STRUCTURAL CHANGES IN LATOSOLS OF THE CERRADO REGION: I – RELATIONSHIPS BETWEEN SOIL PHYSICAL PROPERTIES AND LEAST LIMITING WATER RANGE(1)

Eduardo da Costa Severiano(2), Geraldo César de Oliveira(3), Moacir de Souza Dias Júnior(4), Katia Aparecida de Pinho Costa(5), Fabiano Guimarães Silva(6) & Silvio Marcos Ferreira Filho(7)

SUMMARY

The agricultural potential of Latosols of the Brazilian Cerrado region is high, but when intensively cultivated under inappropriate management systems, the porosity can be seriously reduced, leading to rapid soil degradation. Consequently, accelerated erosion and sedimentation of springs and creeks have been observed. Therefore, the objective of this study was to evaluate structural changes of Latosols in Rio Verde, Goiás, based on the Least Limiting Water Range (LLWR), and relationships between LLWR and other physical properties. Soil samples were collected from the B horizons of five oxidic Latosols representing the textural variability of the Latosols of the Cerrado biome. LLWR and other soil physical properties were determined at various soil compaction degrees induced by uniaxial compression. Soil compaction caused effects varying from enhanced plant growth due to higher water retention, to severe restriction of edaphic functions. Also, inverse relationships were observed between clay content and bulk density values (Bd) under different structural conditions. Bd values corresponding to critical soil macroporosity (Bdc_{MAC}) were more restrictive to a sustainable use of the studied Latosols than the critical Bd corresponding to LLWR (Bdc_{LLWR}). The high tolerable

---

(1) Part of Doctorate thesis of first author. Partial funding by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). Process number 142232/2007-6. Received for publication in August 2010 and approved in February 2011.

(2) Professor, Federal Institute of Education, Science and Technology Goiano, Campus Rio Verde (IFGoiano/Campus Rio Verde), P.O. Box: 66, CEP: 75901-970, Rio Verde, Goiás, Brazil., E-mail: severianoec@yahoo.com.br

(3) Professor, Federal University of Lavras, Department of Soil Science (DCS/UFLA), P.O. Box 3037, CEP 37200-000, Lavras, Minas Gerais, Brazil. E-mail: geraldooliveira@dcs.ufla.br

(4) Professor, DCS/UFLA, E-mail: msouzadj@dcs.ufla.br

(5) Professor, IFGoiano/Campus Rio Verde, E-mail: katiazoo@hotmail.com

(6) Professor, Campus Rio Verde, E-mail: fabianocefetrv@yahoo.com.br

(7) Agronomist, University of Rio Verde, E-mail: silvioagro@gmail.com

compression potential of these oxidic Latosols was related to the high aeration porosity associated to the granular structure.

Index Terms: soil compaction, degradation of agricultural soils, soil penetration resistance, water availability, soil texture.

RESUMO: *ALTERAÇÕES ESTRUTURAIS DE LATOSSOLOS REPRESENTATIVOS DA REGIÃO DO CERRADO: I - RELAÇÕES ENTRE PROPRIEDADES FÍSICAS DO SOLO E INTERVALO HÍDRICO ÓTIMO*

Apesar do elevado potencial agrícola dos Latossolos da região do Cerrado brasileiro, quando inseridos no processo produtivo sob sistemas de manejo inadequados, o seu espaço poroso pode ser seriamente alterado, levando à sua rápida degradação. Como consequência, tem-se observado aceleração do processo erosivo e assoreamento dos mananciais associados na paisagem. Dessa forma, o presente trabalho teve por objetivo avaliar as alterações estruturais de Latossolos do município de Rio Verde, GO, por meio da caracterização do intervalo hídrico ótimo (IHO), e as relações entre IHO e demais propriedades físicas desses solos. O estudo foi conduzido utilizando-se amostras coletadas no horizonte B_w *de cinco Latossolos oxídicos representativos da variabilidade textural observada nos Latossolos ocorrentes no bioma Cerrado. Foram determinados o IHO e os atributos físico-hídricos dos solos em diversos estados de compactação induzidos por compressão uniaxial. Os resultados indicaram que a compactação do solo resultou desde benefícios ao crescimento das plantas, relacionados ao aumento na retenção de água, até condições de severas restrições às suas funções edáficas, sendo observadas relações inversas entre o conteúdo de argila e os valores de densidade do solo (Ds) nas diversas condições estruturais. A Ds correspondente à macroporosidade crítica do solo* (Dsc_{MAC}) *foi mais restritiva ao manejo sustentável dos Latossolos estudados que a Ds crítica correspondente ao IHO* (Dsc_{IHO})*. A maior compactação permissível observada nesses Latossolos oxídicos deve-se à elevada porosidade de aeração conferida pela estrutura do tipo granular.*

Termos de indexação: compactação do solo, degradação estrutural, resistência do solo à penetração, disponibilidade hídrica, textura do solo.

INTRODUCTION

In the last few decades, Brazil has consolidated a leading position in the world's agriculture. This is due to the incorporation of technological innovations, such as the use of inputs and farming machines that have allowed the expansion of the agricultural frontier to previously marginalized regions, for instance, the Cerrado region. Consequently, the rural economy is flourishing with significant contributions from grain, livestock and agrofuel production (Oliveira et al., 2003; Rathmann et al., 2010).

Under natural conditions, the nutrient availability in Latosols, the predominant soil type and main agricultural resource of this biome, is low; in contrast, the physical fertility is high, due to the presence of aluminum and iron oxides in the clay fraction (Ferreira et al., 1999a, b) as a result of the high degree of weathering they were exposed to (Embrapa, 2006).

Given the smooth topography where Latosols occur, these soils are potentially suitable for highly mechanized agriculture. However, the mechanical resistance is low (Leão et al., 2006; Ajayi et al., 2009), which, on the one hand, may favor root growth of plants; on the other hand, when such soils are incorporated into productive processes, these physical properties trigger compaction processes (Oliveira et al., 2007; Severiano et al., 2008; Borges et al., 2009).

Researchers are increasingly concerned about this problem because soil degradation can cause the loss of a soil´s productive potential. In intensively cultivated areas, soil compaction has been explained by the compression resulting from mechanized operations. In particular, when the water content of soils makes it inappropriate for traffic, continuing mechanical operations increase bulk density due to the reduction of the air-filled pore space. Damage to macroporosity is a specific concern because macropores play a fundamental role in many environmental processes regulated by soils (Hamza & Anderson, 2005; Schäffer et al., 2008), especially those related to infiltration and replenishment of underground water.

Therefore, the loss of soil physical quality is frequently connected to the degree to which structural conditions restrict the plant development (Tormena et al., 1998; Lapen et al., 2004). In this context, the least limiting water range (LLWR) has been suggested as a multifactorial index that covers water or oxygen deficit and soil mechanic resistance, which directly affect agricultural productivity (Silva et al., 1994). It defines the water level in the soil at which, theoretically, physical restrictions to plant growth are minimal (Blainski et al., 2009).

The LLWR depends on soil properties, especially texture (Reichert et al., 2009) and structure (Severiano et al., 2008). However, in soils with a preserved or little disturbed structure, the LLWR amplitude is conventionally recognized as that of the available water (AW), which is the water interval in the soil between field capacity (θ_{FC}) and permanent wilting point (θ_{WP}). In physically degraded soils, plant roots may find layers that mechanically impair its growth (θ_{PR}) and cause limited O_2 availability (θ_{AFP}) due to a reduced gas exchange with the atmosphere (Bengough et al., 2006). Therefore, the risk of crop exposure to physical stress is greater, even within the AW interval. Moreover, as suggested by Tormena et al. (2007), the LLWR represents a great advance in biophysical studies of soils, and it is considered as the best indicator in relation to plant growth.

The present study aimed at evaluating structural changes of five oxidic Latosols, in the county of Rio Verde, Goiás State (GO), by the characterization of the LLWR and the determination of relationships between LLWR and other physical properties of these soils.

MATERIAL AND METHODS

Five experimental areas with Latosols were selected to represent the existing textural variability of Latosols in the Cerrado biome (Embrapa, 2006); these areas were covered with native semi-deciduous seasonal forests in the county of Rio Verde, Goiás State - Southeastern Goias microregion (Table 1). The local climate is classified as Megathermal or Humid Tropical (Aw) of the Savanna Tropical subtype, according to Köppen, and is characterized by dry winters and rainy summers. The average annual temperature varies between 20 and 25 °C, and average annual rainfall from 1,500 to 2,000 mm. The maximum rainfall occurs in January and the lowest between June and August. The relative air humidity is approximately 75 % in the summer and below 30 % in the dry winter.

A trench of 1 x 1 x 2 m was opened at each sampling site, from which 128 samples were randomly collected from the 0.8–1.0 m layer, preserving the soil structure. Aluminum rings (diameter 6.4 cm, height 2.5 cm) and an Uhland sampler were used, according to the criteria defined by Ajayi et al. (2009). Due to the morphological uniformity of the soils, the latosolic horizon B (B_w) was sampled, where the granular structure is representatively expressed. In this way, the considerable soil organic matter content was to a great extent evaded, in view of the influence it has on the analyzed properties. Therefore, still according to these authors, the data can be extrapolated to the top of horizon B, where damage by traffic may occur. In addition, in some Brazilian regions, the soil is tilled to a depth of 90 cm, to favor a regular distribution of root systems, especially of perennial species, such as *Eucalyptus* sp.

Undisturbed samples were prepared in a laboratory, and soil material resulting from the matter left in the rings was physically and chemically characterized, following the methodology proposed by Embrapa (1997) (Table 2).

The study was based on a factorial 5 x 4 x 8 design, with five Latosols (Table 1), four water tension values in the soil (Ψ_m = 2, 6, 33 and 1,500 kPa) and eight compaction levels, corresponding to soil without any previous compression (natural structural conditions) and pressures applied by a Terraload S-450 pneumatic

Table 1. Sampling sites and description of Latosols (L)

L(1)	Geographical coordinate	Altitude	Wet color	Soil classification
		m		
L_{152}	17°31'18"S; 51° 38'07"W	898	5YR 5/4	dystrophic Red-Yellow Latosol Sandy Loam texture
L_{263}	17°35'01"S; 51°37'12"W	871	2.5YR 3/3	dystrophic Red Latosol Sandy Clay Loam texture
L_{399}	17°46'02"S; 51°02'17"W	838	2.5YR 4/6	dystrophic Red Latosol Sandy Clay texture
L_{521}	17°47'26"S; 50°57'17"W	727	10R 3/6	dystrophic Red Latosol Clay texture
L_{716}	17°30'52"S; 51°34'05"W	943	2.5YR 4/4	dystrophic Red Latosol Very Clayey texture

(1) Subscripts in the abbreviation of Latosols indicate clay contents (g kg^{-1}).

Table 2. Chemical and physical characterization of the Latosols (L) in the county of Rio Verde, GO

Latosol	Pd [(1)]	Granulometry [(2)]							Sulphidation			Ki [(3)]	Kr [(4)]
		AMG	AG	AM	AF	AMF	S	A	SiO_2	Al_2O_3	Fe_2O_3		
	kg dm^{-3}	g kg^{-1}											
L_{152}	2.66	1	21	343	433	25	25	152	24	67	38	0.6	0.4
L_{263}	2.75	4	9	172	441	50	61	263	24	113	116	0.4	0.2
L_{399}	2.67	1	16	159	276	35	114	399	92	213	78	0.7	0.6
L_{521}	2.92	1	14	94	139	30	201	521	87	205	245	0.7	0.4
L_{716}	2.69	1	3	43	68	11	158	716	180	344	105	0.9	0.7

(1) Pd: Particle density by the pycnometer method. (2) Determined by the pipette method; AMG: very coarse sand; AG: coarse sand; AM: average sand; AF: fine sand; AMF: very fine sand; A: clay; S: silt (average of 12 replications). (3) Ki: molecular relationship SiO_2:Al_2O_3. (4) Kr: molecular relationship SiO_2: (Al_2O_3 + Fe_2O_3); Subscripts in the abbreviation of Latosols indicate clay contents (g kg^{-1}).

consolidometer (Durham Geo Enterprises, USA) (σ = 25, 50, 100, 200, 400, 800, and 1,600 kPa). The pressure was applied using compressed air, with four replications, totaling 640 samples. Undisturbed samples were initially saturated by capillarity, balanced in the matrix potentials and then subjected to one pressure application per sample until 90 % of maximum deformation (Taylor, 1948); the deformation was monitored based on the increase in bulk density.

After compression, the samples were re-saturated and subjected to tension of 6 kPa to determine the microporosity and field capacity (Embrapa, 1997; Mello et al., 2002). Again, water contents were adjusted to correspond to the evaluated tensions. Later, the samples were subjected to a penetrometry test, using a MARCONI-MA 933 penetrometer with an electronic speed variator and a data recording system, according to Tormena et al. (1998). Afterwards, the samples were oven-dried at 105 °C for 48 h to determine the water content corresponding to the soil water tensions and bulk density (Bd), according to Embrapa (1997). Total porosity (TP) was determined by equation 1:

$$TP = [1 - (Bd/Pd)] \qquad (1)$$

where Pd is particle density (average of 12 replications). Soil macroporosity was obtained by the difference between TP and microporosity, according to Embrapa (1997).

For each soil, the penetration resistance curve (PRC) was obtained by adjusting the soil penetration resistance values (PR) according to the water volumetric content (θ) and to Bd by a non-linear model proposed by Busscher (1990), according to equations 2 to 6:

$$L_{152} : PR = 0.002\,\theta^{-1.29}\ Bd^{8.48};\ R^2 = 0.89^{**} \qquad (2)$$

$$L_{263} : PR = 0.028\,\theta^{-0.98}\ Bd^{6.40};\ R^2 = 0.92^{**} \qquad (3)$$

$$L_{399} : PR = 0.008\,\theta^{-2,.0}\ Bd^{6,.9};\ R^2 = 0.86^{**} \qquad (4)$$

$$L_{521} : PR = 0.025\,\theta^{-1.94}\ Bd^{8.24};\ R^2 = 0.92^{**} \qquad (5)$$

$$L_{716} : PR = 0.060\,\theta^{-2.34}\ Bd^{6.59};\ R^2 = 0.83^{**} \qquad (6)$$

where subscripts in the abbreviation of Latosols correspond to the respective clay content (g kg^{-1}).

To determine the LLWR (Silva et al., 1994), the soil water content retained at a tension of 6 kPa as field capacity was considered as the highest limit (θ_{FC}; Mello et al., 2002; Severiano et al., 2008) or that at which the aeration porosity (θ_{AFP}) is 10 % (Silva et al., 1994), calculated for each sample by equation 7:

$$\theta_{AFP} = TP - 0.1 \qquad (7)$$

For the lowest limit, the water content retained at a tension of 1,500 kPa was considered as the permanent wilting point (θ_{WP}; Richards & Weaver, 1943), and the water content corresponding to the soil penetration resistance of 2.5 MPa (θ_{PR}; Camargo & Alleoni, 1997) was determined by equations 2 through 6 for each respective soil.

The LLWR was obtained by adjusting the limits of water content according to Bd, considering the lowest value between θ_{FC} and θ_{AFP} as the highest limit and the highest value between è$_{WP}$ and è$_{PR}$ as the lowest limit. The value of Bd in which the LLWR assumed a null value (*OHI* = 0) was considered as the critical density based on the LLWR (Bdc$_{LLWR}$), because at this density, physical-hydric limitations of the plant development will occur at any level of water content in the soil.

Soil macroporosity values were adjusted according to Bd by linear regression. This parameter is critical for root growth (Vomocil & Flocker, 1966). It is based on macroporosity (Bdc$_{MAC}$) and limited to soil edaphic functions related to water infiltration and underground water cycling; likewise, it considers a Bd value corresponding to a macroporosity of 0.10 dm^3 dm^{-3}.

Values of initial bulk density (Bdi), beneficial (Bdb) and critical to plant growth (Bdc$_{LLWR}$) obtained from LLWRs, together with values of Bdc$_{MAC}$, were used in the development of pedotransfer functions to estimate these properties from clay soil content. These functions were obtained through linear adjustments between the mentioned properties and compared according to statistical procedures described by Snedecor & Cochran (1989).

The regression analyses were adjusted with software SigmaPlot 10.0, Jandel Scientific. The data of soil physical properties prior to compression were subjected to the analysis of variance, based on a completely randomized design, and means were compared with the Tukey test; p values lower than 0.05 were considered significant.

RESULTS AND DISCUSSION

Physical properties of the studied soils are listed in table 3. Due to the high weathering degree, the unit particles of Latosols are arranged in small grains (Vollant-Tuduri et al., 2005), which increased the level of porous space among aggregates and resulted in a naturally low bulk density (Ferreira et al., 1999b; Balbino et al., 2004; Oliveira et al., 2007). Basically, structural variations between soils were observed in the granulometric composition, because the development of texture pores (micropores) increased with clay content (Reatto et al., 2007; Silva et al., 2008).

Macroporosity can be considered high in all soils and far above the value of 0.10 $dm^3 dm^{-3}$, considered critical for plant growth (Vomocil & Flocker, 1966; Oliveira et al., 2003). These properties favor the processes of water conduction (Cooper & Vidal-Torrado, 2005), even in these soils of fine texture (Borges et al., 2009). In general, there was an increase in macroporosity in more clayey soils (Table 3), which is in agreement with Ferreira et al. (1999a), who demonstrated a positive correlation among these properties in oxidic Latosols.

Table 3. Physical properties of Latosols (L) in the county of Rio Verde, GO

Latosol(1)	Bd	Porosity			Mac:Mic
		Total	Macro	Micro	
	kg dm^{-3}	$dm^3 dm^{-3}$			
L_{152}	1.33A	0.50C	0.34B	0.16C	2.13A
L_{263}	1.22B	0.56B	0.32B	0.24B	1.33B
L_{399}	1.08C	0.60B	0.33B	0.27B	1.19C
L_{521}	0.99D	0.66A	0.35AB	0.30AB	1.17C
L_{716}	0.83E	0.70A	0.37A	0.33A	1.12C

(1) Subscripts in the abbreviation of Latosols correspond to the respective clay contents (g kg^{-1}). Bd: Bulk density; Mac:Mic: relationship between macropores and micropores. For each property, averages followed by the same capital letters do not differ from each other by the Tukey test at 5%. Values represent averages of 32 replications.

It is recommendable that under ideal cultivation conditions one third of the total porosity of a soil sould be represented by macropores and the other two thirds by micropores, resulting in a macropore : micropore relationship of 0.5 (Kiehl, 1979; Oliveira et al., 2003). In the studied Latosols, this ratio was two to four times higher (Table 3). Under these conditions, the water in the soil would be quickly percolated, demonstrating a high infiltration capacity, which is positive in terms of recycling underground water.

The soil penetration resistance curve (PRC) demonstrated that RP was inversely related with è and directly related with Bd (equations 2 to 6) because the action of these factors was considered the main reason for the higher cohesion among soil particles (Leão et al., 2006; Blainski et al., 2009). In contrast, with the increase of soil compaction, aeration might become impaired at high water contents (Lapen et al., 2004). Therefore, for both θ_{PR} and θ_{AFP}, the water layers available to crops were reduced, which is likely to affect the growth and yield of cultivated plants by these stress factors (Silva et al., 1994).

Under the initial structural conditions, i.e., when the soil was not affected by any structural change due to previous compression (Table 3), the highest and the lowest limits were, respectively, θ_{FC} and θ_{WP}, which corresponded to the available water content (AW) for all the studied Latosols (Figure 1). Under these conditions, the soil physical quality can be considered ideal; however, stress that limits plant development can only be caused by other soil extrinsic factors such as water deficit, which in turn depend on climatic seasonality (Silva et al., 1994).

At higher soil compaction, these limits were substituted first of all in the θ_{PR} of all the soils; this property was the one that most frequently reduced the LLWR (Figure 1). This behavior was due to the grain structure of these Latosols with more developed structural pores (macropores), which, in turn, favors a high aeration of these pores (Ferreira et al., 1999a,b; Cooper & Vidal-Torrado, 2005; Reatto et al., 2007). The same was observed in other Latosols (Tormena et al., 1998; Leão et al., 2006; Severiano et al., 2008; Freddi et al., 2009), and the results indicate that problems related to anoxia in oxidic Latosols occur only when the structure is extremely degraded (high compaction) or in a relatively short period when the water content is above the field capacity due to the dynamic behavior of water in the soil (Blainski et al., 2009).

In contrast, under natural conditions, the development of textural pores (micropores), responsible for water retention processes (Balbino et al., 2004; Vollant-Tuduri et al., 2005; Reatto et al., 2007) in these soils is low. Therefore, it was suggested by Resende et al. (2007) that some degree of soil compaction could be beneficial in highly weathered Latosols with low water retention capacity, because part of the macropores could be transformed into micropores,

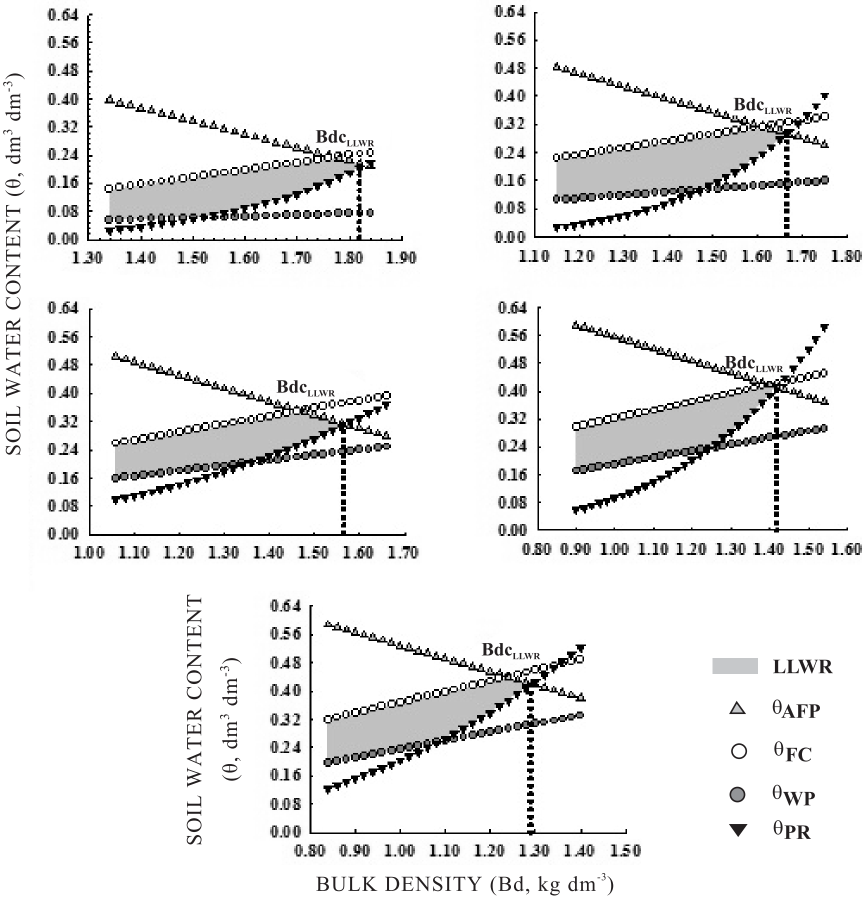

Figure 1. Variation in soil water content (θ) with the increase in bulk density (Bd) in the critical limits of field capacity (θ_{FC}, -6 kPa), permanent wilting point (θ_{WP}, -1,500 kPa), aeration porosity of 10 % (θ_{AFP}) and soil penetration resistance 2.5 MPa (θ_{PR}), of Latosols (L) in the county of Rio Verde. Gray areas represent the least limiting water range (LLWR); Bdc_{LLWR}: critical density for plant development, corresponding to LLWR. Subscripts in the abbreviation of Latosols indicate clay contents (g kg^{-1}).

resulting in an increase in crop productivity, mainly in drier years (Richart et al., 2005; Beutler et al., 2008; Freddi et al., 2009). Severiano et al. (2011) proposed a quantification of the pressure levels indicated to obtain beneficial compaction.

This behavior can be visualized in figures 1 and 2, where water retention in field capacity and, consequently, the LLWR increased as the bulk density increased until θ_{PR} replaced θ_{WP}. At this point, the available water reached the maximum value (Figure 2) whereas no oxygen limitations and mechanical resistance for root growth in the available water layer were observed (Figure 1). Therefore, this level of compaction was beneficial in terms of water retention. Similar results were found by Tormena et al. (1998) and Leão et al. (2006).

The increase in water retention with compaction decreased as the clay content in the soil increased (33 % increase for L_{152}; 28 % for L_{263}; 23 % for L_{399}; 15 % for L_{521} and; 12 % for L_{716}; Figure 2). This fact is important in the management of Latosols of medium texture because, once the water retention capacity is low (Giarola et al., 2002; Embrapa, 2006; Silva et al., 2008), these soils are more vulnerable to the effects of short summer droughts that occur during crop development than clayey soils. The increase in microporosity, obtained through an appropriate management, would minimize the consequences of this feature.

Regardeless of the higher water retention as a consequence of light soil compaction, the amount of available water in the soil, obtained from the LLWR (Figure 2), was similar in the studied Latosols, and the absolute value was always lower than 0.15 dm^3 dm^{-3}, independent of the textural variation among them. These findings are in agreement with results obtained by Giarola et al. (2002) and Silva et al. (2008) through the analysis of water retention curves, which characterized the homogeneity of available water in Oxidic Latosols.

Figure 2 also shows that Bd values at LLWR zero (Bdc_{LLWR}) were higher in all soils than where macroporosity reached a value of 0.10 dm^3 dm^{-3} (Figure 3) and, therefore, the soil had a higher

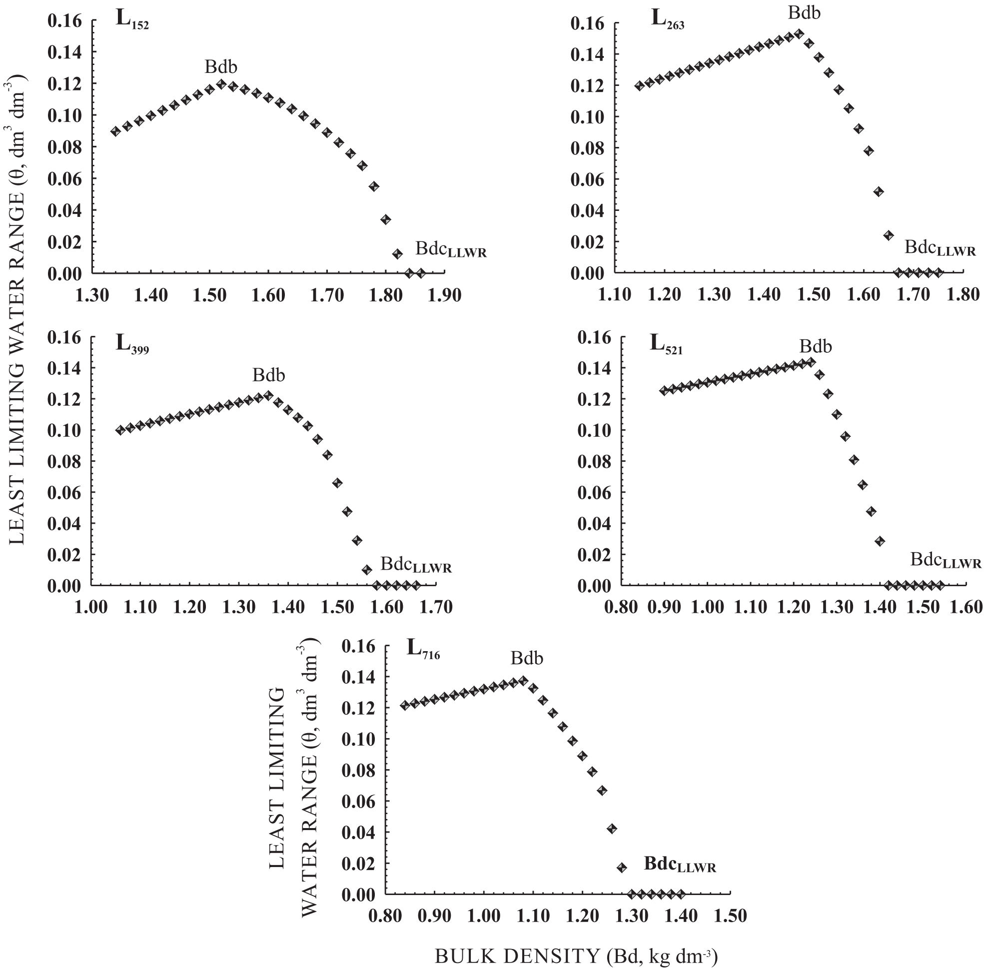

Figure 2. Variation of the least limiting water range (LLWR) with bulk density (Bd) in Latosols (L) in the county of Rio Verde, GO. Bdb: beneficial density to increase soil water retention; BdcLLWR: critical density for plant development, corresponding to LLWR. Subscripts in the abbreviation of Latosols indicate clay contents ($g\ kg^{-1}$).

compaction degree. Severiano et al. (2008) suggested that the determination of Bd reference values that indicate severe structural degradation in studies of soil compaction should be based on macroporosity (Bdc_{MAC}), rather than on Bdc_{LLWR} (Tormena et al., 1998, 2007; Beutler et al., 2008). In this latter case, drainable porosity may already be affected. The maintenance of macroporosity at appropriate levels underlies the physical soil conditions that are favorable to obtain satisfactory yields, and contributes to environmental sustainability. This pore class determines the potential water movement in the soil (Ferreira et al., 1999a; Mesquita & Moraes, 2004), which is fundamental for underground water infiltration and replenishment and for the reduction of soil loss by erosion (Hamza & Anderson, 2005). The lower compaction degree of Bdc_{MAC} as compared to Bdc_{LLWR} was also observed by Reichert et al. (2009). Consequently, soil hydrological properties are affected before soil compaction becomes restrictive to crop growth and yield.

The results discussed above demonstrate that under natural conditions, the plant growth conditions of oxidic Latosols are sub-optimal, since the low microporosity reduces water retention, whereas the high macroporosity may hamper the soil-seed contact, which is fundamental for the germination and establishment of plant populations (Richart et al., 2005; Modolo et al., 2008) (Table 3). Low levels of soil compaction can therefore be beneficial to plant growth owing to the increase in water retention. Likewise, the severe restrictive conditions to edaphic functions related to water infiltration and cycling call for the determination of reference values of soil compaction, even with values of Bd > Bdc_{MAC} or Bdc_{LLWR} (Figures 2 and 3).

Since bulk density is the most direct quantitative measure in the diagnosis of compaction and given its strong correlation with other soil physical-hydric properties (Horn & Fleige, 2003; Fritton, 2006; Oliveira et al., 2007), this property has been widely

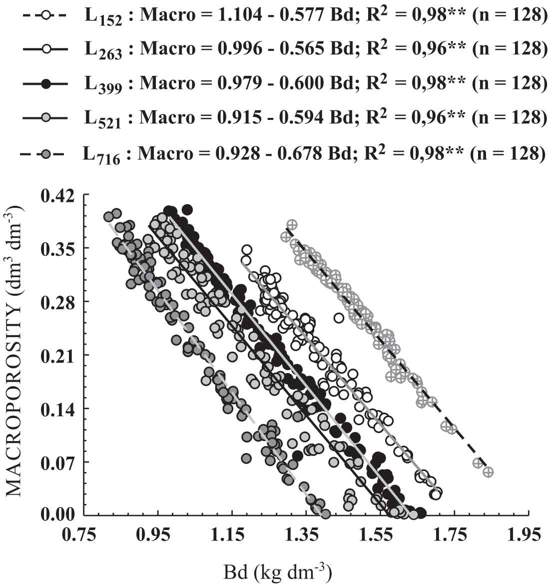

Figure 3. Macroporosity based on the increase of bulk density (Bd) in Latosols (L) in the county of Rio Verde, GO. Subscripts in the abbreviation of Latosols indicate clay contents (g kg^{-1}).

used in studies on soil structural changes. However, the strong influence of soil texture and structure on this property limits the choice of an absolute reference value (Camargo & Alleoni, 1997; Severiano et al., 2008), and mathematical functions are required to determine Bd values in relation with soil functions e.g., plant growth and yield as well as water infiltration, based on easily measurable properties.

These functions were obtained by linear adjustments between Bd values connected to structural changes and to clay content (Figure 4). The comparison of regressions by statistical procedures described by Snedecor & Cochran (1989) detected no differences among values of angular coefficients of the four equations, indicating that the increase in clay fraction reduced Bd values in a similar way, independent of the soil compaction degree, as reported by Reichert et al. (2009). Therefore, based on linear coefficients, an increase of 15 % of the initial bulk density (Bdi) would represent beneficial compaction, 27 % a macroporosity reduction to 0.10 dm^3 dm^{-3} (Bdc$_{MAC}$) and an increase of 35 % restricted plant development, based on the least limiting water range (Bdc$_{LLWR}$).

In a similar study using reference values of different soil classes of subtropical regions in Brazil, Reichert et al. (2009) found Bdc$_{LLWR}$ values lower than presented in figure 4. Probably, due to the predominant caulinitic mineralogy of the soils in this Brazilian region, they skow a trend to block-like structure formation (Kämpf & Schwertmann, 1983; Melo et al., 2004). In contrast, the pedogenesis of this kind of structure is associated with the development of a dense plasma (Ferreira et al., 1999b), with predominance of textural pores (Cooper & Vidal-Torrado, 2005), which increases the natural bulk density compared to oxidic Latosols under similar granulometric conditions (Ferreira et al., 1999a; Ajayi et al., 2009). For this reason, physical restrictions to plant growth and yield may occur at lower Bd values in soils with block-like than in soils with granular structure (Severiano et al., 2008) because its high aeration porosity extends the positive range of LLWR (Figure 1).

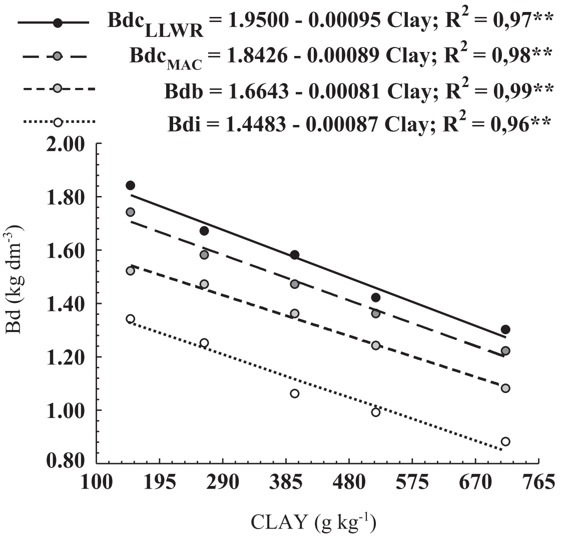

Figure 4. Initial bulk density (Bdi), beneficial density in terms of increase in soil water retention (Bdb), critical density for a reduction of macroporosity to 0.10 dm^3 dm^{-3} (Bdc$_{MAC}$), and critical density to plant growth and yield, based on the least limiting water range (Bdc$_{LLWR}$) and clay content of Latosols (L) in the county of Rio Verde, GO.

CONCLUSIONS

1. On the one hand, soil compaction resulted in benefits to soil water retention and on the other to severe restrictive conditions of its edaphic functions.

2. All compaction levels quantified by reference bulk density values (Bdi, Bdb, Bdc$_{LLWR}$ and Bdc$_{MAC}$) decreased at higher clay contents.

3. Bdc$_{MAC}$ was more restrictive to a sustainable management of the studied Latosols than Bdc$_{LLWR}$.

4. The higher tolerable compaction degree of oxidic Latosols is due to its high aeration porosity related to its granular structure.

LITERATURE CITED

AJAYI, A.E.; DIAS JUNIOR, M.S.; CURI, N.; ARAUJO JUNIOR, C.F.; SOUZA, T.T.T. & INDA JUNIOR, A.V. Strength properties and compaction susceptibility of Brazilian Latosols. Soil Tillage Res., 105:122-127, 2009.

BALBINO, L.C.; BRUAND, A.; COUSIN, I.; BROSSARD, M.; QUÉTIN, P. & GRIMALDI, M. Change in the hydraulic properties of a Brazilian clay Ferralsol on clearing for pasture. Geoderma, 120:297-307, 2004.

BENGOUGH, G.A.; BRANSBY, M.F.; HANS, J.; MCKENNA, S.J.; ROBERTS, T.J. & VALENTINE, T.A. Root responses to soil physical conditions: Growth dynamics from field to cell. J. Exper. Bot., 57:437-447, 2006.

BEUTLER, A.N.; CENTURION, J.F.; SILVA, A.P.; CENTURION, M.A.P.C.; LEONEL, C.L. & FREDDI, O.S. Soil compaction by machine traffic and least limiting water range related to soybean yield. Pesq. Agropec. Bras., 43:1591-1600, 2008.

BLAINSKI, E.; GONÇALVES, A.C.A.; TORMENA, C.A.; FOLEGATTI, M.V. & GUIMARÃES, R.M.L. Intervalo hídrico ótimo num Nitossolo Vermelho distroférrico irrigado. R. Bras. Ci. Solo, 33:273-281, 2009.

BORGES, T.A.; OLIVEIRA, F.A.; SILVA, E.M. & GOEDERT, W.J. Avaliação de parâmetros fisico-hídricos de Latossolo Vermelho sob pastejo e sob Cerrado. R. Bras. Eng. Agríc. Amb., 13:18-25, 2009.

BUSSCHER, W.J. Adjustment of flat-tipped penetrometer resistance data to common water content. Trans. Am. Soc. Agric. Eng., 33:519-524, 1990.

CAMARGO, O.A. & ALLEONI, L.R.F. Compactação do solo e o desenvolvimento de plantas. Piracicaba, Escola Superior de Agricultura “Luiz de Queiroz”, 1997. 132p.

COOPER, M. & VIDAL-TORRADO, P. Caracterização morfológica, micromorfológica e físico-hídrica de solos com horizonte B Nítico. R. Bras. Ci. Solo, 29:581-595, 2005.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. Centro Nacional de Pesquisas de Solos. Manual de métodos de análises de solo. 2.ed. Brasília, Produção de Informação, 1997. 212p.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. Centro Nacional de Pesquisa de Solos. Sistema brasileiro de classificação de solos. 2.ed. Brasília, Produção de Informação, 2006. 306p.

FERREIRA, M.M.; FERNANDES, B. & CURI, N. Influência da mineralogia da fração argila nas propriedades físicas de Latossolos da região sudeste do Brasil. R. Bras. Ci. Solo, 23:515-524, 1999a.

FERREIRA, M.M.; FERNANDES, B. & CURI, N. Mineralogia da fração argila e estrutura de Latossolos da região sudeste do Brasil. R. Bras. Ci. Solo, 23:507-514, 1999b.

FREDDI, O.S.; CENTURION, J.F.; DUARTE, A.P. & PERES, F.S.C. Compactação do solo e produção de cultivares de milho em Latossolo Vermelho: II – Intervalo hídrico ótimo e sistema radicular. R. Bras. Ci. Solo,33:805-818, 2009.

FRITTON, D.D. Fitting uniaxial soil compression using initial bulk density, water content, and matric potential. Soil Sci. Soc. Am. J., 70:1262-1271, 2006.

GIAROLA, N.F.B.; SILVA, A.P. & IMHOFF, S. Relações entre propriedades físicas e características de solos da região sul do Brasil. R. Bras. Ci. Solo, 26:885-893, 2002.

HAMZA, M.A. & ANDERSON, W.K. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil Tillage Res., 82:121-145, 2005.

HORN, R. & FLEIGE, H. A method for assessing the impact of load on mechanical stability and on physical properties of soils. Soil Tillage Res., 73:89-99, 2003.

KÄMPF, N. & SCHWERTMANN, U. Relações entre óxidos de ferro e a cor em solos cauliníticos do Rio Grande do Sul. R. Bras. Ci. Solo, 7:27-31, 1983.

KIEHL, E.J. Manual de edafologia. São Paulo, Ceres, 1979. 262p.

LAPEN, D.R.; TOPP, G.C.; GREGORICH, E.G. & CURNOE, W.E. Least limiting water range indicators of soil quality and corn production, Eastern Ontario, Canada. Soil Tillage Res., 78:151-170, 2004.

LEÃO, T.P.; SILVA, A.P.; MACEDO, M.C.M.; IMHOFF, S. & EUCLIDES, V.P.B. Least limiting water range: A potential indicator of changes in near-surface soil physical quality after the conversion of Brazilian Savanna into pasture. Soil Tillage Res., 88:279-285, 2006.

MELLO, C.R.; OLIVEIRA, G.C.; RESCK, D.V.S.; LIMA, J.M. & DIAS JUNIOR, M.S. Estimativa da capacidade de campo baseada no ponto de inflexão da curva característica. Ci. Agrotec., 26:836-841, 2002.

MELO, G.W.; MEURER, E.J. & PINTO, L.F.S. Fontes de potássio em solos distroférricos cauliníticos originados de basalto no Rio Grande do Sul. R. Bras. Ci. Solo, 28:597-603, 2004.

MESQUITA, M.G.B.F. & MORAES, S.O. A dependência entre a condutividade hidráulica saturada e atributos físicos do solo. Ci. Rural, 34:963-969, 2004.

MODOLO, A.J.; FERNANDES, H.C.; SCHAEFER, C.E.G. & SILVEIRA, J.C.M. Efeito da compactação do solo sobre a emergência de plântulas de soja em sistema plantio direto. Ci. Agrotec., 32:1259-1265, 2008.

OLIVEIRA, G.C.; DIAS JUNIOR, M.S.; RESCK, D.V.S. & CURI, N. Alterações estruturais e comportamento compressivo de um Latossolo Vermelho distrófico argiloso sob diferentes sistemas de uso e manejo. Pesq. Agropec. Bras., 38:291-299, 2003.

OLIVEIRA, G.C.; SEVERIANO, E.C. & MELLO, C.R. Dinâmica da resistência à penetração de um Latossolo Vermelho da microrregião de Goiânia, GO. R. Bras. Eng. Agríc. Amb., 11:265-270, 2007.

RATHMANN, R.; SZKLO, A. & SCHAEFFER, R. Land use competition for production of food and liquid biofuels: an analysis of the arguments in the current debate. Ren. Energy, 35:14-22, 2010.

REATTO, A.; BRUAND, A.; SILVA, E.M.; MARTINS, E.S. & BROSSARD, M. Hydraulic properties of the diagnostic horizon of Latosol of a regional toposequence across the Brazilian central plateau. Geoderma, 139:51-59, 2007.

REICHERT, J.M.; SUZUKI, L.E.A.S.; REINERT, D.J.; HORN, R. & HÅKANSSON, I. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Tillage Res., 102:242-254, 2009.

RESENDE, M.; CURI, N.; REZENDE, S.B. & CORRÊA, G.F. Pedologia: Base para distinção de ambientes. 5.ed. Lavras, Universidade Federal de Lavras, 2007. 322p.

RICHARDS, L.A. & WEAVER, L.R. Fifteen-atmosphere percentage as related to the permanent wilting point. Soil Sci., 56:331-339, 1943.

RICHART, A.; TAVARES FILHO, J.; BRITO, O.R.; LLANILLO, R.F. & FERREIRA, R. Compactação do solo: Causas e efeitos. Semina, 26:321-344, 2005.

SCHÄFFER, B.; STAUBER, M.; MUELLER, T.L.; MÜLLER, R. & SCHULIN, R. Soil and macro-pores under uniaxial compression: I mechanical stability of repacked soil and deformation of different types of macro-pores. Geoderma, 146:183-191, 2008.

SEVERIANO, E.C.; OLIVEIRA, G.C.; DIAS JUNIOR, M.S.; OLIVEIRA, L.F.C. & CASTRO, M.B. Pressão de preconsolidação e intervalo hídrico ótimo como indicadores de alterações estruturais do solo em decorrência das operações de colheita da cana-de-açúcar. R. Bras. Ci. Solo, 32:1419-1427, 2008.

SEVERIANO, E.C.; OLIVEIRA, G.C.; DIAS JÚNIOR, M.S.; COSTA K.A.P.; BENITES, V.M. & FERREIRA FILHO, S.M. Structural changes in Latosols of the Cerrado Region: II – Compressive behavior of soil and modeling of additional compaction. R. Bras. Ci. Solo, 35:783-791, 2011.

SILVA, A.P.; KAY, B.D. & PERFECT, E. Characterization of the least limiting water range. Soil Sci. Soc. Am. J., 58:1775-1781, 1994.

SILVA, A.P.; TORMENA, C.A.; FIDALSKI, J. & IMHOFF, S. Funções de pedotransferência para as curvas de retenção de água e de resistência do solo à penetração. R. Bras. Ci. Solo, 32:1-10, 2008.

SNEDECOR, G.W. & COCHRAN, W.G. Statistical methods. 8.ed. Ames, Iowa State University, 1989. 503p.

TAYLOR, D.W. Fundamentals of soil mechanics. New York, J. Wiley, 1948. 700p.

TORMENA, C.A.; ARAÚJO, M.A.; FIDALSKI, J. & COSTA, J.M. Variação temporal do intervalo hídrico ótimo de um Latossolo Vermelho distroférrico sob sistemas de plantio direto. R. Bras. Ci. Solo, 31:211-219, 2007.

TORMENA, C.A.; SILVA, A.P. & LIBARDI, P.L. Caracterização do intervalo hídrico ótimo de um Latossolo Roxo sob plantio direto. R. Bras. Ci. Solo, 22:573-581, 1998.

VOLLANT-TUDURI, N.; BRUAND, A.; BROSSARD, M.; BALBINO, L.C.; OLIVEIRA, M.I.L. & MARTINS, E.S. Mass proportion of microaggregates and bulk density in a Brazilian clayey oxisol. Soil Sci. Soc. Am. J., 69:559-1564, 2005.

VOMOCIL, J.A. & FLOCKER, W.J. Effect os soil compaction on storage and movement of soil, air and water. Trans. Am. Soc. Agric. Eng., 4:242-246, 1966.