.1-0.2 m (T2) and of the *Planossolo* in the layers of 0-0.1 m (T3) and 0.1-0.2 m (T4). Means were compared by Tukey test at 5% probability level

In the *Planossolo*, animal trampling had major impact on bulk density, especially in the surface layer. Increased clay contents in the soil profile combined with heavy machinery traffic on the soil led to reductions in soil air permeability values (Chen, Weil, & Hill, 2014). Kuncoro, Koga, Satta, and Muto (2014) also noted that the increase in compaction led to a significant reduction in soil air permeability, probably attributed to a reduced volume of macropores.

Soil compaction, indicated by bulk density, caused drastic reduction in soil air permeability, demonstrating the importance of adopting good agricultural practices, although it is important to use other attributes such as total porosity, macroporosity and microporosity to help interpret the results. Soil air permeability depends basically on two factors, moisture content and bulk density, and both influence the geometry and continuity of the soil pore system (Silva et al., 2009).

The air permeability of the compacted *Latossolo* (normal Proctor test) in the 0-0.1 m layer was higher (35.25%) than that in the 0.1-0.2 m layer, since the compacted soil density in the latter was slightly higher than in the former (Figure 6). Highest air permeability was observed in the *Latossolo* in the 0-0.1 m layer, statistically differing from the surface layer of the *Planossolo*, which is due to the higher sand content of this layer (64.3%).

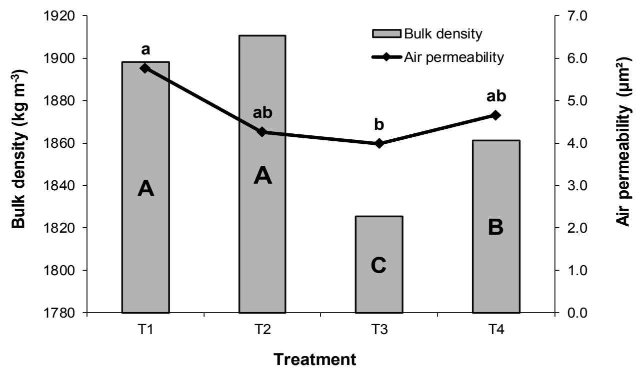

Figure 6. Bulk density and air permeability under maximum compaction of the *Latossolo* in the layers of 0-0.1 m (T1) and 0.1-0.2 m (T2) and of the *Planossolo* in the layers of 0-0.1 m (T3) and 0.1-0.2 m (T4). Means were compared by Duncan test at 5% probability level

Such inverse relationship between bulk density and air permeability is also found in soils that have B_t horizons with cohesive character, which are less functional than those having B_t horizons without cohesive character, with lower air permeability, pore length and connectivity. Regardless of how well the pores are oriented, the highest percentage of blocked pores, *i.e.*, those which do not contribute to air flow, occurs in horizons with cohesive character (Menezes et al., 2018).

The relative soil air permeability (K_{airr}) of the *Latossolo* in the layers of 0-0.1 m and 0.1-0.2 m was equal to 0.1032 and 0.3547, respectively. In the *Planossolo*, the values were 0.4115 and 0.1923 in the layers of 0-0.1 m and 0.1-0.2 m, respectively (Figure 7). Thus, a relative soil air permeability of 0.3 can be considered as critical, and above this value the soil has physical restrictions, with great possibility of effects on the yields of agricultural crops.

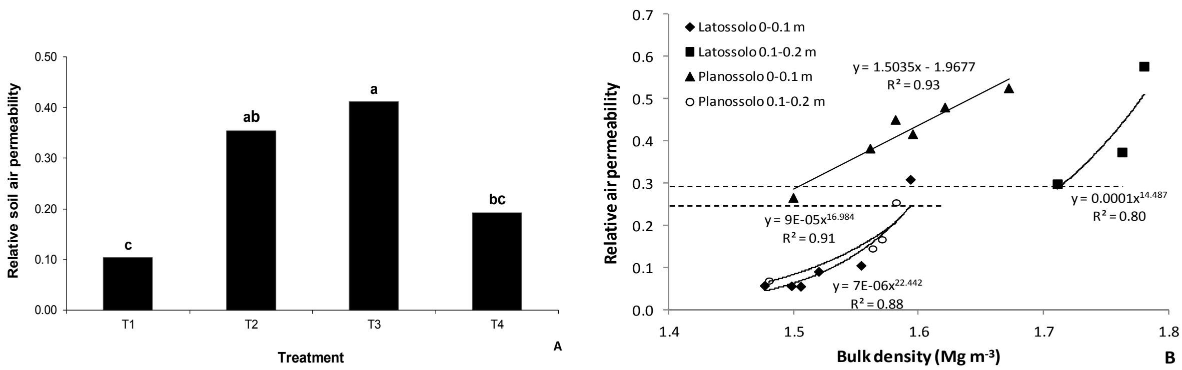

Figure 7. Relative air permeability of the *Latossolo* and *Planossolo* in the layers of 0-0.1 m (T1 and T3, respectively) and 0.1-0.2 m (T2 and T4, respectively), with means compared by Tukey test at 5% probability level (A) and regression between relative soil air permeability and bulk density (B)

4. Conclusions

The *Latossolo* in the 0-0.1 m layer and the *Planossolo* in the 0.1-0.2 m layer showed values of relative soil air permeability close to 0.10 and 0.20, respectively, which indicate good physical quality.

The *Latossolo* in the 0.1-0.2 m layer and the *Planossolo* in the 0-0.1 m layer showed high values of relative soil air permeability, indicating that the value of 0.3 is critical for root development in more sensitive crops and may compromise the yields of agricultural crops.

The types of soil and layers are separated according to their intrinsic characteristics and to the different managements of the areas, which is explained by the differences between their physical attributes.

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