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Ideal subsoiling moisture content of Latosols used in forest plantations

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Abstract

The interaction between moisture and soil significantly affects the performance of soil tillage equipment. This interaction has not been sufficiently studied for the subsoiling of forest areas in Brazil. For this reason, this study was conducted with the objectives of evaluating the degree of soil disturbance as a function of increasing clay and moisture contents, the relationship between soil resistance to penetration plus bulk density and moisture content, and establishing an ideal soil moisture interval for subsoiling, as a function of soil disturbance and bulk density. The research plots were established in a sandy clay loamy dystrophic Red Latosol (LVd-1), a kaolinite-rich clayey dystrophic Red Latosol (LVd-2), and a clayey dystrophic Red Latosol (LVd-3). The higher clay and organic matter contents in the LVd-3 imparted lower soil resistance to penetration, in view of the greater water adsorption of this soil. The three Latosols presented an inverse and quadratic relation between soil disturbance and moisture content increase. The increase in clay and kaolinite contents in these soils caused lower soil maximum densities and higher amounts of water required to reach their maximum densities. The LVd-1 showed better subsoiling conditions between the moisture contents of 0.07 and 0.13 $cm^3 cm^{-3}$, the LVd-3 between moisture contents of 0.14 and 0.27 $cm^3 cm^{-3}$, while the kaolinitic LVd-2 presented the lowest water range for subsoiling when compared to the other soils, between the moisture contents of 0.12 and 0.19 $cm^3 cm^{-3}$. The subsoiling water interval was based on two parameters (standard Proctor test and soil disturbance area) that may present much variation. These limitations suggest that new studies should be conducted to determine whether this interval should be adopted as an index for consideration when deciding upon the best condition for soil tillage.

Keywords: Subsoiler; Soil disturbance; Proctor test

1. Introduction

The tillage of forest soils comprises a set of operations with the objective of directly or indirectly promoting plant survival, their growth and uniformity, and ultimately increasing forest productivity. Rational tillage practices can prevent physical, chemical, and biological soil degradation, contributing to maintain, and in some cases increase its production potential, avoiding aggradation and the inflow of sediments and nutrients into water streams. In the early 1990s, great emphasis was given to soil conservation, which, in practice, meant applying conservation soil tillage techniques, termed the minimum tillage system (Vital et al., 1999; Gonçalves et al., 2002).

Minimum or reduced soil tillage consists of turning the soil as little as necessary, maintaining plant residues (from crops and invasive plants) on its surface. In most forest plantations in Brazil, only restricted tillage is performed, with soil mobilization exclusively on the planting row or pit, allowing fast root growth, and consequently greater efficiency in the use of water and nutrients adjacent to plants. The most commonly used implements in areas managed under the reduced soil tillage system are subsoiler, chisel plow and pit digger. Due to its greater operational capacity and low cost, subsoiling is the operation most commonly employed by Brazilian forestry companies, despite its operational limitations in areas with slopes greater than 20%, or on significantly rocky terrain or land containing very large stumps (Gava, 2002; Gonçalves et al., 2002; Silva et al., 2002b).

Although the presence of various pan layers is one of the basic premises for the use of subsoilers (Taylor and Beltrame, 1980; Rípoli et al., 1985; Gadanha Júnior et al., 1991; Silveira, 1988), in silviculture this operation often does not have the objective of breaking the compaction layer; instead, the goal is to displace a small portion of soil for planting and for the establishment of

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Table 1
Some physical attributes in the 0–40 cm layer of the studied soils

Soil	Clay ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Sand ($g\ kg^{-1}$)				Density ($Mg\ m^{-3}$)		Total ($m^3\ m^{-3}$)
			Fine	Medium	Coarse	Total	Particle	Bulk	Porosity
LVd-1	240	90	230	400	40	670	2.68	1.49	0.44
LVd-2	460	150	300	70	20	390	2.61	1.35	0.48
LVd-3	620	70	110	90	110	310	2.63	1.22	0.54

plants (Gonçalves, 2002b; Sasaki et al., 2002). In general, factors such as the configuration and number of tines, type of chisel, work speed and depth, water content, as well as soil type, the presence of pan layers, stumps and crop residues, are the parameters mostly interfering with the performance of subsoilers (Beltrame, 1983; Rípoli et al., 1985; Garner et al., 1987; Yshimine, 1993; Gava, 2002; Sasaki et al., 2002; Bentivenha et al., 2003). Although water content and soil type significantly affect the performance of soil tillage implements (Baver et al., 1972; McKyes, 1985), only a small number of studies have been conducted on this interaction during subsoiling, which motivated the conduction of this study. The objectives of this research were to evaluate the degree of soil disturbance (soil disturbed by the subsoiler) as a function of increasing clay and water contents, to evaluate the relation between resistance to penetration plus bulk density as a function of the water content, and to establish an ideal moisture interval for subsoiling, as a function of disturbance and bulk density.

2. Material and methods

The study was developed at Fazenda das Estrelas, located in the Municipality of Alambari/SP, with geographical coordinates 23°29′S and 47°42′W, and at Fazenda Santa Rosa, located in the Municipality of São Miguel Arcanjo/SP, with geographical coordinates 23°51′S and 47°51′W. The climate in the Alambari region is Cfa, according to Köeppen's classification, with a mean temperature in the hottest month (January) between 22 and 23 °C, while in the coolest month (July) it ranges 15 and 16 °C; during the 2 years of the research, the precipitation in this region was of 2825 mm. São Miguel Arcanjo has a Cfb climate, with a mean temperature in the hottest month (January) between 21 and 22 °C, and in the coolest month (July) it ranges 14 and 15 °C; during the 2 years of the research, the precipitation in this region was of 2792 mm.

The soil in the experimental area at Fazenda das Estrelas has been characterized as a loamy-textured Dark Red Dystrophic Latosol (LVd-1). At Fazenda Santa Rosa, the soils in the experimental areas have been characterized as a clayey-textured Dark Red Dystrophic Latosol (LVd-2) and a very clayey-textured Dark Red Dystrophic Latosol (LVd-3), according to EMBRAPA (1999a). Forty-eight intact samples were collected per soil at the depth of 0–20 cm, with the use of a soil probe, for characterization of oxides, by sulfuric attack, texture, by the pipette method and particle density, by the pycnometer method (EMBRAPA, 1997). The samples were collected with aluminum ring collectors bulk sampling rings, each one with approximately 98 cm^3 (ring diameter = 50 mm; ring height = 50 mm). Organic matter was determined according to EMBRAPA (1999b). Some of the morphological, physical, and chemical characteristics of the soil are presented in Tables 1–3.

The soil physic-mechanical analyses were performed in 24 intact samples for each soil type, collected at a 0–20 cm depth, in rings with a 50 mm diameter by 50 mm height. After saturation, these samples were subjected to potentials of −0.01 and −1.5 MPa, using pressure values applied to porous-plate apparatuses, according to Klute (1986). Once drainage had stopped and when apparent hydraulic equilibrium was reached, the samples were weighed and then dried in an oven at ± 105 °C for 24 h, for bulk density determination (Blake and Hartge, 1986).

The tractor used for pulling the subsoiler was a model 985S Valtra, equipped with a four cylinder, four-stroke forced aspiration engine, with a power of 77 kW (105 HP) at 2300 rpm and a torque of 390 Nm at 1400 rpm. The maximum lifting capacity of the hydraulic system was 25,408 N (2590 kgf) at 610 mm from the eyebolt. The 2H gear (second fast gear) was used during the evaluations, with an auxiliary front wheel drive engaged and engine rotation set at 2500 revolutions per minute.

A single-tine subsoiler was evaluated, mounted to the tractor's hydraulic three-point hitch, with depth control provided by a locking clamp. The subsoiling tine had a parabolic configuration represented by the equation $f(x) = 1.881 - 0.163x + 0.091x^2$ (Fig. 1). The subsoiler point had a width of 6.5 cm (Fig. 1), which enabled work at depths of 32.5–45.5 cm, since the ideal work depth should be five to seven times the point width (Spoor and Godwin, 1978).

The experimental treatments consisted of performing the subsoiling operations between field capacity (FC) and the

Table 2
Some chemical attributes in the 0 to 40 cm layer of the studied soils

Soil	H_2SO_4 attack ($d = 1.47$) ($g\ kg^{-1}$)			Ki[a]	Kr[b]	Organic matter ($g\ kg^{-1}$)
	SiO_2	Al_2O_3	Fe_2O_3			
LVd-1	36	84	27	0.73	0.61	1.8
LVd-2	96	140	87	1.16	0.83	3.1
LVd-3	68	211	84	0.55	0.44	3.5

[a] Ki is the molecular ratio between silica (SiO_2) and alumina (Al_2O_3); calculated by the formula: $\%SiO_2 \times 1.70 / \%Al_2O_3$.
[b] Kr is the molecular ratio between silica (SiO_2) and the sum of alumina (Al_2O_3) plus ferrous oxide (Fe_2O_3); calculated by the formula: $\%\ SiO_2 \times 1.70 / [\%Al_2O_3 + (\%Fe_2O_3 \times 0.64)]$.

Table 3
Some morphological attributes in the 0 to 40 cm layer of the studied soils

Soil	Moist color	Structure		Consistence			
		Type	Degree	Dry	Moist	Wet	
						Plasticity	Stickiness
LVd-1	2.5YR 3/4	Granular	Weak	Slightly hard	Friable	Slightly plastic	Slightly sticky
LVd-2	2.5YR 3/6	Subangular blocks	Strong	Hard	Friable	Plastic	Sticky
LVd-3	10R 3/6	Granular	Moderate	Slightly hard	Friable	Plastic	Sticky

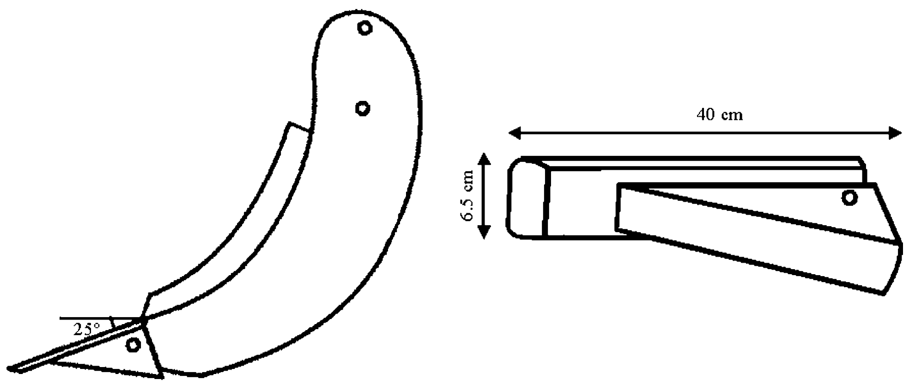

Fig. 1. Parabolic tine and dimensions of the subsoiler chisel without wings.

permanent wilting point (PWP). Subsoiling was performed for each soil type at five water content levels, found in situ during different drought periods. At the time of each subsoiling, 48 deformed soil samples were collected for water content determination by the gravimetric method (EMBRAPA, 1997). The samples were collected at the depths of 0–10, 10–20, 20–30 and 30–40 cm. The experimental design consisted of split-plots, with 15 treatments (3 soils and 5 water content levels) and four replicates. In the LVd-1, the water contents were 0.079; 0.087; 0.102; 0.115; 0.143 $cm^3\ cm^{-3}$. In the LVd-2, the water contents were 0.127; 0.152; 0.161; 0.177; 0.213 $cm^3\ cm^{-3}$, and in the LVd-3, the water contents were 0.151; 0.192; 0.227; 0.273; 0.322 $cm^3\ cm^{-3}$. FC in the LVd-1 was 0.17 $cm^3\ cm^{-3}$, in the LVd-2 it was 0.23 $cm^3\ cm^{-3}$, and in the LVd-3 it was 0.34 $cm^3\ cm^{-3}$. PWP in the LVd-1 was 0.07 $cm^3\ cm^{-3}$, in the LVd-2 it was 0.12 $cm^3\ cm^{-3}$, and in the LVd-3 it was 0.14 $cm^3\ cm^{-3}$. Each experimental plot had an area of 60 m^2, 20 m long and 3 m wide. Fifteen meters were reserved before each plot to allow subsoiler work speed and operation depth stabilization. Another 15 m after the plot were used for maneuvers and other operations. The data were submitted to descriptive statistical analysis, analysis of variance (ANOVA), and regression analysis as appropriate, all at the 5% probability level. The statistical programs used in the analyses were Sigmaplot (2002) and Statgraphics Plus for Windows (1995).

The soil disturbance area (SDA) was evaluated by the resistance zones method (Stape et al., 2002; Bentivenha et al., 2003). This method consists in making an initial evaluation of soil resistance to penetration with an impact penetrometer (Stolf et al., 1982) before subsoiling. Twenty randomized samples per experimental plots were collected at the maximum depth of 60 cm. After subsoiling, the impact penetrometer was used on three transects per experimental plot, perpendicularly to the central subsoiling row. These transects had a total width of 90, 45 cm to the left and 45 cm to the right of the central row. Probing was obtained every 15 cm (Fig. 2). The SDA was considered as the entire portion of soil that showed lower resistance to penetration than the resistance to penetration obtained before subsoiling. In the example of Fig. 2, the soil resistance to penetration obtained before subsoiling was 2.4 MPa (S.D. = 0.2 MPa), at a water content of 0.227 $cm^3\ cm^{-3}$. The soil disturbance area was, therefore, the soil portion showing a resistance to penetration lower than this value, highlighted in Fig. 2. The isolines with a resistance to penetration higher than the 2.4 MPa isoline resulted from the soil displacement caused by the passage of the subsoiler (Nichols et al., 1958).

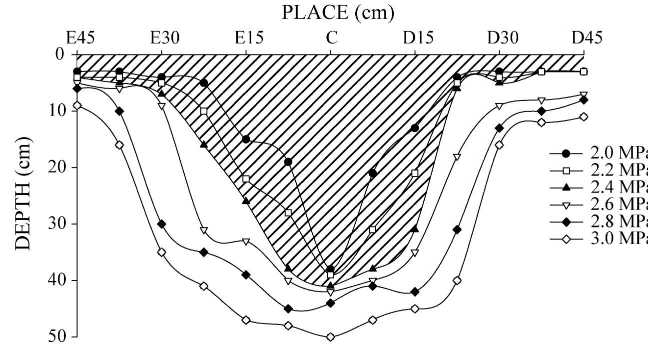

Fig. 2. Example illustrating soil resistance to penetration isolines, obtained with an impact penetrometer. On the X axis, point C is located on the central subsoiling row, and the others are located at a 15 cm distance to the left or to the right from one another. The highlighted area is delimited by the isoline that corresponds to the resistance to penetration before subsoiling (2.4 MPa); therefore, it designates the soil area displaced by subsoiling (SDA).

Maximum soil compaction was evaluated by the Proctor test, which provides a way to determine the water content at which a certain amount of energy will compact the soil to its densest state (maximum bulk density). Approximately 20 kg of each soil type were collected with an auger at a 20 cm depth. The test was replicated six times for each soil type, following the methodology described by Stancati et al. (1981).

3. Results and discussion

Soil resistance to penetration, evaluated before subsoiling, varied slightly among the Latosols and much among their water contents (Fig. 3). The clayey-textured Dark Red Dystrophic Latosol (LVd-2) showed resistance to penetration values close to the loamy-textured Dark Red Dystrophic Latosol (LVd-1), despite the fact that this soil has much higher contents of clay and silt.

The lower mean resistance of the LVd-3 (F-ratio = 15,51; P-value < 0.01) could be attributed to the higher clay and organic matter contents in the LVd-3 (Table 1), which increase the soil's water adsorption capacity (Baver et al., 1972; Seixas, 2002). Since soil resistance to penetration is strongly dependent upon soil moisture (Baver et al., 1972; Voorhees et al., 1978; Tormena et al., 1998; Seixas, 2002), the higher amount of adsorbed water in the LVd-3 suggests there will be lower resistance to penetration values, because resistance decreases exponentially as moisture increases (Silva et al., 2002a). Similar resistance to penetration values of the LVd-2 and the LVd-1 are attributed to the amount of kaolinite in this soil (Table 1), which results in greater hardness, cohesion, and mechanical resistance at lower water contents (Baver et al., 1972; Gonçalves, 2002a).

Just in the highest water content, layer 0–10 cm, there were differences among the soils for the resistance to penetration. At layer 10–30 cm, the resistance to penetration did not differ statistically in the less clayey soils (LVd-1 and LVd-2) and, in the clayey (LVd-3), it was always lower regardless of the water content (Fig. 4). The most probable explanation for the lower resistance to penetration values of the 0–10 cm layer, when compared with the 10–30 cm layer, was the higher degree of structure development in the surface layer, responsible for a lower bulk density and greater soil friability (Baver et al., 1972). Higher resistance to penetration values in the 10–30 cm layer for the three Latosols could have been caused by vehicle traffic (wheel pressure) on the soil surface, propagating through

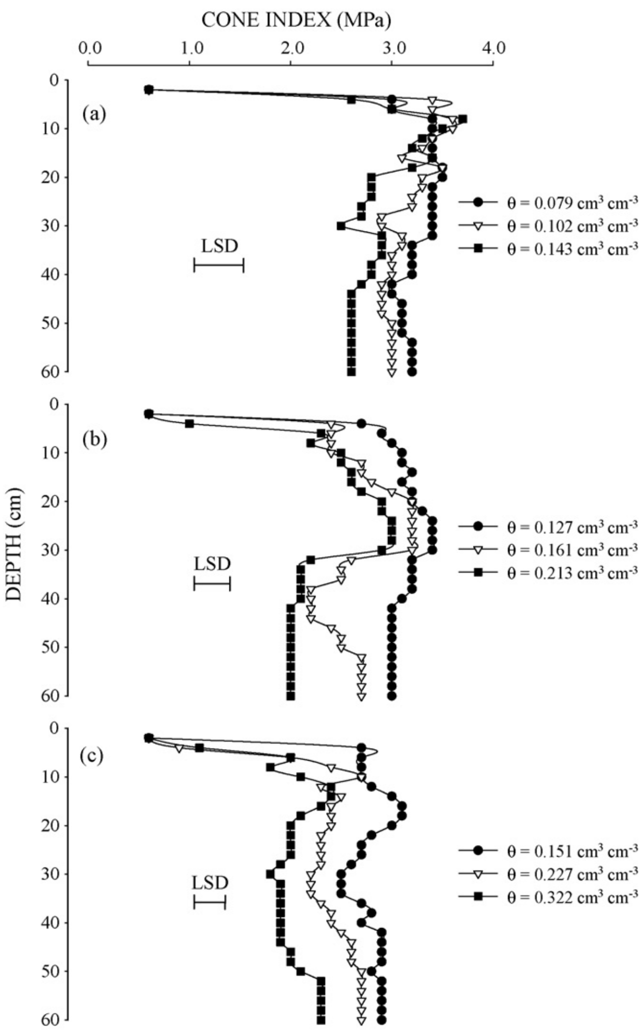

Fig. 3. Soil resistance to penetration, evaluated before subsoiling, under different water contents: (a) loamy-textured Dark Red Dystrophic Latosol (LVd-1), (b) clayey-textured Dark Red Dystrophic Latosol (LVd-2), and (c) very clayey-textured Dark Red Dystrophic Latosol (LVd-3). The horizontal error bars indicate the least significative difference (LSD) at $p = 0.05$.

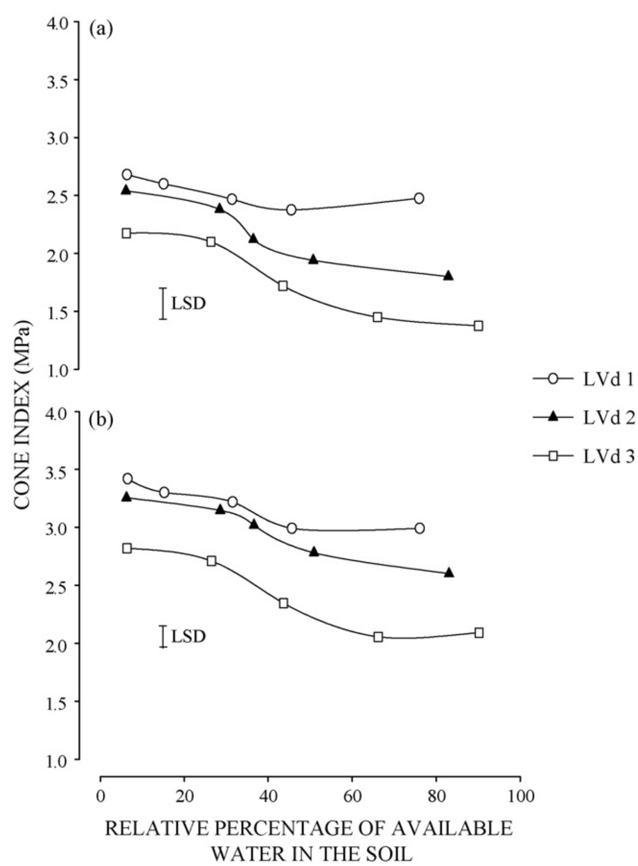

Fig. 4. Resistance to penetration variation as a function of relative percentage of available water in three Latosols: (a) 0–10 cm layer and (b) 10–30 cm layer. The error bars indicate the least significative difference at $p = 0.05$.

the soil (Gill and Reaves, 1956; Chancellor et al., 1962; Raghavan et al., 1976), since the areas had been harvested a few weeks before the experiment was started.

Water content affected the shape of displaced soil sections (Fig. 5). Soil lateral shear, from the subsoiler point up to the soil surface, follows a slope in relation to the horizon of approximately 45°, especially when the soil has low water contents. This trait was observed in the LVd-1 and LVd-3, which had lower water contents; however, at higher contents, the lateral shear angle for these soils was below 45° (Fig. 5a and c).

The lateral shear angle of less than 45°, observed for the LVd-1 and LVd-3, is attributed to the lubricating power of water, which does not support friction between the subsoiling tine and the soil, when it is significantly wet (Baver et al., 1972; Rosa Junior, 2000; Silva et al., 2002a). The lateral shear angle in the LVd-2 was greater than 45°, even at higher water contents (Fig. 5b). The most possible reason for this effect is the block structure caused by a higher amount of kaolinite, and consequently greater cohesion in this soil (Gonçalves et al., 2002a). Among the more friable soils, the fine-textured, moderately granular-structured LVd-3 showed greater disturbance than the coarser-textured, weakly granular-structured LVd-1. According to Baver et al. (1972) and Gonçalves (2002a), fine-textured soils are more cohesive when dry. Yshimine (1993) also observed greater SDA in a clayey Red Latosol when compared with a loamy-textured Red Latosol.

The LVd-1 had the highest maximum bulk density value, followed by the LVd-2 and the LVd-3 (Fig. 6). The water contents in the three Latosols, required to achieve their maximum bulk densities, also showed great variations. The maximum density increased with clay content. LVd-1 showed a maximum density with 0.15 $cm^3\ cm^{-3}$ water content, LVd-2

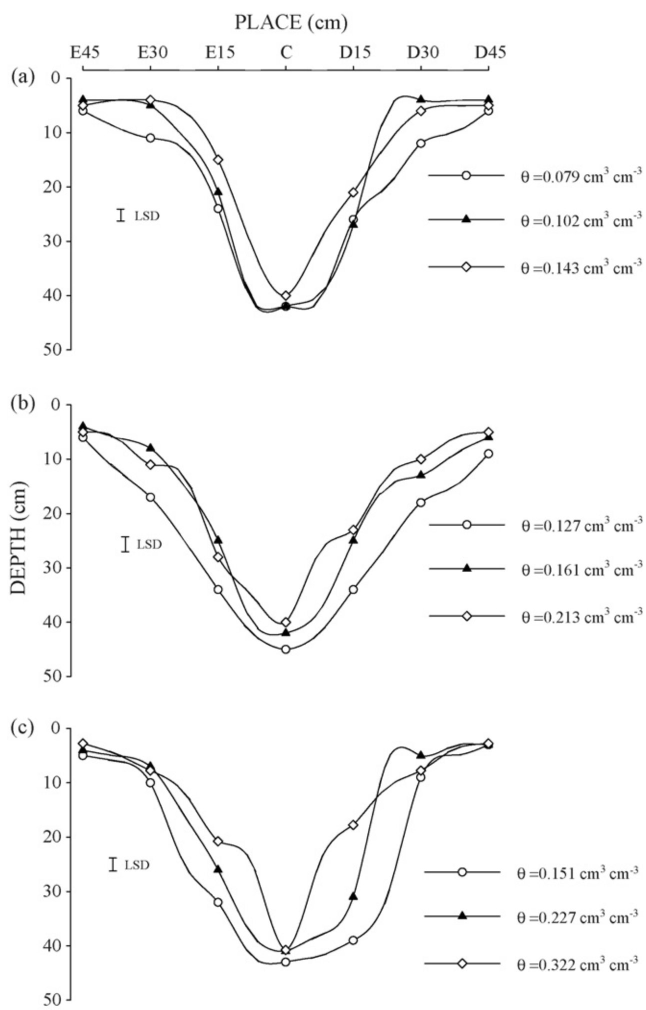

Fig. 5. Soil disturbance area as a function of water content: (a) loamy-textured Dark Red Dystrophic Latosol (LVd-1), (b) clayey-textured Dark Red Dystrophic Latosol (LVd-2), and (c) very clayey-textured Dark Red Dystrophic Latosol (LVd-3). On the X axis, point C is located on the central subsoiling row, and the others are located at a 15 cm distance to the left or to the right from one another. The error bars indicate the least significative difference (LSD) at $p = 0.05$.

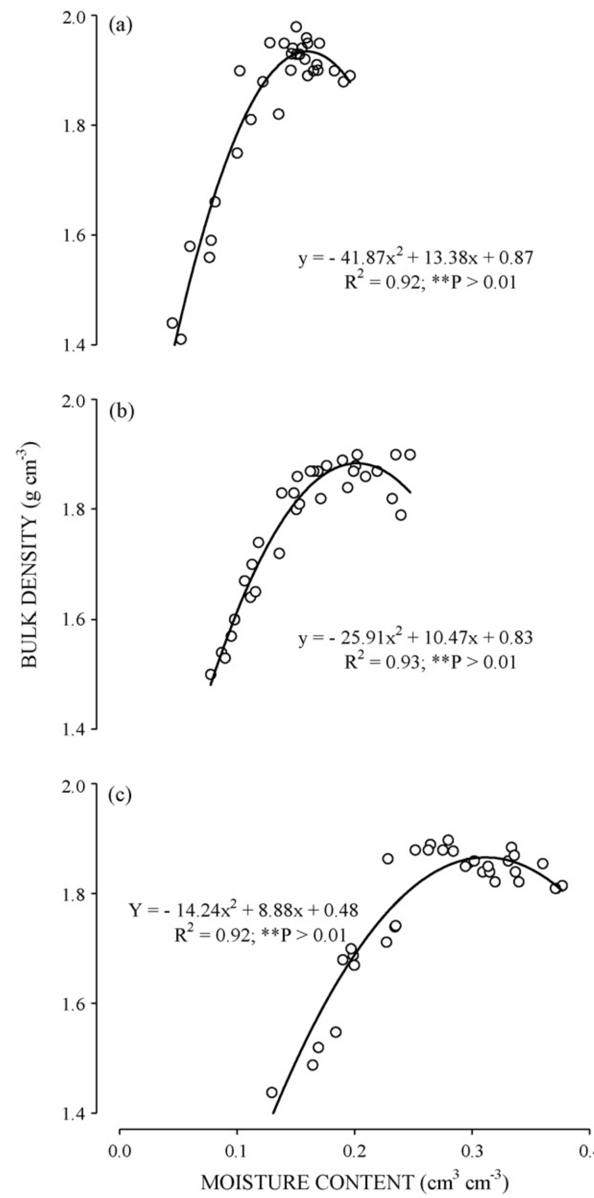

Fig. 6. Compaction curves obtained with standard Proctor test: (a) Loamy-textured Dark Red Dystrophic Latosol (LVd-1), (b) clayey-textured Dark Red Dystrophic Latosol (LVd-2), and (c) very clayey-textured Dark Red Dystrophic Latosol (LVd-3).

with 0.20 and LVd-3 with 0.32 $cm^3\ cm^{-3}$ water contents. The larger maximum bulk density of the LVd-1, followed by LVd-2 and LVd-3 is directly related to the texture and mineralogical composition of the soils. Clay and organic matter contents have an influence on the compaction curve position along the water content axis, while the sand content influences compaction curve amplitude (Howard et al., 1981; Ohu et al., 1986; Silva et al., 1986; Ekwue and Stone, 1997).

The lowest maximum bulk density for the LVd-3 occurred due to the higher clay and organic matter contents in this soil (Table 1), which increase water adsorption capacity by the soil (Howard et al., 1981; Ohu et al., 1986; Silva et al., 1986; Ekwue and Stone, 1997; Dias Júnior and Estanislau, 1999). Given the low compressibility of water, the soils with higher clay and organic matter contents, which adsorb more water, generally show smaller compaction indices (Baver et al., 1972; Voorhees et al., 1978; Tormena et al., 1998; Figueiredo et al., 2000). Although the LVd-2 had intermediate clay and organic matter contents, this soil showed a maximum bulk value that was statistically equal to the LVd-3. This is due to its kaolinitic mineralogy, which increases the soil's water retention capacity and expansion as compared with the mineralogy of the iron- and aluminum-oxide-rich soil (LVd-1), and of the loamy-textured soil (LVd-3) (Baver et al., 1972).

Fig. 7 shows the soil disturbance area as a function of the water contents in the Latosols. The soil disturbance decreased with the water content and increased with the clay content. The amplitude of variation of soil disturbance area varied less in the soils with less clay content in a smaller range of humidity.

Since the Proctor test is not performed as a routine analysis in soil physics laboratories, some researchers have sought

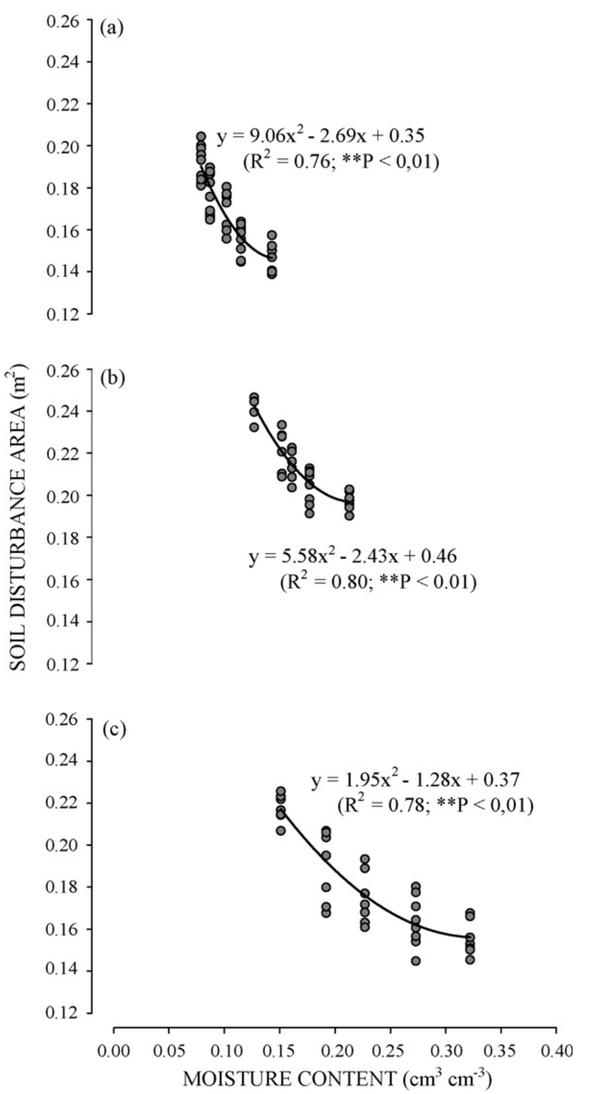

Fig. 7. Soil disturbance area as a function of water content: (a) loamy-textured Dark Red Dystrophic Latosol (LVd-1), (b) clayey-textured Dark Red Dystrophic Latosol (LVd-2), and (c) very clayey-textured Dark Red Dystrophic Latosol (LVd-3).

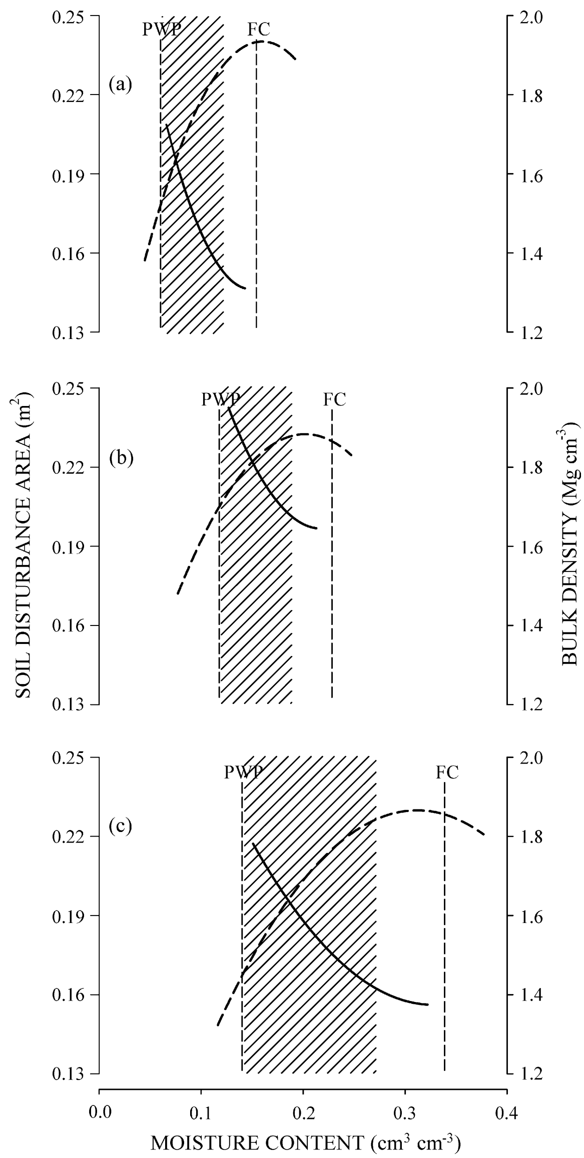

Fig. 8. Subsoiling water interval as a function of density (- - -), disturbance area (—) and water content in the soils: (a) loamy-textured Dark Red Dystrophic Latosol (LVd-1), (b) clayey-textured Dark Red Dystrophic Latosol (LVd-2), and (c) very clayey-textured Dark Red Dystrophic Latosol (LVd-3). PWP stands for permanent wilting point (−1.5 MPa); FC is the field capacity (−0.01 MPa). The hatched area represents the water interval at which subsoiling should be performed.

alternative methods to determine the moisture value at which maximum bulk density occurs. Thus, some attributes have been used, such as 90% of the plasticity limit, 90% of water retained at −0.01 Mpa, or water retained at −0.033 MPa (Figueiredo et al., 2000). In fact, the 90% field capacity values for the three Latosols (0.15 for LVd-1, 0.21 for LVd-2, and 0.31 $cm^3 cm^{-3}$ for LVd-3) were very close to the water contents required to obtain maximum density in these soils (0.15 for LVd-1, 0.20 for LVd-2, and 0.32 $cm^3 cm^{-3}$ for LVd-3).

Based on our soil disturbance and standard Proctor test results, we tried to obtain a water interval that would present higher SDA values and acceptable soil compaction levels, termed the subsoiling water interval (Fig. 8). Considering that Ojeniyi and Dexter (1979), Campbell et al. (1980), Howard et al. (1981), McKyes (1985), and Figueiredo et al. (2000) recommended soil mechanization be performed below the critical water content values (90% of the plasticity limit, 90% of water retained at −0.01 MPa or water retained at −0.033 MPa), we chose to use 80% of the field capacity and the permanent wilting point as upper and lower water limits, respectively. One observed that the LVd-1 should be subsoiled at water contents between 0.07 and 0.13 $cm^3 cm^{-3}$, the LVd-2 at water contents between 0.12 and 0.19 $cm^3 cm^{-3}$, and the LVd-3 at water contents between 0.14 and 0.27 $cm^3 cm^{-3}$. These results showed that subsoiling is more effective when performed at lower water contents, as stated by some researchers (Beltrame, 1983; McKyes, 1985; Rípoli et al., 1985; Lanças, 1988; Bicudo, 1990; Yshimine, 1993; Gava, 2002; Gonçalves, 2002b; Sasaki et al., 2002; Bentivenha et al., 2003).

The LVd-2 showed greater water restrictions to subsoiling when compared with the LVd-1 and the LVd-3 (Fig. 8). This may have occurred because of the soil's greater amounts of kaolinite, resulting in greater adherence and plasticity at higher water contents (Baver et al., 1972; Gonçalves, 2002a), decreased the subsoiler performance. The LVd-1 and LVd-3 showed less water restriction to subsoiling, probably because of their higher permeability, structuring degree, adherence, and friability (Baver et al., 1972; Gonçalves, 2002a).

4. Conclusions

1. The three soils showed a parabolic and inverse relation between soil disturbance area and increase in their water contents.
2. The kaolinitic Latosol (LVd-2) presented more water restrictions to be subsoiled than the other Latosols.
3. The subsoiling water interval was based on two parameters (standard Proctor test and soil disturbance area) that may present much variation. These limitations suggest that new studies should be conducted to determine whether this interval should be adopted as an index for consideration when deciding the best condition for soil tillage.

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