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# Impacts of land-use and management systems on organic carbon and water-physical properties of a Latossolo Amarelo (Oxisol)[1]

# Impactos de sistemas de uso e manejo no carbono orgânico e atributos físico-hídricos de um Latossolo Amarelo

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## Abstract

The Cerrado biome has outstanding territorial relevance in the state of Piauí, in which weather conditions, relief and favorable soil has made this region one reference in food production. This study focused to evaluate the effects of different land uses, management systems and their respective terms on organic carbon content and physical properties of a Latossolo Amarelo (Oxisol) in the Southwestern Piauí state. The study was performed in the city of Uruçuí, situated in the southwestern Piauí state. We assessed nine farming areas with different backgrounds regarding land-use, management system and run time. The treatments consisted of areas under no-till for 3 and 6 years (NT3 and NT6), under pasture for 2 and 5 years (PA2 and PA6), under eucalyptus plantation for six and twelve years (EU6 and EU12), under conventional tillage for two and 8 years (CT2 and CT8) and under native Cerrado (NC), which represented a reference condition. Conversion of the native Cerrado into no-till and grazing areas increased soil organic carbon content over time.

**Key words**: Eucalyptus. Conventional planting. Grazing. Tillage. Soil water.

## Resumo

O bioma Cerrado tem notável relevância territorial no estado do Piauí, e devido as suas características de clima, relevo e solos favoráveis tem tornado essa região uma referência na produção de alimentos no estado. A partir desse estudo se objetivou avaliar as implicações dos diferentes sistemas de uso, manejo e tempo de adoção nos teores de carbono orgânico e em atributos físicos do solo em um Latossolo Amarelo da região Sudoeste do estado do Piauí. O estudo foi realizado no município de Uruçuí, locado na região sudoeste do estado do Piauí. Neste estudo foram avaliados nove sistemas de produção com diferentes históricos de uso, manejo e tempo de adoção disposto da seguinte forma: áreas sob sistema de plantio direto (PD3 e PD9, respectivamente com três e nove anos de cultivo), áreas sob pastagem (PA2 e PA6, respectivamente com dois e seis anos de cultivo), áreas sob plantio de eucalipto (EU6 e EU12, respectivamente com seis e doze anos de cultivo), áreas sob sistema de preparo convencional

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(PC2 e PC8, respectivamente com dois e oito anos de cultivo) e Cerrado nativo (CN), representando uma condição de referência. A conversão do Cerrado nativo em plantio direto e pastagem ocasionou evolução no conteúdo de carbono orgânico com o passar do tempo.

**Palavras-chave**: Água no solo. Alteração estrutural. Eucalipto. Pastagem. Plantio convencional. Plantio direto.

## Introduction

The Cerrado biome covers 46% of the Piauí state area which corresponds to approximately 11.8 million hectares (AGUIAR; MONTEIRO, 2005). Given the climate, relief and favorable soil properties for food production, it is expected a large increase in local population purchasing power with the advancement of agriculture in this region, thereby improving the Human Development Index (HDI) of this state, which is considered one of the lowest in Brazil (IBGE, 2013).

During the 2013/14 crop season, areas grown with soybeans, corn and rice reached respectively 630, 404 and 177 thousand hectares within this state. It corresponds to an increase of 15, 7 and 6% of the cropped area compared to the previous harvest (CONAB, 2014). Moreover, according to an agricultural census (IBGE, 2006), the areas cultivated with annual/ permanent crops, planted forest/ pasture increased by about 220%, 173%, 618% and 454% respectively, from 1970 until 2006. These data highlight the growing expansion of farming and forestry sectors in this part of the country. Meanwhile, it becomes necessary to point out concerns of technicians and researches on the inappropriate use of natural resources in this region (SILVA et al., 2015b). Thus, without using an appropriate soil management, environmental negative consequences might arise within a medium to long-term, reflecting in crop yield losses (SILVA et al., 2011).

In studies on suitable techniques for cropland use and management, several Brazilian authors have suggested as soil quality indicators a large number of physical and mechanical properties as aeration, water storage capacity and penetration resistance (PR) (OLIVEIRA et al., 2004; ARAÚJO et al., 2007; SEVERIANO et al., 2011; LIMA et al., 2012; SERAFIM et al., 2013; SILVA et al., 2015a). These properties are chosen for being sensitive to impacts against soil (MENDES et al., 2006; PRAGANA et al., 2012; SILVA et al., 2015a). Thus, the least limiting water range appears as an auxiliary tool for soil hydro-physical quality assessment (GUIMARAES et al., 2013), once it relates soil density to critical aeration intensity, water potentials as well as soil resistance to penetration (LETEY, 1985; SILVA et al., 1994), serving as a subsidy to compare land uses and managements.

Accordingly, a few factors such as ongoing soil disturbance, intensive agricultural mechanization (BERTOL et al., 2004), crop harvest, deforestation (DIAS JUNIOR et al., 2005) and cattle trampling (FIGUEIREDO et al., 2009) can provide intense compaction, reducing macroporosity and increasing PR. Thus, these factors may affect least limiting water range (TORMENA et al., 2007; GUIMARAES et al., 2013), besides changing soil organic carbon content (MACHADO et al., 2014).

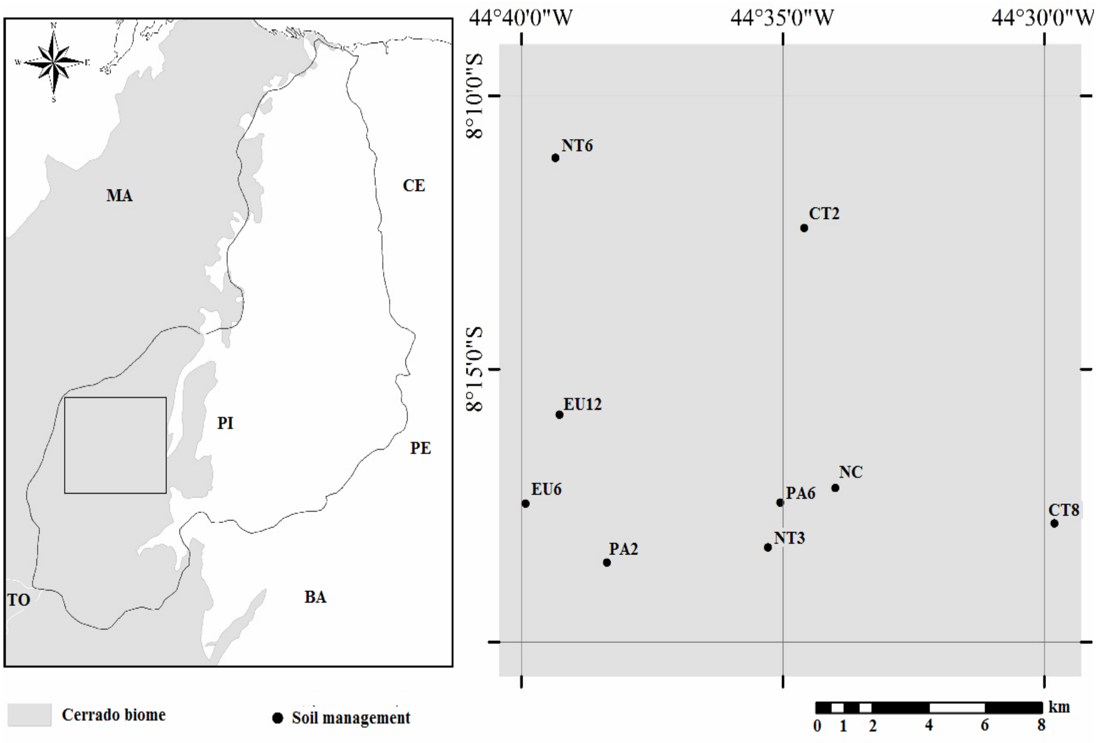
Hence, this study aimed to evaluate the impacts caused by different land uses, management systems and respective terms on water-physical properties and organic carbon content in a Latossolo Amarelo Distrófico típico caulinítico (Oxisol) from Piauí state Cerrado area.

## Material and Methods

### *Area description*

The study area is located in Nova Santa Rosa, Uruçuí district (at geographical coordinates of 7º 14’ 2” south latitude, 44º 33’ 14” west longitude) in Western Piauí state (Figure 1). In the study area, the dominant soils are Latossolos Amarelos Distróficos típicos cauliníticos (Oxisols) (PRAGANA et al., 2012). According to the Köppen's classification, local climate is tropical (*Aw* type), which is characterized by hot and humid weather and average rainfall of 1,100 mm yr$^{-1}$, and temperature of 29 °C (SOUSA et al., 2013).

**Figure 1.** Location of the study areas in the district of Nova Santa Rosa, Uruçuí, state of Piauí (PI). Soil management: native Cerrado (NC); eucalyptus plantation of six years (EU6); eucalyptus plantation of twelve years (EU12); pasture of two years (PA2); pasture of six years (PA6); conventional tillage of two years (CT2); conventional tillage of eight years (CT8), no-till of three years (NT3), no-till of six years (NT6).



*Soil sampling and treatments*

We assessed nine farming areas with distinct backgrounds concerning land-use, management system and run time. These areas were divided in no-till for 3 and 9 years (NT3 and NT9), pasture for 2 and 5 years (PA2 and PA6), eucalyptus plantation for six and twelve years (EU6 and EU12), conventional tillage for two and 8 years (CT2 and CT8) and under native Cerrado (NC), which represented a reference condition (Table 1).

For soil sampling, we set a one-ha central area with the aid of a GPS device and a metric tape. From this area, twenty-five points were established at a 25 m distance from each other. Subsequently, four of these points were chosen randomly, making the four replications, in which were taken samples at depth ranges of 0-0.10; 0.10-0.20; 0.20-0.30 and 0.30-0.40 m. In native Cerrado areas, a 15-m border was set from the edge of the legal reserve to further pursuit of the above-mentioned procedure.

**Table 1.** History of use of a dystrophic Latossolo Amarelo Distrófico típico caulinítico (Oxisol) from a Cerrado area within Piauí state, after several years of adoption of different land uses and soil management systems.

| Treatment | Detailing of the land uses and managements, number of years and location of each area |
|---|---|
| NC | Native Cerrado with no history of human disturbance, in terms of agricultural use. Geographical coordinates: 08° 17' 10.8" S. 44° 33' 59.4" W and altitude of 569 m. |
| EU 6 | Native Cerrado deforested in the 2007/ 2008 crop season, being limed with 5,000 kg $ha^{-1}$ dolomitic limestone. The area was grown with rice in the first year, applying 35 kg $ha^{-1}$ $P_2O_5$ and 18 kg $ha^{-1}$ $K_2O$ in planting row. In the following years, eucalyptus was planted without extra fertilizations. Geographical coordinates: 08° 17' 27.7" S. 44° 39' 55.4" W and altitude of 578 m. |
| EU 12 | Native Cerrado deforested in the 2000/ 2001 season, being limed with 4,000 kg $ha^{-1}$ dolomitic limestone. The area was grown with rice in the first year, applying 35 kg $ha^{-1}$ $P_2O_5$ and 18 kg $ha^{-1}$ $K_2O$ in planting row. In the following years, eucalyptus was planted without extra fertilizations. Geographical coordinates: 08° 15' 50.3" S. 44° 39' 16.3" W and altitude of 580 m. |
| PA 2 | Area converted into farming system in the crop year of 2001/2002, with liming throughout the years of 2003, 2005, 2010 and 2012, using 2,000 kg $ha^{-1}$ dolomitic limestone. The area was grown with rice in the first two years and then with soybeans. In the crop seasons of 2009/2010 and 2010/2011, corn was cropped. In the last two years, pastures of *Urochloa brizantha* were inserted, and since 2009 soil was not tilled. Average fertilization was of 100 and 80 kg $ha^{-1}$ $P_2O_5$ and $K_2O$, respectively, for both soybean and corn crops, however, adding 120 kg $ha^{-1}$ N during corn cultivation. Geographical coordinates: 08° 28' 32.6" S. 44° 57' 82" W and altitude of 550 m. |
| PA 6 | Area converted into farming system in the crop year of 2000/2001, initial soil tillage using 4,000 kg $ha^{-1}$ dolomitic limestone and 2,000 kg $ha^{-1}$ in the years of 2003, 2006 and 2010. The area was grown with rice in the first two years, soybeans in the following ones. In the last six years, grazing areas with *Urochloa brizantha* was inserted. Average fertilization applied in the planting rows was of 100 kg $ha^{-1}$ $P_2O_5$ and 80 kg $ha^{-1}$ $K_2O$ for soybean crop. Geographical coordinates: 08° 17' 26.8" S. 44° 35' 03" W and altitude of 553 m. |
| CT2 | Area under conventional tillage - rice monocrop in the 2011/ 2012 season applying 35 kg $ha^{-1}$ $P_2O_5$ and 18 kg $ha^{-1}$ $K_2O$ in the planting row, without dolomitic limestone use. In the 2012/ 2013 crop season, the area was limed with 5,000 kg $ha^{-1}$ limestone and soybeans fertilized with 130 kg $ha^{-1}$ $P_2O_5$ and 95 kg $ha^{-1}$ $K_2O$ in the planting row. Geographical coordinates: 08° 12' 25" S. 44° 34' 35.3" W and altitude of 500 m. |
| PC 8 | Native Cerrado deforested in the 2006/ 2007 crop season, being afterwards cropped under conventional tillage with intensive tilling, being previously limed using 5,000 kg $ha^{-1}$ dolomitic limestone, and a further application of 2,000 kg $ha^{-1}$ of the same product in 2009 and in 2012. Area under soybean monocrop over almost all years, except in 2012/ 2013 season, when corn was grown. Average fertilization applied in the planting rows was of 100 kg $ha^{-1}$ $P_2O_5$ and 120 kg $ha^{-1}$ $K_2O$ in all soybean crop seasons, adding 130 kg $ha^{-1}$ N in the corn cultivation year. Geographical coordinates: 08° 17' 49.7" S. 44° 29' 47.9" W and altitude of 572 m. |
| PD 3 | Area converted into farming in 1999/ 2000, with initial application, and every three years of 5,000 and 2,000 kg $ha^{-1}$ limestone, respectively. In the first crop year, the area was grown with rice and then with soybeans, using millet as second crop or mulching in most years of cultivation by 2008/ 2009. In the 2009/ 2010 season, a no-till system was adopted (NTS) using millet for straw interspersing crops of corn and soybeans until the crop year of 2012/2013, with average fertilization using 100 and 120 kg $ha^{-1}$ $P_2O_5$ and $K_2O$, respectively, adding 130 kg $ha^{-1}$ $P_2O_5N_2$ for corn crops. Geographical coordinates: 08° 18' 16" S. 44° 35' 17" W and altitude of 572 m. |
| PD 6 | Area converted into farming in 2002/2003, being deforested and cultivated under a conventional tillage system, previously limed with 5 tons $ha^{-1}$ of dolomitic limestone. In the following years, 2 tons $ha^{-1}$ of limestone were applied every 3 years. It was grown with rice in the first crop year. In the following years, it was cropped with soybeans up to the growing season of 2006/2007. From the seasons of 2007/2008 up to 2012/2013, three corn crops were interspersed with soybeans. In 2007/2008, no-till system was adopted using millet for straw. Average fertilization was performed using 100 kg $ha^{-1}$ $P_2O_5$ and 120 kg $ha^{-1}$ $K_2O$ for all crop seasons of soybeans and corn, adding 130 kg $ha^{-1}$ N during corn cultivation. Geographical coordinates: 08° 30' 68.1" S. 44° 58' 81.1" W and altitude of 572 m. |

### *Analyses: soil organic carbon (OC), sulfuric acid digestion and particle size*

Both particle size and OC analyses were made in 144 disturbed soil samples taken at the four depth ranges from the nine assessed areas with four replications each. Soil particle size was determined by the pipette method (DONAGEMA et al., 2011), and the fractions were classified according to the system adopted by the Brazilian Society of Soil Science (EMBRAPA, 2013).

The organic carbon content was determined by automated dry combustion using an organic carbon analyzer (Vario TOC Cube model, Elementar). To this end, two milligrams of undisturbed soil samples were weighed for each study condition (144 samples) by means of an analytical balance with an accuracy of 0.00001 g. Then, these samples were ground in a mortar, sieved (0.250 mm mesh) and dried at 65 °C for 48 h for moisture removal. Samples were then wrapped and sealed in tin capsules to be incinerated at 950 °C for 5 min. After combustion, all the organic matter was converted into carbon dioxide ($CO_2$) and an infrared sensor detected the amount of $CO_2$ generated. This gas amount was automatically converted into elemental C concentrations.

Silica ($SiO_2$), aluminum oxide ($Al_2O_3$), iron ($Fe_2O_3$) and titanium ($TiO_2$) were extracted via sulfuric acid digestion as in Resende et al. (1987), solely in soil samples from native Cerrado (16 samples). Ki and Kr molecular relationships were calculated according to IBGE (2007) (Table 2). Thus, soil was classified as kaolinitic (K> 0.75, Kr> 0.75), and medium texture (clay content between 150 and 350 g $kg^{-1}$) (EMBRAPA, 2013).

**Table 2.** Physical properties of a dystrophic Latossolo Amarelo Distrófico típico caulinítico under the different land management systems.

| Soil fraction | Management systems [1] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | NC | EU6 | EU12 | PA2 | PA6 | TC2 | TC8 | NT3 | NT6 |
| | ----------g $kg^{-1}$---------- | | | | | | | | |
| | 0.00-0.10 m | | | | | | | | |
| Coarse sand | 257 | 190 | 238 | 240 | 194 | 241 | 426 | 285 | 228 |
| Fine sand | 448 | 623 | 554 | 539 | 590 | 532 | 349 | 483 | 533 |
| Silt | 62 | 22 | 35 | 23 | 51 | 42 | 67 | 42 | 39 |
| Clay | 233 | 165 | 172 | 198 | 165 | 185 | 158 | 190 | 200 |
| OC[2] | 23.8 | 13.7 | 12.3 | 17.4 | 20.3 | 15.1 | 15.6 | 15.7 | 21.0 |
| | 0.10-0.20 m | | | | | | | | |
| Coarse sand | 262 | 198 | 216 | 212 | 197 | 251 | 418 | 225 | 161 |
| Fine sand | 452 | 605 | 574 | 584 | 597 | 528 | 372 | 539 | 605 |
| Silt | 56 | 29 | 30 | 24 | 38 | 33 | 58 | 28 | 35 |
| Clay | 230 | 167 | 180 | 180 | 168 | 188 | 152 | 208 | 198 |
| OC | 14.2 | 11.5 | 11.2 | 13.1 | 12.8 | 11.8 | 11.1 | 10.0 | 14.7 |
| | 0.20-0.30 m | | | | | | | | |
| Coarse sand | 205 | 171 | 182 | 196 | 178 | 225 | 404 | 213 | 179 |
| Fine sand | 521 | 624 | 600 | 594 | 615 | 537 | 376 | 559 | 572 |
| Silt | 50 | 23 | 40 | 22 | 43 | 53 | 62 | 31 | 56 |
| Clay | 225 | 183 | 178 | 187 | 165 | 185 | 158 | 197 | 193 |
| OC | 10.3 | 7.9 | 8.4 | 8.2 | 9.1 | 7.5 | 6.6 | 7.8 | 10.5 |
| | 0.30-0.40 m | | | | | | | | |
| Coarse sand | 237 | 138 | 194 | 207 | 140 | 205 | 371 | 257 | 253 |
| Fine sand | 472 | 663 | 599 | 571 | 640 | 573 | 428 | 516 | 505 |
| Silt | 63 | 29 | 41 | 25 | 55 | 42 | 50 | 24 | 32 |
| Clay | 227 | 170 | 165 | 197 | 165 | 180 | 151 | 202 | 210 |
| OC | 9.2 | 6.8 | 7.5 | 6.6 | 6.5 | 6.4 | 5.2 | 5.9 | 9.3 |
| | Native Cerrado 0-0.40 m | | | | | | | | |
| Sulphidation | $P_2O_5$ | $\%SiO_2$ | $\%Al_2O_3$ | $\%Fe_2O_3$ | $\%TiO_2$ | $\%P_2O_5$ | [3] Ki | [4] Kr | $Al_2O_3/Fe_2O_3$ |
| | 0.01 | 9.19 | 8.99 | 4.43 | 0.486 | 0.006 | 1.74 | 1.32 | 3.18 |

[1] Soil managements: native Cerrado (NC); eucalyptus plantation of six years (EU6); eucalyptus plantation of twelve years (EU12); pasture of two years (PA2); pasture of six years (PA6); conventional tillage of two years (CT2); conventional tillage of eight years (CT8), no-till of three years (NT3), no-till of six years (NT6). [2] Organic carbon. [3] Ki: $SiO_2/Al_2O_3$ molecular ratio. [4] Kr: $SiO_2/(_{Al2O3} + Fe_2O_3)$ molecular ratio..

*Soil bulk density, porosity and least limiting water range (LLWR)*

Soil samples with preserved structure were used for determining density/ porosity of the soil and LLWR. These samples were collected from four mini-trenches dug per area (repetitions) for each management system and land use. The collection of samples was performed on soil core (with an approximate volume of 100 cm$^3$), and then saturated by capillarity from the base.

A retention curve was built by testing eight matrix potentials of thirty-two samples taken from each situation. These matrix potentials were -2, -4, -6 and -10 kPa, for a tension table; and -33, -100, -500 and -1500 kPa, for Richards' extractors, according Donagema et al. (2011). After reaching water balance, the samples were weighed for further determination of soil resistance to penetration as proposed by Tormena et al. (1998). Then, the samples were dried at ± 105 °C for 24 h for measurements of bulk density (Bd) and water volumetric content of the soil ($\Theta$) at the various tested tensions. The value $\Theta$ (-6kPa) was used to estimate microporosity - MiP (DONAGEMA et al., 2011). The total pore volume (TP) was obtained according to equation 1 (Eq. 1) and particle density (Dp) according to Donagema et al. (2011). Macroporosity (MaP) was calculated from the difference between TP and MiP (DONAGEMA et al., 2011).

$$TP = 1 - \frac{Bd}{Dp} \qquad \text{Eq. 1}$$

The force required to penetrate soil (kgf) was measured by a digital penetrographer (Marconi model MA 933) consisted of a metal rod with a 45 ° half-angle and 0.1256 cm diameter at a constant speed of 0.01 m min$^{-1}$. The measured force values, in kgf, were thereafter converted to penetration resistance (PR) in MPa, considering the rod area, according to equations 2, 3 and 4 (Eq. 2, Eq. 3 and Eq. 4 ), which were adapted from Serafim et al. (2013):

$$PR = \frac{F\,g}{\left[\dfrac{\pi r^2}{\cos(45^{o})}\right]}\frac{1}{10^6} \qquad \text{Eq. 2}$$

$$PR = \frac{9.806648\,F}{\left[\dfrac{3.1415926 \text{ x } 0.00192^{\,2}}{0.7071}\right]}\frac{1}{10^6} \qquad \text{Eq. 3}$$

$$PR = 0.598755\ F \qquad \text{Eq. 4}$$

In which: PR is the soil penetration resistance to roots, in MPa; F is the resistance value provided by the equipment, in kgf; g is the gravity (9.806648 m s$^{-2}$); $\pi$ is a dimensionless value (3.1415926); r is the rod radius (0.00192 m); and cos(45º) is the cone surface cosine angle, which is equivalent to 0.7071.

The LLWR was obtained through integration of effects of soil bulk density (Bd), penetration resistance (PR), water content ($\Theta$) and water potential ($\psi$), aiming to estimate the ideal water content in soil under varied land-use, managements during different terms in a Latossolo Amarelo Distrófico típico caulinítico (Oxisol).

Curves of water retention (WRC) and soil resistance to penetration (PRC) were adjusted to establish the LLWR. The curves were fitted at two situations. First, both WRC and PRC were adjusted to the soil in a general role, without considering the management systems and evaluated depth. Second, each management system and depth range individually adjusted both curves.

For WRC, the functional relationship between $\Theta$ and $\psi$ was incorporated with the effect of Bd; thus, in this case, it was used the model proposed by Leão et al. (2006) (Eq. 5). In the case of PRC, the functional relationship between PR and $\Theta$ was incorporated with the effect of Bd to a non-linear model, being adjusted according model described by Silva et al. (1994) (Eq. 6).

$$\Theta = \mathrm{Exp}\,(a + b\,Bd)\,\Psi^{c} \qquad \text{Eq. 5}$$

$$PR = d\,\Theta^{e}\,Bd^{f} \qquad \text{Eq. 6}$$

In which: $\Theta$ is the soil water volume ($m^3\ m^{-3}$); $\psi$ is the soil water potential (MPa); PR is the soil penetration resistance to roots, in MPa; and *a*, *b*, *c*, *d*, *e*, *f* are coefficients obtained from data adjustment to the above-mentioned equations.

The LLWR was ascertained according to Silva et al. (1994) and Tormena et al. (1998). PR was determined using limiting value of 2.0 MPa (TAYLOR et al., 1966). The water potentials of -6 (MELLO et al., 2002) and -1500 kPa (DONAGEMA et al., 2011) were used to calculate $\Theta_{FC}$ and $\Theta_{PWP}$, respectively, in addition to the WRC and the values of water content wherein PR ($\Theta_{PR}$) reaches a critical value (2 MPa), obtained by the PRC. The ΘAW value was obtained by the equation 5 (Eq. 7). (DONAGEMA et al., 2011).

$$\Theta_{AW} = \left[\left(1 - \frac{Bd}{Dp}\right) - 0.1\right] \qquad \text{Eq. 7}$$

Afterwards, the LLWR of each management system and sampled depth was set based on $\Theta_{FC}$, $\Theta_{PWP}$, $\Theta_{AW}$ and $\Theta_{PR}$. In order to choose $\Theta$ values for LLWR calculations, we adopted the method proposed by Silva et al. (1994), in which the following situations are found:

If $\Theta_{AW} \geq \Theta_{FC}$ and $\Theta_{PR} \leq \Theta_{PWP} \therefore LLWR = \Theta_{FC} - \Theta_{PWP}$;

If $\Theta_{AW} \geq \Theta_{FC}$ and $\Theta_{PR} \geq \Theta_{PWP} \therefore LLWR = \Theta_{FC} - \Theta_{PR}$;

If $\Theta_{AW} \leq \Theta_{FC}$ and $\Theta_{PR} \leq \Theta_{PWP} \therefore LLWR = \Theta_{AW} - \Theta_{PWP}$;

If $\Theta_{AW} \leq \Theta_{FC}$ and $\Theta_{PR} \geq \Theta_{PWP} \therefore LLWR = \Theta_{AW} - \Theta_{PR}$.

### *Statistics*

The data concerning soil bulk density, macroporosity, microporosity and total porosity were submitted to a descriptive analysis for observing specific traits of each management system and land use type. We also used the Pearson's correlation to understand the relationship between physical water parameters and soil organic carbon content. The Bd ranges at the different soil management systems were grouped into a single LLWR. For this purpose, we estimated the confidence interval (CI) within a random sample of 128 units, $t_{n-1}$ g.l.; α/2, wherein *n* is the sample size; α is the significance level; and CI was given by y ± tα. The adjustments of WRC and PRC equations, as well as other statistical analyzes were performed using the R software version 3.2.3 (RDCT, 2015).

## Results and Discussion

The various management systems and land use types had variations in Bd, TP, MaP and MiP, for all evaluated depths (Table 3). These results are consistent with those obtained by Oliveira et al. (2004), who evaluated soil bulk density and porosity.

**Table 3.** Mean values of physical properties (soil bulk density, macroporosity, microporosity and total porosity), obtained in the different land uses and management systems in various soil depth ranges.

| Variáveis (1) | Bd (2) | | | MaP (3) | | | MiP (4) | | | TP (5) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | --------kg $dm^{-3}$------- | | | ---------------------------------------%--------------------------------------- | | | | | | | | |
| | Med | Max | Min | Med | Max | Min | Med | Max | Min | Med | Max | Min |
| 0.00 - 0.10 m | | | | | | | | | | | | |
| NC | 1.20 ± 0.08 | 1.27 | 1.12 | 28.2 ± 4.1 | 31.1 | 22.2 | 26.6 ± 2.7 | 30.0 | 23.6 | 54.8 ± 0.2 | 58.0 | 52.2 |
| EU6 | 1.28 ± 0.04 | 1.32 | 1.12 | 31.1 ± 2.1 | 33.2 | 28.5 | 20.9 ± 1.1 | 21.7 | 19.3 | 52.0 ± 1.5 | 53.9 | 50.2 |
| EU12 | 1.30 ± 0.05 | 1.37 | 1.25 | 28.1 ± 2.9 | 32.0 | 24.8 | 23.2 ± 1.5 | 24.5 | 21.0 | 51.3 ± 1.9 | 53.0 | 48.6 |
| PA2 | 1.48 ± 0.03 | 1.50 | 1.44 | 16.5 ± 4.6 | 21.2 | 12.4 | 28.0 ± 3.8 | 31.5 | 24.7 | 47.5 ± 1.0 | 45.9 | 43.6 |
| PA6 | 1.60 ± 0.06 | 1.66 | 1.53 | 12.4 ± 1.1 | 13.6 | 11.0 | 27.4 ± 2.8 | 31.3 | 25.3 | 39.8 ± 2.2 | 42.3 | 37.7 |
| CT2 | 1.42 ± 0.09 | 1.54 | 1.32 | 19.4 ± 5.2 | 26.6 | 15.2 | 27.2 ± 2.7 | 30.5 | 23.9 | 46.1 ± 3.6 | 50.5 | 42.0 |
| CT8 | 1.22 ± 0.04 | 1.26 | 1.18 | 23.1 ± 3.8 | 27.3 | 18.2 | 23.9 ± 2.6 | 27.4 | 21.4 | 40.0 ± 1.3 | 48.6 | 45.6 |
| NT3 | 1.56 ± 0.08 | 1.66 | 1.47 | 12.9 ± 3.7 | 17.7 | 8.8 | 28.6 ± 1.2 | 29.5 | 26.9 | 41.5 ± 2.9 | 44.5 | 37.6 |
| NT6 | 1.54 ± 0.04 | 1.59 | 1.49 | 13.0 ± 3.2 | 16.2 | 9.2 | 29.0 ± 1.9 | 31.0 | 27.1 | 42.0 ± 1.5 | 43.9 | 40.2 |
| CV (%) | 9.89 | | | 37.03 | | | 12.80 | | | 11.48 | | |
| 0.10 - 0.20 m | | | | | | | | | | | | |
| NC | 1.27 ± 0.05 | 1.33 | 1.21 | 27.6 ± 4.5 | 34.2 | 24.3 | 24.4 ± 3.0 | 26.6 | 20.1 | 52.1 ± 1.9 | 54.33 | 50.11 |
| EU6 | 1.38 ± 0.12 | 1.49 | 1.26 | 24.5 ± 7.0 | 31.9 | 17.1 | 23.5 ± 2.5 | 26.7 | 20.7 | 48.0 ± 4.7 | 52.60 | 43.79 |
| EU12 | 1.37 ± 0.04 | 1.41 | 1.32 | 25.3 ± 1.5 | 26.5 | 23.1 | 23.2 ± 1.0 | 24.1 | 22.0 | 48.5 ± 0.5 | 50.44 | 46.91 |
| PA2 | 1.59 ± 0.02 | 1.61 | 1.56 | 12.8 ± 2.1 | 15.9 | 11.4 | 27.6 ± 2.2 | 29.4 | 24.4 | 40.4 ± 0.9 | 41.42 | 39.33 |
| PA6 | 1.50 ± 0.07 | 1.57 | 1.43 | 15.9 ± 4.1 | 20.7 | 11.1 | 27.8 ± 2.3 | 29.8 | 24.7 | 43.7 ± 2.5 | 46.16 | 40.90 |
| CT2 | 1.45 ± 0.10 | 1.55 | 1.32 | 19.5 ± 5.5 | 25.9 | 12.6 | 26.0 ± 2.1 | 29.1 | 24.4 | 45.5 ± 3.7 | 50.32 | 41.63 |
| CT8 | 1.55 ± 0.03 | 1.58 | 1.51 | 17.3 ± 2.6 | 20.6 | 14.2 | 24.5 ± 2.5 | 27.2 | 21.8 | 41.9 ± 1.1 | 43.10 | 40.56 |
| NT3 | 1.56 ± 0.05 | 1.60 | 1.50 | 13.0 ± 2.1 | 15.1 | 11.2 | 28.5 ± 0.6 | 29.1 | 27.7 | 41.5 ± 1.7 | 43.48 | 39.92 |
| NT6 | 1.57 ± 0.02 | 1.59 | 1.54 | 13.6 ± 2.6 | 16.5 | 10.2 | 27.5 ± 2.1 | 30.3 | 25.5 | 41.1 ± 0.8 | 42.03 | 40.38 |
| CV (%) | 7.90 | | | 33.82 | | | 10.30 | | | 9.90 | | |
| 0.20 - 0.30 m | | | | | | | | | | | | |
| NC | 1.28 ± 0.06 | 1.33 | 1.20 | 29.4 ± 2.8 | 33.5 | 27.4 | 22.5 ± 0.9 | 23.3 | 21.3 | 51.8 ± 2.1 | 54.7 | 49.8 |
| EU6 | 1.51 ± 0.05 | 1.58 | 1.46 | 19.6 ± 3.8 | 23.6 | 16.1 | 23.6 ± 2.8 | 27.4 | 21.3 | 43.2 ± 1.9 | 44.9 | 40.5 |
| EU12 | 1.51 ± 0.05 | 1.55 | 1.46 | 20.7 ± 2.4 | 22.1 | 17.1 | 22.4 ± 2.1 | 24.8 | 19.9 | 43.1 ± 1.7 | 45.2 | 41.6 |
| PA2 | 1.54 ± 0.06 | 1.57 | 1.45 | 16.9 ± 3.7 | 22.4 | 14.1 | 25.3 ± 1.5 | 26.8 | 23.2 | 42.2 ± 2.3 | 45.6 | 40.9 |
| PA6 | 1.51 ± 0.03 | 1.57 | 1.49 | 17.9 ± 1.3 | 19.1 | 16.0 | 25.2 ± 0.7 | 25.8 | 24.3 | 43.1 ± 1.3 | 44.0 | 41.2 |
| CT2 | 1.45 ± 0.09 | 1.54 | 1.34 | 21.9 ± 4.9 | 27.7 | 17.1 | 23.5 ± 1.5 | 24.8 | 21.8 | 45.5 ± 3.4 | 49.5 | 41.9 |
| CT8 | 1.57 ± 0.03 | 1.60 | 1.54 | 18.5 ± 3.2 | 21.5 | 14.1 | 22.3 ± 2.7 | 26.0 | 20.1 | 40.8 ± 1.1 | 41.9 | 39.8 |
| NT3 | 1.53 ± 0.10 | 1.64 | 1.39 | 15.1 ± 3.9 | 19.3 | 10.2 | 27.4 ± 1.5 | 28.3 | 25.2 | 42.5 ± 3.8 | 47.6 | 38.5 |
| NT6 | 1.56 ± 0.05 | 1.63 | 1.53 | 15.9 ± 3.1 | 19.3 | 11.8 | 25.4 ± 1.6 | 26.8 | 23.1 | 41.4 ± 1.9 | 42.5 | 38.6 |
| CV (%) | 6.59 | | | 25.55 | | | 9.45 | | | 8.60 | | |
| 0.30 - 0.40 m | | | | | | | | | | | | |
| NC | 1.44 ± 0.05 | 1.51 | 1.38 | 20.7 ± 2.1 | 22.6 | 17.8 | 25.1 ± 1.4 | 26.9 | 23.9 | 45.8 ± 2.0 | 48.0 | 43.3 |
| EU6 | 1.52 ± 0.04 | 1.55 | 1.46 | 18.5 ± 2.6 | 21.2 | 16.0 | 24.4 ± 1.6 | 25.7 | 22.4 | 42.9 ± 1.6 | 45.2 | 41.7 |
| EU12 | 1.53 ± 0.05 | 1.61 | 1.48 | 20.2 ± 4.0 | 24.6 | 14.9 | 22.2 ± 2.0 | 24.5 | 19.6 | 42.4 ± 2.1 | 44.2 | 39.4 |
| PA2 | 1.53 ± 0.09 | 1.64 | 1.43 | 15.8 ± 4.3 | 20.4 | 10.0 | 26.7 ± 1.1 | 28.2 | 25.9 | 42.5 ± 3.3 | 46.3 | 38.2 |
| PA6 | 1.47 ± 0.05 | 1.52 | 1.42 | 19.1 ± 2.3 | 21.1 | 16.7 | 25.5 ± 0.5 | 26.0 | 24.9 | 44.7 ± 2.0 | 46.7 | 42.7 |
| CT2 | 1.46 ± 0.04 | 1.49 | 1.41 | 19.1 ± 2.3 | 22.4 | 15.7 | 27.1 ± 1.6 | 28.2 | 24.7 | 45.2 ± 1.4 | 47.1 | 43.7 |
| CT8 | 1.60 ± 0.05 | 1.66 | 1.53 | 16.7 ± 3.3 | 20.3 | 12.6 | 23.4 ± 1.7 | 25.0 | 21.9 | 40.0 ± 2.0 | 42.3 | 37.5 |
| NT3 | 1.54 ± 0.03 | 1.58 | 1.51 | 15.7 ± 1.6 | 17.0 | 13.4 | 26.2 ± 0.8 | 27.2 | 25.4 | 42.0 ± 1.2 | 43.4 | 40.6 |
| NT6 | 1.54 ± 0.08 | 1.65 | 1.46 | 15.5 ± 5.6 | 22.1 | 8.5 | 26.6 ± 2.8 | 29.5 | 22.9 | 42.2 ± 3.0 | 45.1 | 38.0 |
| CV (%) | 4.44 | | | 19.57 | | | 8.29 | | | 5.96 | | |

(1) Soil managements: native Cerrado (NC); eucalyptus plantation of six years (EU6); eucalyptus plantation of twelve years (EU12); pasture of two years (PA2); pasture of six years (PA6); conventional tillage of two years (CT2); conventional tillage of eight years (CT8), no-till of three years (NT3), no-till of six years (NT6). (2) soil bulk density (Bd). (3) macroporosity (MaP). (4) microporosity (MiP), ). (5) total porosity (TP).

Taking native Cerrado area as reference, we observed major changes in soil density within 0-0.10 m depth under pasture and no-till systems. Meanwhile, there was no difference between Bd values for NT3 and NT6, which shows that when soil is not inverted, this parameter remains constant. This may be due to soil compaction throughout the first three years that reaches a steady state between pressure exerted by machine traffic and soil pre-consolidation pressure. Such balance consists of the ability of soil to support loads without being compacted (DIAS JUNIOR et al., 2005). Under grazing areas, however, the same trend was not observed when comparing Bd in PA6 and PA2. This is likely due to a decline in vegetal coverage with the passing of years, reducing soil protection against direct impacts from animal trampling, raising the pressure exerted on the soil (PIRES et al., 2012).

Gas exchanges and water percolation in the soil are held within MaP portion. In all systems, this parameter was kept above critical point - aeration porosity (<10%) (GRABLE; SIEMER, 1968), as shown in Table 3. Initially, the models of adjustment of data were studied to better understand potential changes in water retention capacity and resistance to penetration of the evaluated soils. We infer that the adjusted equations explained more than 80% of the variability for both water content and PR.

The magnitude of the model coefficients adjusted to the WRC and the CRP denotes a negative correlation of water content and PR with matric potential, and a positive one with Bd. It could be observed due to a negative sign of $b$ and $e$ parameters; as well as a positive of $c$ and $f$, in each equation (Table 4). Tormena et al. (1998), Blainski et al. (2009) and Serafim et al. (2013) had also reported the same correlations. The PR reduction with increased $\Theta$ is due to a lubricating effect of water, which reduces soil particle cohesion (TORMENA et al., 2007; PETEAN et al., 2010). Yet the increase in PR with the rise of Bd values is related to the effect of soil compaction according to Vepraskas (1984), resulting in increased contact or friction between particles. The positive relationship of $\Theta$ with Bd and negative with $\psi$ could be attributed to increased soil density under all land uses and managements, reducing MaP and increasing MiP (Table 3). As consequence, water retention increases, but not necessarily its availability, which is in agreement with findings by Tormena et al. (1999) and Torres et al. (2014).

Figure 2 shows the LLWR estimated for all assessed conditions for all Bd values and depth ranges. The CI of Bd ($CI_{Bd}$) enabled predicting alterations undergone by all soil properties under all land uses and management systems, anticipating potential negative consequences for soil physical quality. In this sense, Serafim et al. (2013) suggested these indexes to be taken into consideration in farm planning, aiming to maintain physical quality of the soils.

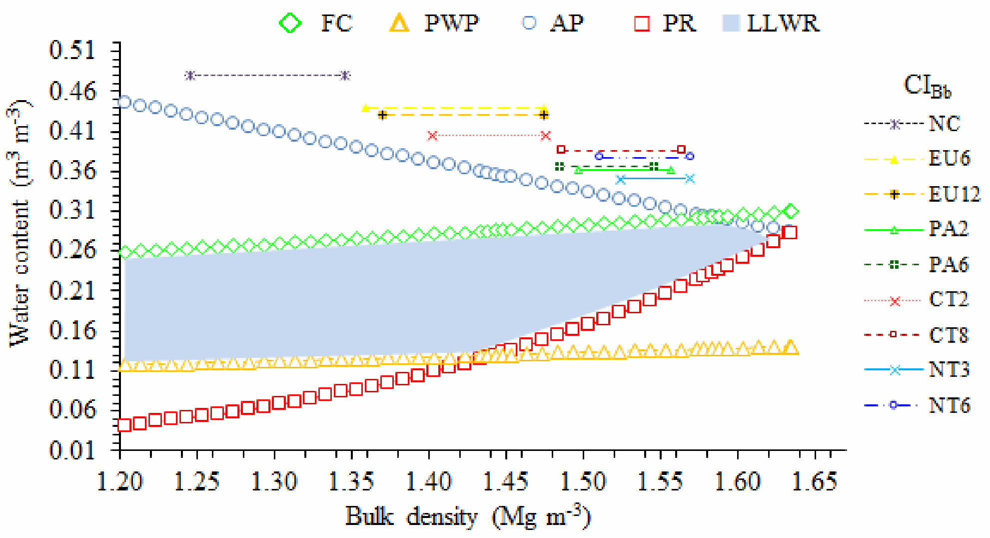
In all land uses and management systems as well as cultivation times, the upper limit of LLWR in the Latossolo Amarelo was defined by $\Theta_{FC}$ (Figure 2), indicating conservation of an appropriate aeration for a soil moisture at field capacity (FC). On the other hand, $\Theta_{PR}$ set the lower limit of LLWR to Bd above 1.43 Mg m$^{-3}$, thereby reducing water availability in PA2, PA6, NT3, NT6 and CT8. For values below 1.43 Mg m$^{-3}$, the lower limit of LLWR was defined by $\Theta_{PWP}$, which is equivalent to the amount of available water (AW) at a ceiling limit, indicating better soil physical quality in NC, EU6, EU12 and CT2.

**Table 4.** Equations for curves of soil water retention (WRC) and penetration resistance (PRC), wherein Θ is the amount of water in the soil ($m^3\ m^{-3}$); Ψ is the water matrix potential in soil (kPa); Bd is the soil bulk density ($Mg\ m^{-3}$), and PR is the soil penetration resistance (MPa).

| Management | WRC [(1)] | $R^2$ | PRC [(2)] | $R^2$ |
|---|---|---|---|---|
| General | $\Theta = Exp\ (-2.317 + 0.4146\ Bd)\ \Psi^{-0.1190}$ | 0.86** | $PR = 0.0027\ \Theta^{-1.5274} Bd^{9.5637}$ | 0.88** |
| 0.00-0.10 m | | | | |
| NC | $\Theta = Exp\ (-1.8498 + 0.1896\ Bd)\ \Psi^{-0.1060}$ | 0.89** | $PR = 0.0331\ \Theta^{-1.7134} Bd^{2.0165}$ | 0.86** |
| EU6 | $\Theta = Exp\ (-3.7100 + 1.4172\ Bd)\ \Psi^{-0.1210}$ | 0.90** | $PR = 0.0160\ \Theta^{-1.0561} Bd^{4.7738}$ | 0.82** |
| EU12 | $\Theta = Exp\ (-2.6139 + 0.5266\ Bd^{)}\ \Psi^{-0.1678}$ | 0.97** | $PR = 0.0150\ \Theta^{-1.6154} Bd^{3.5001}$ | 0.89** |
| PA2 | $\Theta = Exp\ (-8.3645 + 4.6197\ Bd)\ \Psi^{-0.1015}$ | 0.95** | $PR = 0.0001\ \Theta^{-1.8547} Bd^{21.3010}$ | 0.96** |
| PA6 | $\Theta = Exp\ (-3.2158 + 1.0128\ Bd)\ \Psi^{-0.1086}$ | 0.95** | $PR = 0.0034\ \Theta^{-2.0515} Bd^{6.7138}$ | 0.98** |
| CT2 | $\Theta = Exp\ (-2.4262 + 0.5179\ Bd)\ \Psi^{-0.1172}$ | 0.96** | $PR = 0.0013\ \Theta^{-2.0461} Bd^{8.9320}$ | 0.97** |
| CT8 | $\Theta = Exp\ (-4.1008 + 1.6570\ Bd)\ \Psi^{-0.1228}$ | 0.92** | $PR = 0.0017\ \Theta^{-1.9352} Bd^{7.0638}$ | 0.99** |
| NT3 | $\Theta = Exp\ (-2.7325 + 0.7191\ Bd)\ \Psi^{-0.1388}$ | 0.96** | $PR = 0.0003\ \Theta^{-1.5205} Bd^{14.3136}$ | 0.80** |
| NT6 | $\Theta = Exp\ (-3.4820 + 1.2590\ Bd)\ \Psi^{-0.0955}$ | 0.87** | $PR = 0.0012\ \Theta^{-1.9713} Bd^{9.7582}$ | 0.84** |
| 0.10-0.20 m | | | | |
| NC | $\Theta = Exp\ (-1.7263 + 0.0115\ Bd)\ \Psi^{-0.1289}$ | 0.97** | $PR = 0.0238\ \Theta^{-1.8573} Bd^{2.2676}$ | 0.93** |
| EU6 | $\Theta = Exp\ (-2.8402 + 0.6830\ Bd)\ \Psi^{-0.1597}$ | 0.98** | $PR = 0.0023\ \Theta^{-1.9478} Bd^{5.9564}$ | 0.89** |
| EU12 | $\Theta = Exp\ (-2.1277 + 0.1482\ Bd)\ \Psi^{-0.1720}$ | 0.99** | $PR = 0.0013\ \Theta^{-1.6790} Bd^{9.95911}$ | 0.91** |
| PA2 | $\Theta = Exp\ (-2.2207 + 0.3904\ Bd)\ \Psi^{-0.1155}$ | 0.94** | $PR = 0.0001\ \Theta^{-2.3793} Bd^{18.4094}$ | 0.92** |
| PA6 | $\Theta = Exp\ (-2.6307 + 0.6665\ Bd)\ \Psi^{-0.1259}$ | 0.96** | $PR = 0.0027\ \Theta^{-1.2760} Bd^{10.3297}$ | 0.88** |
| CT2 | $\Theta = Exp\ (-2.4262 + 0.5179\ Bd)\ \Psi^{-0.1172}$ | 0.96** | $PR = 0.0013\ \Theta^{-2.0461} Bd^{8.9320}$ | 0.97** |
| CT8 | $\Theta = Exp\ (-2.2703 + 0.2847\ Bd)\ \Psi^{-0.1131}$ | 0.95** | $PR = 0.0004\ \Theta^{-1.9629} Bd^{11.5205}$ | 0.82** |
| NT3 | $\Theta = Exp\ (-2.7755 + 0.7493\ Bd)\ \Psi^{-0.1123}$ | 0.94** | $PR = 0.0016\ \Theta^{-3.2498} Bd^{3.6851}$ | 0.95** |
| NT6 | $\Theta = Exp\ (-1.9047 + 0.1812\ Bd)\ \Psi^{-0.1306}$ | 0.98** | $PR = 0.0048\ \Theta^{-2.3766} Bd^{5.2216}$ | 0.97** |
| 0.20-0.30 m | | | | |
| NC | $\Theta = Exp\ (-2.4303 + 0.4902\ Bd)\ \Psi^{-0.1104}$ | 0.99** | $PR = 0.0058\ \Theta^{-2.2205} Bd^{4.3847}$ | 0.92** |
| EU6 | $\Theta = Exp\ (-3.0715 + 0.7525\ Bd)\ \Psi^{-0.1756}$ | 0.95** | $PR = 0.0088\ \Theta^{-1.6339} Bd^{4.5469}$ | 0.95** |
| EU12 | $\Theta = Exp\ (-3.0103 + 0.7493\ Bd)\ \Psi^{-0.1564}$ | 0.98** | $PR = 0.0165\ \Theta^{-1.6848} Bd^{3.6434}$ | 0.90** |
| PA2 | $\Theta = Exp\ (-3.3403 + 1.0938\ Bd)\ \Psi^{-0.1015}$ | 0.95** | $PR = 0.0001\ \Theta^{-3.1825} Bd^{10.579}$ | 0.89** |
| PA6 | $\Theta = Exp\ (-3.3049 + 1.0959\ Bd)\ \Psi^{-0.0971}$ | 0.96** | $PR = 0.0001\ \Theta^{-2.1866} Bd^{17.5474}$ | 0.84** |
| CT2 | $\Theta = Exp\ (-2.9788 + 0.8536\ Bd)\ \Psi^{-0.1048}$ | 0.97** | $PR = 0.0004\ \Theta^{-2.3189} Bd^{10.4241}$ | 0.91** |
| CT8 | $\Theta = Exp\ (-4.8008 + 1.9214\ Bd)\ \Psi^{-0.1017}$ | 0.80** | $PR = 0.0009\ \Theta^{-2.2538} Bd^{8.4957}$ | 0.90** |
| NT3 | $\Theta = Exp\ (-2.6113 + 0.5963\ Bd)\ \Psi^{-0.1123}$ | 0.97** | $PR = 0.0005\ \Theta^{-2.7975} Bd^{7.7718}$ | 0.85** |
| NT6 | $\Theta = Exp\ (-2.2304 + 0.4058\ Bd)\ \Psi^{-0.1126}$ | 0.97** | $PR = 0.0242\ \Theta^{-1.8805} Bd^{3.7728}$ | 0.83** |
| 0.30-0.40 m | | | | |
| NC | $\Theta = Exp\ (-1.5474 + 0.0824\ Bd)\ \Psi^{-0.1002}$ | 0.97** | $PR = 0.0022\ \Theta^{-3.1635} Bd^{2.5768}$ | 0.97** |
| EU6 | $\Theta = Exp\ (-3.9790 + 1.4742\ Bd)\ \Psi^{-0.1198}$ | 0.80** | $PR = 0.0004\ \Theta^{-1.9121} Bd^{10.6029}$ | 0.89** |
| EU12 | $\Theta = Exp\ (-4.2396 + 1.5444\ Bd)\ \Psi^{-0.1337}$ | 0.98** | $PR = 0.0001\ \Theta^{-3.0872} Bd^{10.8440}$ | 0.99** |
| PA2 | $\Theta = Exp\ (-2.4785 + 0.5303\ Bd)\ \Psi^{-0.1241}$ | 0.99** | $PR = 0.0003\ \Theta^{-3.4171} Bd^{7.5904}$ | 0.86** |
| PA6 | $\Theta = Exp\ (-2.0230 + 0.2313\ Bd)\ \Psi^{-0.1099}$ | 0.96** | $PR = 0.0008\ \Theta^{-3.8704} Bd^{2.1616}$ | 0.93** |
| CT2 | $\Theta = Exp\ (-2.4418 + 0.5803\ Bd)\ \Psi^{-0.1042}$ | 0.96** | $PR = 0.0010\ \Theta^{-2.4006} Bd^{8.6215}$ | 0.97** |
| CT8 | $\Theta = Exp\ (-3.3169 + 0.9905\ Bd)\ \Psi^{-0.1030}$ | 0.96** | $PR = 0.0001\ \Theta^{-3.1345} Bd^{15.1276}$ | 0.95** |
| NT3 | $\Theta = Exp\ (-3.2008 + 1.0333\ Bd)\ \Psi^{-0.1034}$ | 0.95** | $PR = 0.0001\ \Theta^{-3.3070} Bd^{11.9047}$ | 0.93** |
| NT6 | $\Theta = Exp\ (-2.8088 + 0.7368\ Bd)\ \Psi^{-0.1202}$ | 0.99** | $PR = 0.0004\ \Theta^{-2.7958} Bd^{9.5948}$ | 0.98** |

[(1); (2)] The coefficients of the models of water retention curve and soil penetration resistance were significant ($p<0.01$) by the F test; ** ($p < 0.01$), $^{ns}$ ($p > 0.01$). Soil managements: native Cerrado (NC); eucalyptus plantation of six years (EU6); eucalyptus plantation of twelve years (EU12); pasture of two years (PA2); pasture of six years (PA6); conventional tillage of two years (CT2); conventional tillage of eight years (CT8), no-till of three years (NT3), no-till of six years (NT6).

**Figure 2.** Changes in water content (Θ) due to alterations in soil bulk density (Bb) for the studied cases at a depth range of 0.0 to 0.40 m, in an average texture Latossolo Amarelo Distrófico típico caulinítico (Oxisol). Values for the critical levels of field capacity ($\Theta_{FC}$), permanent wilting point ($\Theta_{PWP}$), aeration porosity of 0.10 $m^3\ m^{-3}$ ($\Theta_{AP}$) and soil penetration resistance of 2.0 MPa ($\Theta_{PR}$). $CI_{Bb}$: Confidence interval for bulk density at each soil management: native Cerrado (NC); eucalyptus plantation of six years (EU6); eucalyptus plantation of twelve years (EU12); pasture of two years (PA2); pasture of six years (PA6); conventional tillage of two years (CT2); conventional tillage of eight years (CT8), no-till of three years (NT3), no-till of six years (NT6).



Considering the $CI_{Bd}$ values, NC conversion into eucalyptus areas (EU6 and EU12) as well as conventional tillage for two years (CT2) did not cause significant changes in soil due to the similarity of these systems with natural conditions (Figure 2). Apparently, the lowest soil degradation in CT2 is due to the short time. This statement is supported by Fontenele et al. (2009), who concluded that soil density is higher in farm systems under no-till and conventional tillage, compared to areas recently cleared of a Latossolo Amarelo in southern Piauí state. The smallest $CI_{Bd}$ values for EU6 and EU12, in comparison to the other agricultural systems, may be related to the fact that these areas have not been deforested yet. Overall, the most significant impact on physical properties of soils under forests comes from vehicle traffic during mechanized operations, mainly harvesting as well as extraction of timber (DIAS JUNIOR et al., 2005).

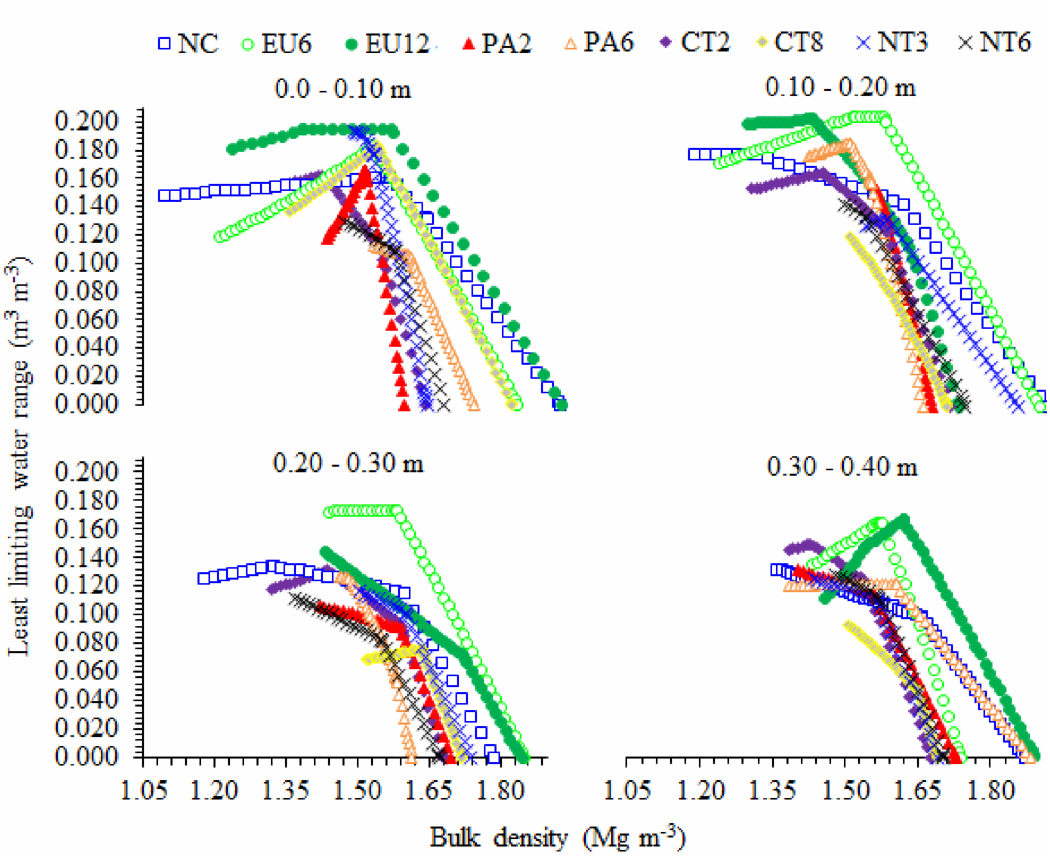
No-till systems (NT3 and NT6), pastures (PA2 and PA6) and conventional tillage (CT8) were the ones that apparently have had soil structure mostly degraded (Table 3 and Figure 2). The high values of $CI_{Bd}$ for NT6 and NT3 may be associated with soil lack of disturbance, as well as traffic of agricultural machinery. According Richart et al. (2005), traffic is the main cause of soil compaction, which has been enhanced by agriculture modernization, with the increased weight of machinery and equipment besides high land use intensity.

Even though the present study evaluates physical quality of soil under different situations, Bd should be used with caution for not making errors when itemizing some systems, as well as not being the only parameter used as benchmark. Still, in view of the importance of organic matter in soil quality studies, in the specific case of this study, it is important to note that the only areas with evolution in organic carbon were PA6 and NT6 (Table 2), which shows the need to relate the physical quality of the soil with various parameters.

According Albuquerque et al. (2001), under pasture, degradation occurs due to animal trampling, what may cause drastic changes in soil physical conditions that eventually interfere with root development, maximize physical degradation, thereby jeopardizing plant growth (BETTERIDGE et al., 1999). In conventional tilling, e.g. in CT8, it is noteworthy mention that soil preparation was performed with harrow, which moves soil at short depths. However, after several consecutive years, a continuous use of such agricultural implement may have led to the formation of compacted layers in subsurface (Table 3), which would limit root growth and, consequently, crop yields (SILVA et al., 2000).

Figure 3 shows the relationships between LLWR and Bd under the different land uses, management systems and all evaluated depths. Through this, we can note that in 0.0-0.10-m depth, the Bd value in which LLWR was 0, i.e. soil critical density ($Bd_c$), was 1.61 Mg m$^{-3}$ for NC, 1.88 for EU6, 1.88 for EU12, 1.79 for PA2, 1.57 for PA6, 1.71 for CT2, 1.78 for CT8, 1.61 for NT3 and 1.65 for NT6. In the 0.10-0.20-m depth, the $Bd_c$ values were 1.68, 1.86, 1.70, 1.85, 1.64, 1.63, 1.67, 1.81 and 1.71 Mg m$^{-3}$ for NC, EU6, EU12, PA2, PA6, CT2, CT8, NT3 and NT6, respectively. In the 0.20-0.30-m depth, these values were 1.68, 1.79, 1.85, 1.85, 1.70, 1.62, 1.72, 1.74 and 1.64 Mg m$^{-3}$, respectively. And for 0.30-0.40-m depth, they were 1.68, 1.87, 1.89, 1.74, 1.73, 1.88, 1.69, 1.69 and 1.70 Mg m$^{-3}$, respectively for the listed above systems.

**Figure 3.** Least limiting water range (LLWR) as a function of bulk density (Bb) for the depth ranges of 0-0.10; 0.10-0.20; 0.20-0.30 and 0.30-0.40 m of a Latossolo Amarelo Distrófico típico caulinítico under different soil managements: native Cerrado (NC); eucalyptus plantation of six years (EU6); eucalyptus plantation of twelve years (EU12); pasture of two years (PA2); pasture of six years (PA6); conventional tillage of two years (CT2); conventional tillage of eight years (CT8), no-till of three years (NT3), no-till of six years (NT6).



For the depth range of 0.0-0.10 m, in CT2, EU6, EU12, PA2 and CT8, we observed that raises in Bd had positive influence on available water amount in the soil. Such fact can also be observed in subsurface, mainly under eucalyptus plantations, corroborating the findings of Tormena et al. (1998). Moreover, this influence evinces a gain in water retention inasmuch as Bd increases, which can be justified by MaP reduction and redistribution of pore sizes (Table 3 and Figure 3). Thus, LLWR was greater in the 0-0.10-m depth, and decreased for each depth range as seen in Figure 3. This fact has occurred because of a raise in PR, which consisted of a limiting factor of LLWR (Table 3 and Figure 2). These findings corroborate those observed by Imhoff et al. (2001), Petean et al. (2010) and Fidalski et al. (2013).

Analyzing the correlation matrix of properties in a Latossolo Amarelo, we observed a positive correlation of LLWR with TP, MaP, AP and OC; conversely, for PR and Bd, it was negative (Table 5). Thus, it is clear that LLWR had improved relations with properties that are most likely to change by management system action. In this sense, Ramos et al. (2012) also found a positive correlation between LLWR and soil organic matter. This is justified since LLWR is directly affected by alterations in soil structure, which is favored by increasing contents of OC, which is an important agent in aggregate formation and stabilization (CASTRO FILHO et al., 1998; FONSECA et al., 2007).

**Table 5.** Correlation matrix between soil water-physical properties and organic carbon content of a Latossolo Amarelo Distrófico típico caulinítico (Oxisol), regardless of management and soil depth layer.

| | LLWR | TP | MaP | MiP | CS | FS | TS | S | C | OC | AP | PR | Bd | AW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LLWR | 1 | 0.82** | 0.81** | -0.36$^{ns}$ | -0.14$^{ns}$ | 0.01$^{ns}$ | -0.09$^{ns}$ | 0.20$^{ns}$ | 0.51* | 0.64** | 0.82** | -0.63** | -0.82** | 0.06$^{ns}$ |
| TP | | 1 | 0.93** | -0.28$^{ns}$ | -0.15$^{ns}$ | 0.01$^{ns}$ | -0.18$^{ns}$ | 0.09$^{ns}$ | 0.48** | 0.58** | 0.97** | -0.84** | -0.97** | -0.06$^{ns}$ |
| MaP | | | 1 | -0.62** | -0.09$^{ns}$ | 0.01$^{ns}$ | -0.06$^{ns}$ | 0.13$^{ns}$ | 0.19$^{ns}$ | 0.48* | 0.94** | -0.80** | -0.94** | -0.07$^{ns}$ |
| MiP | | | | 1 | -0.12$^{ns}$ | 0.05$^{ns}$ | -0.21$^{ns}$ | -0.17$^{ns}$ | 0.54* | 0.19$^{ns}$ | 0.38$^{ns}$ | 0.40* | 0.48** | 0.43* |
| CS | | | | | 1 | -0.94** | -0.02$^{ns}$ | 0.28$^{ns}$ | 0.20$^{ns}$ | -0.17$^{ns}$ | -0.04$^{ns}$ | 0.10$^{ns}$ | 0.04$^{ns}$ | 0.32$^{ns}$ |
| FS | | | | | | 1 | -0.16$^{ns}$ | 0.26$^{ns}$ | -0.62* | 0.01$^{ns}$ | -0.09$^{ns}$ | -0.05$^{ns}$ | 0.09$^{ns}$ | 0.52* |
| TS | | | | | | | 1 | 0.36$^{ns}$ | -0.64** | 0.18$^{ns}$ | -0.17$^{ns}$ | 0.05$^{ns}$ | 0.16$^{ns}$ | 0.08$^{ns}$ |
| S | | | | | | | | 1 | 0.00$^{ns}$ | 0.16$^{ns}$ | 0.18$^{ns}$ | 0.04$^{ns}$ | -0.18$^{ns}$ | -0.38$^{ns}$ |
| C | | | | | | | | | 1 | 0.53** | 0.43* | -0.11$^{ns}$ | -0.33$^{ns}$ | 0.13$^{ns}$ |
| OC | | | | | | | | | | 1 | 0.56** | -0.33$^{ns}$ | -0.36$^{ns}$ | 0.26$^{ns}$ |
| AP | | | | | | | | | | | 1 | -0.80** | -0.98** | -0.01$^{ns}$ |
| PR | | | | | | | | | | | | 1 | 0.80** | -0.03$^{ns}$ |
| Bd | | | | | | | | | | | | | 1 | 0.01$^{ns}$ |
| AW | | | | | | | | | | | | | | 1 |

** ($p \leq 0.01$), * ($0.01 < p \leq 0.05$), $^{ns}$ ($p > 0.05$). (1) Variables: least limiting water range (LLWR), total porosity (TP), macroporosity (MaP), microporosity (MiP), coarse sand (CS), fine sand (FS), total sand (TS), silt (S), clay (C), organic carbon (OC), aeration porosity (AP), penetration resistance (PR), soil bulk density (Bd) and available water (AW).

Table 5 displays a positive correlation among AW, MiP and FS. Such result might be connected to soil-pore continuity, seeing that elevated contents of FS within the soil particle size (Table 2) may contribute the deposition of this material into macropores, forming micropores that will reduce continuity. Some studies point out that certain particles as clay, silt and fine sand are carried through porous medium and laid on macropore surfaces, leading to clogging (DRIESE; McKAY, 2004; CEY et al., 2009), holding a larger amount of water within the soil at higher potentials (up to -0.06 MPa), increasing as consequence water availability.

## Conclusions

The conversion of native Cerrado areas into conventional tillage of 2 years, eucalyptus plantation of six and twelve resulted in fewer changes of water-physical properties in a Latossolo Amarelo Distrófico típico caulinítico.

Longer-term conventional tillage promoted degradation of water-physical properties, as well as a reduction of organic carbon in the soil.

The conversion of native Cerrado areas into no-till system and grazing areas raised contents of organic carbon over time.

The correlation analysis highlighted the influence of organic carbon on the least limit water range of a Latossolo Amarelo Distrófico típico caulinítico, while available water has influence of the content of fine sand.

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