Comissão 2.2 - Física do solo

SOIL PHYSICAL PROPERTIES AND SUGARCANE ROOT GROWTH IN A RED OXISOL[1]

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SUMMARY

Sugarcane, which involves the use of agricultural machinery in all crop stages, from soil preparation to harvest, is currently one of the most relevant crops for agribusiness in Brazil. The purpose of this study was to investigate soil physical properties and root growth in a eutroferric red Oxisol (Latossolo Vermelho eutroférrico) after different periods under sugarcane. The study was carried out in a cane plantation in Rolândia, Paraná State, where treatments consisted of a number of cuts (1, 3, 8, 10 and 16), harvested as green and burned sugarcane, at which soil bulk density, macro and microporosity, penetration resistance, as well as root length, density and area were determined. Results showed that sugarcane management practices lead to alterations in soil penetration resistance, bulk density and porosity, compared to native forest soil. These alterations in soil physical characteristics impede the full growth of the sugarcane root system beneath 10 cm, in all growing seasons analyzed.

Index terms: *Saccharum* spp., compaction, monoculture.

RESUMO: *PROPRIEDADES FÍSICAS DE SOLO E CRESCIMENTO RADICULAR DE CANA-DE-AÇÚCAR EM UM LATOSSOLO VERMELHO*

A cana-de-açúcar é, na atualidade, uma das culturas de maior importância no agronegócio brasileiro, a qual envolve o uso de máquinas agrícolas em todas as fases do cultivo – do preparo do solo até a colheita. O objetivo deste trabalho foi estudar os atributos físicos e o crescimento de raízes em Latossolo Vermelho eutroférrico cultivado com cana-de-açúcar

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por diferentes períodos de tempo. O estudo foi conduzido em uma área de produção de cana-de-açúcar em Rolândia, Paraná, com diferentes tratamentos (número de cortes: 1, 3, 8, 10 e 16); a colheita foi realizada com cana queimada e corte manual, determinando-se: densidade, macro e microporosidade, resistência do solo à penetração, densidade do solo, densidade de comprimento e área de raízes. Conclui-se que as práticas de manejo na cultura da cana-de-açúcar promovem alterações na resistência, densidade e porosidade do solo, em comparação com a mata nativa; essas alterações nos atributos físicos foram impeditivas ao pleno desenvolvimento radicular da cana-de-açúcar além de 10 cm de profundidade, em todos os períodos de cultivo analisados.

Termos de indexação: Saccharum *spp., compactação, monocultivo.*

INTRODUCTION

Sugarcane is currently one of the most relevant crops for agribusiness in Brazil, not only for production of sugar, but of an alternative energy source (ethanol) as well, which helps reduce the dependence on non-renewable and increasingly less abundant energy sources such as oil. A number of studies have documented the significant changes brought about by the substitution of natural ecosystems by cane plantations (Silva et al., 2006a,b).

Growing sugarcane involves the use of agricultural machinery in all crop stages, from soil preparation to harvesting. According to Camilotti et al. (2005), the pressure of the heavy tractor and harvester traffic, as well as of agricultural implements in the crop inter-rows causes compaction and affects soil structure and root growth, reducing yields and the lifetime of the crop to a greater or lesser extent, according to the conditions.

The intensity at which soil physical properties under sugarcane are degraded varies widely and depends on the natural soil characteristics (Dominy et al., 2002; Silva et al., 2005; Centurion et al., 2007; Luca et al., 2008), the soil tillage system (Camilotti et al., 2005), cropping system (Maia & Ribeiro, 2004b), harvesting processes (Souza et al., 2005; Luca et al., 2008), soil conditions when farming operations are carried out (Ralisch et al., 1994), and the type of fertilization (Maia & Ribeiro, 2004b; Silva et al., 2006a).

The main changes observed in the soil consisted of a drop in organic matter content (OM) (Centurion et al., 2007; Luca et al., 2008), structural degradation evidenced by an increase in soil bulk density (Souza et al., 2005; Camilotti et al., 2005; Centurion et al., 2007), a decrease in macroporosity (Silva et al., 2005; Centurion et al., 2007), as well as increased soil penetration resistance (Souza et al., 2005; Brito et al., 2006; Iaia et al., 2006; Souza et al., 2006), mainly in soils under long-term monoculture.

Several studies have shown that penetration resistance (PR) between 1.0 and 3.5 MPa (Taylor & Gardner, 1963; Beutler & Centurion, 2004a,b; Beutler et al., 2006) and macroporosity lower than 0.10 $m^3 m^{-3}$ (Centurion et al., 2007), are restrictive and can impede root growth and development. However, Azevedo (2008) found that PR values between 1.5 and 9.6 MPa did not restrict sugarcane root growth due to the considerable heterogeneity of soil structures, allowing root growth even in the presence of compacted layers. This confirms that root growth and distribution are also affected by the soil structure, be it undisturbed or disturbed by human activity (Ralisch et al., 1994; Tavares Filho et al., 2001). Therefore, the purpose of this study was to investigate the physical characteristics and root growth of an eutroferric red Oxisol (Latossolo Vermelho eutroférrico) under sugarcane for different periods of time.

MATERIAL AND METHODS

The study was carried out on a sugarcane plantation of the farmers´ cooperative of Rolândia (Cooperativa de Produtores de Rolândia) (23º 15’ 01” S, 51º 28’ 36” W), Paraná - BR. The soil is a very clayey, eutroferric red Oxisol (Latossolo Vermelho eutroférrico - LVef), with tropical semi-evergreen forest vegetation and a flat to slightly undulating landscape (Embrapa, 2006). The regional climate was classified as Cfa (Köppen system), with an average annual rainfall of 1650 mm, maximum temperature of 27 °C and minimum of 18 °C.

Prior to sugarcane, the land was used for crop rotation of corn (maize), soybean and wheat in a conventional tillage system. Before planting cane, the area was disked once with a heavy, 32-inch disk plow, subsoiled to a depth of 0.40 m, harrowed once with a leveling harrow and furrows (depth 0.40 m) were opened, spaced 1.40 m apart. After the first cut, a three-fold management practice (i.e., chiseling in inter- rows of ratoon cane, associated with fertilization and harrowing) was carried out every year. This involves disking and subsoiling in the inter-row to decompact and fertilize the soil, and herbicide application to eliminate weeds. The triple management was not applied in treatment NH 16 because of the stumps scattered in the inter-rows. Sugarcane was harvested by hand. The number of harvests (NH), clay content (assessed according to Tavares Filho & Magalhães, 2008), organic C (Embrapa, 1997), varieties planted, and the main fertilizer applied in the areas studied are listed in table 1.

Six undisturbed soil samples were randomly collected from the inter-row of each area, 0.35 m away from the stumps, in 98 cm^3 volumetric rings, from the layers 0.0–0.10; 0.10–0.20 and 0.20–0.40 m, to determine bulk density (BD), macro (Ma) and microporosity (Mi). The porosity was assessed based on a tension table, according to Embrapa (1997).

Soil penetration resistance (PR) was determined m at intervals of 0.05 m, to a depth of 0.45, at two distances from the stumps (0.35 and 0.70 m) in the inter-row, at the second distance, samples were taken from the area treated with triple management At each distance, 10 replications were sampled per area, using a standard ASAE penetrometer (ASAE, 1986, Spectrum Technologies; base diameter 12.8 mm, angle 30°), in addition to automatic pressure recording (MPa) at 0.05 m intervals. The device was also equipped with a penetration speed control to minimize the risk of experimental errors if used by different operators. Soil penetration was tested soon after a period of prolonged rainfall, when the soil water content approached field capacity, and all areas were sampled on the same day.

To study the roots, trenches (length 2.10 m, depth 0.80 m, width 1.0 m) were opened across two sugarcane rows each. Three sets of root samples were taken by the cylindrical auger method (Bohm, 1979) within the same trench, from three layers (0.05–0.15; 0.20–0.30 and 0.35–0.45 m), at a distance of 0.05 m from the stumps and 0.35 m in the inter-row (auger diameter 0.101m, length 0.10 m).

The soil samples containing the roots were taken to the laboratory, separated under running water in sieves (1 mm mesh) and oven-dried at 60 ºC for 24 h, to obtain the dry weight (root dry weight density) on a precision balance. The roots were then scanned and the images analyzed using the Integrated System for Root and Soil Coverage Analysis (SIARCS - Sistema Integrado para Análise de Raízes e Cobertura do Solo. 3.0®) to determine root length, density and area (Jorge et al., 1996).

The data were analyzed independently for each soil in a completely randomized design and compared by the Tukey test at 5 %, using the SISVAR 5.0 computer program (Ferreira, 2000).

RESULTS AND DISCUSSION

In terms of the result accuracy (Table 2) for soil BD, PR, Ma and Mi, note that the coefficient of variance (CV) varied from low (< 10 %) to medium (10–20 %) for penetration resistance (Pimentel-Gomes, 1990), indicating a high level of experimental accuracy (Cargnelutti Filho & Storck, 2007).

Bulk density (BD) and soil penetration resistance (PR)

The mean soil bulk density (BD, Table 2) of the forest area differed from the treatments (NH), which in turn did not differ from each other. In terms of depth, the highest mean value was found in the 10–20 cm layer and differed from the other layers. These results show an increase in BD in soil under sugarcane and are in line with Souza et al. (2005);

Table 1. Number of harvests (NH), clay content and organic carbon content (OC) in the 0–40 cm layer, varieties and fertilization applied in the plantations

Treatment (NH)	Soil texture			OC	Variety	Mineral fertilization	Organic fertilization
	Clay	Silt	Sand				
	g kg^{-1}						
Forest	730	125	145	50.5			
1	654	137	209	14.7	SP 77-5181	250 kg ha^{-1} surface-applied Super N (46 % N) by spraying	103 m^3 ha^{-1} vinasse + filter cake 35 t ha^{-1}
3	656	140	204	17.6	SP 77-5181		103 m^3 ha^{-1} vinasse
8	762	117	121	16.4	SP 77-5181		103 m^3 ha^{-1} vinasse
10	699	100	201	18.3	RB 85-5156		103 m^3 ha^{-1} vinasse
16	708	100	192	20.5	RB 72-454		103 m^3 ha^{-1} vinasse

Camilotti et al. (2005); Centurion et al. (2007); and Tavares Filho et al. (2010).

Bulk density is known to be affected by plant cover, organic matter content and soil use and management (Corsini & Ferraudo, 1999; Silva et al., 2006a). In our study, the increase in soil BD under sugarcane indicates how harmful soil disaggregation following the intense use of agricultural machinery and implements can be for sugarcane, by gradually compressing the soil particles, leading to structural degradation and increased bulk density (Bertol et al., 2004; Costa et al., 2003; Silva et al., 2005). In addition, in the former management with burning before harvesting, the organic matter content had certainly been reduced (Table 1), causing a drop in soil microbial activity and affecting soil structure and stability (Tavares Filho et al., 2010).

The critical limit at which BD is believed to affect the normal growth of plant root systems varies from one author to another. For Arshad et al. (1996), a value of 1.40 kg dm^{-3} is generally accepted as the threshold, which increases as clay content decreases. For Derpsch et al. (1991), density is critical for values above 1.25 kg dm^{-3}, whereas for Corsini & Ferraudo (1999), density restricts root growth and water infiltration into the soil at values ranging from 1.27 to 1.57 kg dm^{-3}. Reinert et al. (2001) consider density critical for clayey soils at values of around 1.45 kg dm^{-3}. Therefore, since the clay content was > 650 g kg^{-1} (Table 1) in all treatments and the soil texture clayey, it was concluded that the mean BD values were 1.46 Mg m^{-3} (NH 10). Consequently, the values of 1.48 Mg m^{-3} (NH 1 and 8) and 1.49 Mg m^{-3} (NH 3 and 16) indicate compaction, which could restrict root growth and development, in addition to aggravating problems of water infiltration and soil aeration, and restricting biological activity.

In terms of PR (Table 2), the mean results show the same tendency as observed for BD, ie. the mean value under native forest was different from the cane areas, but not different between cultivation periods. The increased PR under cane, as opposed to native forest, showed that PR, as well as BD,

Table 2. Values for soil bulk density (BD), soil penetration resistance (PR), macro (Ma) and microporosity (Mi) in three layers of a eutroferric red Oxisol (Latossolo Vermelho eutroférrico) under sugarcane for different cultivation periods (number of harvests - NH) and under native forest

Treatment	Depth (cm)				Depth (cm)			
	0–10	10–20	20–40	MEAN(1)	0–10	10–20	20–40	MEAN(1)
	Soil bulk density (BD) (Mg m^{-3})				Penetration resistance* (PR) (MPa)			
Forest	1.13	1.29	1.16	1.19 B	0.97	1.21	1.06	1.08 C
NH 1	1.40	1.58	1.45	1.48 A	2.03	3.29	2.07	2.46 B
NH 3	1.42	1.57	1.47	1.49 A	2.52	3.66	2.72	2.97AB
NH 8	1.44	1.57	1.43	1.48 A	2.96	3.27	3.01	3.08 A
NH 10	1.42	1.51	1.45	1.46 A	3.71	3.83	3.51	3.68 A
NH 16	1.51	1.57	1.40	1.49 A	3.51	4.11	3.54	3.72 A
MEAN(1)	1.39 b	1.52 a	1.39 b	---	2.62 b	3.23 a	2.65 b	---
CV (%)		0.44				6.56		
LSD(Treat.)		0.10				0.76		
CV (%)		0.61				17.50		
LSD(Dpth.)		0.07				0.54		
	Soil Porosity (m^3 m^{-3})							
	Macroporosity (Ma)				Microporosity (Mi)			
Forest	0.20	0.20	0.20	0.20 A	0.13	0.30	0.30	0.24 A
NH 1	0.12	0.05	0.05	0.07 B	0.13	0.30	0.28	0.24 A
NH 3	0.10	0.07	0.05	0.07 B	0.13	0.35	0.32	0.27 A
NH 8	0.11	0.05	0.07	0.08 B	0.13	0.35	0.34	0.27 A
NH 10	0.10	0.07	0.05	0.07 B	0.14	0.34	0.32	0.27 A
NH 16	0.10	0.06	0.07	0.08 B	0.14	0.36	0.32	0.27 A
MEAN(1)	0.12 a	0.08 b	0.08 b	---	0.13 b	0.33 a	0.31 a	---
CV (%)		0.96				4.69		
LSD(Treat.)		0.04				0.04		
CV (%)		1.62				3.32		
LSD(Dpth.)		0.03				0.03		

(1) Means followed by the same letters, uppercase in columns and lowercase on rows, do not differ statistically from each other by the Tukey test at 5 %. CV: coefficient of variation. LSD: least significant difference. *Values obtained by gravimetric moisture (kg kg^{-1}) varying from 0.22 to 0.24 (±0.02)

was affected by soil management involving the use of agricultural machinery. The longer the system had been in use, the higher the variation in PR. In terms of depth, the highest mean value was found in 10–20 cm and differed from the mean values in the other layers. These results show a clear increase in the PR of soil under sugarcane and are in line with results obtained by Souza et al. (2005); Camilotti et al. (2005); Centurion et al. (2007); Tavares Filho et al. (2010).

A PR value of 2 MPa is normally considered high for the development of crop root systems, although the critical PR value can vary widely, according to the soil texture, structural conditions and management, as well as the crop type (Tavares Fiho et al., 2001). The mean values (2.46 to 3.72 MPa, respectively for (NH 1) and (NH 16)) are above the critical value and could therefore restrict crop root development.

Macroporosity (Ma) and Microporosity (Mi)

The results for soil Ma and Mi are shown in table 2. In terms of Ma, it can be seen that the forest area differs from the treatment areas (NH), but there is no difference among treatment areas. In terms of depth, the mean was highest in the 0–10 cm and differed from the other layers. For Mi, there was no difference in the mean between forest and treatment areas (NH), nor among the treatment areas. In terms of depth, the mean was highest in 10–40 cm and differed from the value in the 0–10 cm layer. These results show that the increase in BD, followed by the increase in PR of the soil, according to the number of harvests in sugarcane plantations (NH), caused a considerable Ma reduction, probably because of the intense use of agricultural machinery that destroys macropores and reduces the soil organic matter content (Neves et al., 2003; Bertol et al., 2004; Tavares Filho et al., 2010).

The effects of the different management periods were more marked in the 10–20 cm layer, so the difference between the mean macroporosity under forest (0.20 $m^3\ m^{-3}$) at this depth compared to the mean macroporosity (0.05 $m^3\ m^{-3}$) of soil under cane (NH1, NH 3, NH 5) resulted in a variation of 0.15 $m^3\ m^{-3}$, produced by the increase in soil mass due to the increase in BD from 1.29 (forest) to 1.56 $Mg\ m^{-3}$ (mean for treatment in the sugarcane areas) (Table 2). It is known that an increase in BD reduces soil porosity (mainly macroporosity), with a difference in the order of 0.01 $m^3\ m^{-3}$ in soil pore volume, accounting for a 10 $m^3\ Mg^{-1}$ decrease in the overall number of pores in the soil (Assouline et al., 1997; Tavares Filho & Tessier, 1998; Tavares Filho et al., 2010). Consequently, in the soil volume of 1 ha at a depth of 0.20 m, the macropores per hectare are reduced by 5.40 m^3, compared to soil under forest.

Since macroporosity is a direct result of the organization of primary particles in the soil, it represents one of the best quantitative parameters for detecting and assessing phenomena of structural degradation affecting oxygen diffusion, rainwater drainage and root development in the soil profile. It is known that macroporosity > 0.10 $m^3\ m^{-3}$ is necessary for gaseous exchange and root growth in most upland crops. According to the number of harvests in sugarcane plantations, macroporosity sinks below the threshold (10 %), indicating that the conditions in these areas are not favorable for plant development. These results reinforce the above studies, showing the extent to which the management of areas under sugarcane, from planting to harvesting, stresses the soil by machinery use, inducing processes of soil compaction and particle rearrangement (Silva et al., 2005; Tavares Filho et al., 2010).

Root length density (RLD) and dry mass density (DMD) and root area

The accuracy of the results (Table 3) for root length density, dry mass density and root area was reflected by the fact that CV values were low to medium (between 0 and 20 %) for root length density and dry mass density, and very high (CV > 30 %) for root area (Pimentel-Gomes, 1990). However, there seems to be a consensus among researchers on the use of CV as a measurement of experimental accuracy, and cases of experiments with average, high and very high values should not cause concern (Cargnelutti Filho & Storck, 2007), mainly with regard to rooting-related results.

The RLD data for different cane varieties in red Oxisol (LVef) with different crop periods (NH) (Table 3) show that RLD was highest for variety SP77-5181, with NH 8, differing from the lowest mean value (NH 1) observed for the same variety. There was no difference between the varieties RB 85-5156 and RB72-454 in relation to the two situations described above. In terms of depth, the mean RLD was highest in the 0–10 cm layer and differed from the other layers.

The dry mass density (DMD) and root area of different cane varieties in red Oxisol (LVef) grown over a number of years (NH) (Table 3) show the highest mean DMD and root area values for the variety SP77-5181, at NH 8, differing from the other varieties studied and other NH mean values (1, 3, 10, and 16). In terms of depth, the highest mean values for DMD and root area were obtained in the 0–10 cm layer and differed from the other layers.

The indices RLD, DMD and Root area differed significantly between the different crop periods (NH), and the NH 8 showed the highest values. These values was due to the root system increase over the years.

Table 3. Values for root length density (RLD), dry mass density (DMD) and root area at three depths in eutroferric red Oxisol (Latossolo Vermelho eutroférrico) after varying periods of sugarcane (number of harvests - NH)

Treatment	Variety	Depth (cm)			
		0–10	10–20	20–40	MEAN(1)
			RLD (cm cm^{-3})		
NH1	SP 77-5181	1.11	0.36	0.70	0.72 B
NH3	SP 77-5181	0.84	0.49	0.56	0.63 B
NH8	SP 77-5181	2.02	1.30	0.96	1.43 A
NH10	RB 85-5156	1.32	0.63	0.77	0.91 AB
NH16	RB 72-454	1.16	0.99	0.53	0.89 AB
MEAN(1)		1.29 a	0.75 b	0.70 b	-----
CV (%)			14.41		
LSD(Treat.)			0.60		
CV (%)			9.43		
LSD (Dpth.)			0.46		
			DMD (mg cm^{-3})		
NH1	SP 77-5181	0.58	0.31	0.37	0.42 B
NH3	SP 77-5181	0.57	0.39	0.20	0.39 B
NH8	SP 77-5181	0.96	0.67	0.38	0.67 A
NH10	RB 85-5156	0.65	0.38	0.30	0.44 B
NH16	RB 72-454	0.65	0.35	0.22	0.41 B
MEAN(1)		0.68 a	0.42 b	0.29 b	-----
CV (%)			9.15		
LSD(Treat.)			0.22		
CV (%)			3.19		
LSD(Dpth.)			0.17		
			Root Area (mm^2 cm^{-3})		
NH1	SP 77-5181	4.06	1.64	2.33	2.68 B
NH3	SP 77-5181	2.89	2.03	1.61	2.18 B
NH8	SP 77-5181	7.68	6.11	4.09	5.96 A
NH10	RB 85-5156	5.26	2.93	3.00	3.73 B
NH16	RB 72-454	5.63	3.50	2.35	3.83 B
MEAN(1)		5.10 a	3.24 b	2.68 b	-----
CV (%)			50.29		
LSD(Treat.)			1.83		
CV (%)			53.53		
LSD(Dpth.)			1.42		

(1) Means followed by the same letters, uppercase in columns and lowercase on rows, do not differ statistically from each other by the Tukey test at 5 %. CV: coefficient of variation. LSD: least significant difference.

The values of RLD, DMD and root area in the 0–0.10 m layer (1.29 cm cm^{-3}, 0.68 mg cm^{-3} and 5.10 mm^2 cm^{-3}, respectively) were 77; 89 and 72 % times higher than the values for the same characteristics in the 10–40 cm layer, indicating a high root concentration in the surface layer.

These results are in line with Dominy et al. (2002), Vasconcelos et al. (2003); Faroni & Trivelin (2006); Costa et al., 2007; and Luca et al. (2008), and correlate well with the physical characteristics (Table 2), ie. the values of RLD and DMD are lowest at depths where soil bulk density and penetration resistance are highest, and the RLD and DMD values highest at depths where macroporosity is highest. A higher root concentration in a given soil layer tends to produce greater amounts of OC, which may influence the physical, chemical and biological characteristics of this soil.

In addition, one of the known characteristics of tropical grasses is root accumulation near the surface, with a drop in biomass, root length density and root area in deeper layers, as reported by Smith et al. (2005) and Azevedo (2008). The results could also be due to the normally higher nutrient content in the top layer of soils under sugarcane (Maia & Ribeiro, 2004a). The authors would therefore attribute the root distribution in the soil to a set of complex and dynamic processes that include interactions between the environment, soil and plants in full growth.

CONCLUSIONS

1. Sugarcane management practices promote changes in soil penetration resistance, bulk density and porosity in comparison with native forest.

2. These changes in physical characteristics impeded the full root growth of sugarcane at depths below 10 cm in all cropping periods analyzed.

LITERATURE CITED

ARSHAD, M.A.; LOWERY, B. & GROSSMAN, B. Physical tests for monitoring soil quality. In: DORAN, J.W. & JONES, A.J., eds. Methods for assessing soil quality. Madison, Soil Science Society of America, 1996. p.123-141. (SSSA Special Publication, 49)

AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS - ASAE. Standards. 32.ed. St. Joseph, 1986. (S313.2)

ASSOULINE, S.; TAVARES FILHO, J. & TESSIER, D. Effect of compaction on soil physical and hydraulic properties: Experimental results and modeling. Soil Sci. Soc. Am. J., 61:391-398, 1997.

AZEVEDO, M.C.B. Efeito de três sistemas de manejo físico do solo no enraizamento e na produção de cana-de-açúcar. Londrina, Universidade Estadual de Londrina, 2008. 102p (Tese de Doutorado)

BERTOL, I.; ALBUQUERQUE, J.A.; LEITE, D.; AMARAL, A.J. & ZOLDAN JÚNIOR, W.A. Propriedades físicas do solo sob preparo convencional e semeadura direta em rotação e sucessão de culturas, comparadas à do campo nativo. R. Bras. Ci. Solo, 28:155-163, 2004.

BEUTLER, A.M. & CENTURION J.F. Resistência à penetração em Latossolos: Valor limitante à produtividade de arroz de sequeiro. Ci. Rural, 34:1793-1800. 2004a.

BEUTLER, A.M. & CENTURION, J.F. Compactação do solo no desenvolvimento radicular e na produtividade de soja. Pesq. Agropec. Bras., 39:581-588. 2004b.

BEUTLER, A.M.; CENTURION, J.F.; SILVA, A.P. & BARBOSA, J.C. Intervalo hídrico ótimo e produtividade de cultivares de soja. R. Bras. Eng. Agric. Amb., 10:639-645, 2006.

BÖHM, W. Methods of studying root systems. Berlim: Springer, 1979. 188p.

BRITO, L.F.L.; SOUZA, Z.M.; MONTANARI, R.; MARQUES JUNIOR, J.; CAZETTA, D.; CALZAVARA, S.A. & OLIVEIRA, L. Influência de formas do relevo em atributos físicos de um Latossolo sob cultivo de cana-de-açúcar. Ci. Rural, 36:1746-1755, 2006.

CAMILOTTI, F.; ANDRIOLI, I.; DIAS, F.L.F.; CASAGRANDE, A.A.; SILVA, A.R.; MUTTON, M.A. & CENTURION, J.F. Efeito prolongado de sistemas de preparo do solo com e sem cultivo de soqueira de cana crua em algumas propriedades físicas do solo. Eng. Agric., 25:189-198, 2005.

CARGNELUTTI FILHO, A. & STORCK, L. Estatísticas de avaliação da precisão experimental em ensaios de cultivares de milho Pesq. Agroec. Bras., 42:17-24, 2007.

CENTURION, J.F.; FREDDI, O.S.; ARATANI, R.G.; METZNER, A.F.M.; BEUTLER, A.N. & ANDRIOLI, I. Influência do cultivo da cana-de-açúcar e da mineralogia da fração argila nas propriedades físicas de Latossolos Vermelhos. R. Bras. Ci. Solo, 31:199-209. 2007.

CORSINI, P.C. & FERRAUDO, A.S. Efeitos de sistemas de cultivo na densidade e macroporosidade do solo e no desenvolvimento radicular do milho em Latossolo Roxo. Pesq. Agroec. Bras.,34:289-298, 1999.

COSTA, F.S.; ALBUQUERQUE, J.A.; BAYER, C.; FONTOURA, S.M.V. & WOBETO, C. Propriedades físicas de um Latossolo Bruno afetadas pelos sistemas plantio direto e preparo convencional. R. Bras. Ci. Solo, 27:527-535, 2003.

COSTA, M.C.G.; MAZZA, J.A.; VITTI, G.C. & JORGE, L.A.C. Distribuição radicular, estado nutricional e produção de colmos e de açúcar em soqueiras de dois cultivares de cana-de-açúcar em solos distintos. R. Bras. Ci. Solo, 31:1503-1514, 2007.

DERPSCH, R.; ROTH, C.H.; SIDIRAS, N. & KÖPKE, U. Controle da erosão no Paraná, Brasil: Sistemas de cobertura do solo, plantio direto e preparo conservacionista do solo. Eschborn, GTZ/IAPAR, 1991. 268p.

DOMINY, C.S.; HAYNES, R.J. & ANTWERPEN, R.V. Loss of soil organic matter and related soil properties under long-term sugarcane production on two contrasting soils. Biol. Fert. Soils, 36:350-356, 2002.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. Centro Nacional de Pesquisa do Solo. Sistema brasileiro de classificação de solos. 2.ed. Rio de Janeiro, 2006. 306p.

EMPRESA BRASILERA DE PESQUISA AGROPECUARIA-EMBRAPA. Centro Nacional de Pesquisa do Solo. Manual de métodos de analise de solos. Rio de Janeiro, 1997. 212p.

FARONI, C.E. & TRIVELIN, P.C.O. Quantificação de raízes metabolicamente ativas de cana-de-açúcar. Pesq. Agropec. Bras., 42:1007-1013. 2006.

FERREIRA, D.F. Análises estatísticas por meio do Sisvar para Windows versão 4.0. In: REUNIÃO ANUAL DA REGIÃO BRASILEIRA DA SOCIEDADE INTERNACIONAL DE BIOMETRIA, 45., São Carlos, 2000. Anais... São Carlos, Universidade Federal de São Carlos, 2000. p.255-258.

IAIA, A.M.; MAIA, J.C.S. & KIM, M.E. Uso do penetrômetro eletrônico na avaliação da resistência do solo cultivado com cana-de-açúcar. R. Bras. Eng. Agric. Amb., 10:523-530, 2006.

JORGE, L.A.C.; RALISCH, R.; ABI SAAB, O.J.G.; MEDINA, C.C.; GUIMARÃES, M.F.; NEVES, C.S.V.J.; CINTRA, F.L.D.; BASSOI, L.H. & FERNANDES, S.B.V. Recomendações práticas para análise de imagens digitais através do SIARCS. São Carlos, Embrapa/Instrumentação Agropecuária, 1996. CD ROM. (Circular Técnica)

LUCA, E.F.; FELLER, C.; CERRI, C.C.; BARTHÈS, B.; CHAPLOT, V.; CAMPOS, D.C. & MANEQUINI, C. Avaliação de atributos físicos e estoques de carbono e nitrogênio em solos com e sem queima de canavial. R. Bras. Ci. Solo, 32:789-800, 2008.

MAIA, J.L.T. & RIBEIRO, M.R. Cultivo contínuo da cana-de-açúcar e modificações químicas de um Argissolo Amarelo fragipânico. Pesq. Agroec. Bras., 39:1127-1132, 2004a.

MAIA, J.L.T. & RIBEIRO, M.R. Propriedades de um Argissolo Amarelo fragipânico de Alagoas sob cultivo contínuo da cana-de-açúcar. Pesq. Agroec. Bras., 39:79-87, 2004b.

NEVES, C.S.V.J.; FELLER, C.; GUIMARÃES, M.F.; MEDINA, C.C.; TAVARES FILHO, J. & FORTIER, M. Soil bulk density and porosity of homogeneous morphological units identified by the Cropping Profile Method in clayey Oxisols in Brazil. Soil Tillage Res., 71:109-119, 2003.

PIMENTEL-GOMES, F. Curso de estatística experimental. 12.ed. São Paulo, Nobel, 1990. 467p.

RALISCH, R.; GUIMARÃES, M.F. & MEDINA, C.C. The cultural profile methodology utilization to evaluate the tillage effects and tillage equipment efficiency. In: WORLD CONGRESS ON AGRICULTURAL ENGINEERING, 12., Milano, 1994. Proceedings... Merelbeke, CIGR, 1994. p.1273-1279.

REINERT, D.J.; REICHERT, J.M. & SILVA, V.R. Propriedades físicas dos solos em sistemas de plantio direto irrigado. In: CARLESSO, R.; PETRY, M.T.; ROSA, G.M. & CERETTA, C.A. Irrigação por aspersão no rio Grande do Sul. Santa Maria, Palloti, 2001. 156p.

SILVA, A.J.N.; CABEDA, M.S.V.; CARVALHO, F.G. & LIMA, J.F.W.F. Alterações físicas e químicas de um Argissolo amarelo sob diferentes sistemas de uso e manejo. R. Bras. Eng. Agric. Amb., 10:76-83, 2006a.

SILVA, A.J.N.; CABEDA, M.S.V. & CARVALHO, F.G. Matéria orgânica e propriedades físicas de um Argissolo Amarelo Coeso sob sistemas de manejo com cana-de-açúcar. R. Bras. Eng. Agric. Amb., 10:579-585, 2006b.

SILVA, A.J.N.; CABEDA, M.S.V. & LIMA, J.F.W.F. Efeito de sistemas de uso e manejo nas propriedades físico-hídricas de um Argissolo Amarelo de tabuleiro costeiro. R. Bras. Ci. Solo, 29:833-842, 2005.

SILVA, V.R.; REINERT, D.J. & REICHERT, J.M. Resistência mecânica do solo à penetração influenciada pelo tráfego de uma colhedora em dois sistemas de manejo do solo. Ci. Rural, 30:795-801, 2000.

SMITH, D.M.; INMAN-BAMBER, N.G. & THORNBURN, P.J. Growth and function of the sugarcane root system. Field Crops Res., 92:163-189, 2005.

SOUZA, Z.M.; CAMPOS, M.C.C.; CAVALCANTE, I.H.L.; MARQUES JUNIOR, J.; CESARIN, L.G. & SOUZA, S.R. Dependência espacial da resistência do solo à penetração e do teor de água do solo sob cultivo contínuo de cana-de-açúcar. Ci. Rural, 36:128-134, 2006.

SOUZA, Z.M.; PRADO, R.M.; PAIXÃO, A.C.S. & CESARIN, L.G. Sistemas de colheita e manejo da palhada de cana-de-açúcar. Pesq. Agroec. Bras., 40:271-278, 2005.

TAVARES-FILHO, J. & MAGALHÃES, F.S. Dispersão de amostras de Latossolo Vermelho eutroférrico influenciadas por pré-tratamento para oxidação da matéria orgânica e pelo tipo de agitação mecânica. R. Bras. Ci. Solo, 32:1429-1435, 2008.

TAVARES FILHO, J. & TESSIER, D. Influence des pratiques culturales sur le comportement et les propriétés de sols du Paraná (Brésil). Étude Gest. Sols, 5:61-71, 1998.

TAVARES FILHO, J.; BARBOSA, G.M.C. & RIBON, A.A. Physical properties of dystrophic Red Latosol (oxisol) under different agricultural uses. R. Bras. Ci. Solo, 34:925-933, 2010.

TAVARES FILHO, J.; BARBOSA, G.M.C.; GUIMARÃES, M.F. & FONSECA, I.C.B. Resistência do solo à penetração e desenvolvimento radicular do milho (*Zea mays*) sob diferentes sistemas de manejo em Latossolo Roxo. R. Bras. Ci. Solo, 25:725-730, 2001.

TAYLOR, H.M. & GARDNER, H.R. Penetration of cotton seedlings taproots as influenced by bulk density, moisture and strength of soil. Soil Sci., 96:153-156, 1963.

VASCONCELOS, A.C.M.; CASAGRANDE, A.A.; PERECIN, D.; JORGE, L.A.C. & LANDELL, M.G.A. Avaliação do sistema radicular da cana-de-açúcar por diferentes métodos. R. Bras. Ci. Solo, 27:849-858, 2003.