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Comissão 2.2 - Física do solo

LEAST LIMITING WATER RANGE IN SOIL UNDER CROP ROTATIONS AND CHISELING[1]

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SUMMARY

Soil water availability to plants is affected by soil compaction and other variables. The Least Limiting Water Range (LLWR) comprises soil physical variables affecting root growth and soil water availability, and can be managed by either mechanical or biological methods. There is evidence that effects of crop rotations could last longer than chiseling, so the objective of this study was to assess the effect of soil chiseling or growing cover crops under no-till (NT) on the LLWR. Crop rotations involving triticale (X *Triticosecale*) and sunflower (*Helianthus annuus*) in the fall-winter associated with millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*) and sunn hemp (*Crotalaria juncea*) as cover crops preceding soybean (*Glycine max*) were repeated for three consecutive years. In the treatment with chiseling (performed only in the first year), the area was left fallow between the fall-winter and summer crops. The experiment was carried out in Botucatu, São Paulo State, Brazil, from 2003 to 2006 on a Typic Rhodudalf. The LLWR was determined in soil samples taken from the layers 0–20 cm and 20–40 cm, after chemical desiccation of the cover crops in December of the first and third year of the experiment. Chiseling decreases soil bulk density in the 0–20 cm soil layer, increasing the LLWR magnitude by lowering the soil water content at which penetration resistance reaches 2.0 MPa; this effect is present up to the third year after chiseling and can reach to a depth of 0.40 m. Crop rotations involving sunflower + sunn hemp, triticale + millet and triticale + sunn hemp for three years prevented soil bulk density from exceeding the critical soil bulk density in the 0–0.20 m layer. This effect was observed to a depth of 0.40 m after three years of chiseling under crop rotations involving forage sorghum. Hence, chiseling and some crop rotations under no tillage are effective in increasing soil quality assessed by the LLWR.

Index terms: cover crops, crop rotation, soil compaction, no till, soil water.

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RESUMO: *INTERVALO HÍDRICO ÓTIMO EM SOLO SOB ROTAÇÃO DE CULTURAS E ESCARIFICAÇÃO*

A disponibilidade de água às plantas é alterada pela compactação do solo e outras variáveis. O Intervalo Hídrico Ótimo (IHO) integra variáveis físicas do solo que alteram o crescimento radicular e a disponibilidade de água e pode ser manejado por métodos mecânicos ou biológicos. Há evidências de que os efeitos da rotação de culturas são mais duradouros que os da escarificação. O objetivo deste trabalho foi avaliar o efeito da escarificação e, ou, rotação de culturas em sistema de semeadura direta (SSD) no IHO. Rotações envolvendo triticale (X Triticosecale*) e girassol (*Helianthus annuus*) no outono-inverno e milheto (*Pennisetum glaucum*), sorgo (*Sorghum bicolor*) e crotalária (*Crotalaria juncea*) com plantas de cobertura precedendo a soja (*Glycine max*) foram repetidas por três anos. No tratamento com escarificação, a área foi deixada em pousio entre as culturas de outono-inverno e verão. O experimento foi conduzido em Botucatu, São Paulo, Brasil, de 2003 a 2006 em um Nitossolo Vermelho. O IHO foi determinado em amostras de solo das profundidades de 0–20 e 20–40 cm, logo após a dessecação química das plantas de cobertura, em dezembro do primeiro e do terceiro ano do experimento. A escarificação diminui a densidade do solo na camada de 0–20 cm, aumentando o IHO por meio da redução da umidade do solo em que a resistência à penetração atinge 2,0 MPa; esse efeito mantém-se até o terceiro ano após a escarificação, podendo chegar a até 40 cm de profundidade. As rotações de culturas envolvendo girassol + crotalária, triticale + milheto e triticale + crotalária por três anos ajudaram a prevenir o aumento na densidade do solo acima do valor crítico na camada de 0–20 cm. Esse efeito é observado na camada de 20–40 cm após três anos da escarificação e com rotações de culturas envolvendo sorgo. Assim, a escarificação e algumas rotações de culturas em sistema de semeadura direta são eficientes em melhorar a qualidade do solo avaliada pelo IHO.*

Termos de indexação: plantas de cobertura, rotação de culturas, compactação do solo, semeadura direta, água no solo.

INTRODUCTION

The factors that affect plant growth and development directly (oxygen, water, temperature and mechanical impediment) are not only influenced by soil structure (bulk density, aggregation state and porosity), but also by climate, which vary from year to year (Dexter, 1988). Thus, it is difficult to define critical limits beyond which crop growth and development is impaired (Torres & Saraiva, 1999). The recognition of these interactions suggests that soil physical quality should be assessed using parameters that integrate the physical characteristics of the soil affecting plant growth, and using water as an equilibrium variable, diminishing or aggravating the effects of aeration and soil penetration resistance (Letey, 1985).

Plant growth is affected when soil physical-hydric characteristics such as aeration porosity, root penetration resistance and/or soil water content impairs water acquisition. The interaction of these attributes in a single variable was defined by Silva et al. (1994) as the "Least Limiting Water Range" (LLWR). According to these authors, root growth is less restricted within this interval, whose upper limit is the soil water content at field capacity (FC) or the soil water content when the air-filled porosity equals 10 %. The LLWR lower limit is the soil water content at the permanent wilting point (PWP) or the soil water content where soil penetration resistance is equal to 2.0 MPa. There are reports showing that soil management systems leading to lower LLWR expose crops to more frequent stress due to excess or lack of water (Kay, 1990; Silva & Kay, 1996; Lapen et al., 2004).

Soil water contents at the adequate aeration porosity and soil penetration resistance (SR) are more severely affected by soil bulk density (Db) than by soil water contents at FC and PWP, indicating that the LLWR is more sensitive to soil structural changes than the available water (Silva et al., 1994; Tormena et al., 1998; Betz et al., 1998; Zou et al., 2000). Thus, soil water contents to avoid limitations to plant growth vary with the state of soil compaction (Silva et al., 1994), and compaction alleviation may result in higher water availability to plants in addition to decreasing SR.

Soil compaction alleviation can be achieved by mechanical and/or biological processes. In the mechanical method, equipments with shanks are preferred because they operate below the compacted layer, have less surface contact and soil tillage is low (Vernetti Júnior & Gomes, 1999). However, there is evidence that the positive effects of chiseling are short-lived (Araujo et al., 2004; Busscher et al., 2002). On the other hand, important benefits have been observed in soil structure in the medium and long terms as a result of cover crops (Fidalski et al., 2010) with high-carbon fixing potential and vigorous, deep root systems (Dias Júnior, 2000), able to grow through soil layers with high resistance to penetration and creating biopores where the roots of the subsequent crop can grow (Silva & Rosolem, 2001a). Black oat, pigeon pea and pearl millet favor soybean root growth below compacted soil layers (Silva & Rosolem, 2002) resulting in better mineral nutrition (Silva & Rosolem, 2001b), however, the effects on soil bulk density and penetration resistance were not clear. Although grasses are generally more sensitive to high soil penetration resistance, they have high root length densities in compacted soil layers. This was observed for pearl millet and grain sorghum that are also very efficient in recycling nutrients. These two species proved to be very appropriate as cover crops in tropical regions with dry winters (Rosolem et al., 2002; Silva & Rosolem, 2003).

In view of the transient effect of chiseling, and that the positive effects of cover crops on root growth and development of cash crops as well as the effects of crop rotations on soil water availability are not well understood, the objective of this study was to determine the effects of soil compaction management with chiseling and no-till cover crops on the least limiting water range of a tropical soil.

MATERIAL AND METHODS

An experiment was carried out in Botucatu, State of São Paulo, Brazil, from 2003 to 2006 on a Typic Rhodudalf (Soil Survey Staff, 2006) or Nitossolo Vermelho distroférrico A moderado (Embrapa, 2006), in an area that had been under no tillage for six years, with a soybean/black oats/corn/triticale rotation. The geographic location of this area is latitude 22 ° 49 ' S, longitude 48 ° 25 ' WGrw and 786 m asl. The climate (Köppen classification) is CWa, i.e., a subtropical humid climate with dry winter. The dry season is well-defined between May and September. The mean annual rainfall is approximately 1,400 mm, the highest monthly mean temperature is over 22 °C and the lowest below 18 °C. Before starting the experiment, a one meter-deep trench was opened and a compacted layer was diagnosed 5 to 20 cm deep in the soil profile. The soil was then sampled for chemical (Raij et al., 2001) and physical (Embrapa, 1997) analyses (Table 1). The soil resistance (SR) of the profile was determined using an electronic penetrograph.

Treatments consisted of planting triticale (X *Triticosecale* Wittmack) and sunflower (*Helianthus annuus*) in the fall-winter, combined with pearl millet (*Pennisetum glaucum* L., var. BN-2), forage sorghum (*Sorghum bicolor* (L.) Moench) and sunn hemp (*Crotalaria juncea* L.) in the spring, and an additional treatment that was chiseled, all preceding the summer crop (soybean – *Glycine max* L. (Merrill), var. Embrapa 48). The chisel plow had seven shanks on two parallel bars on a square tool carrier. The shanks, inclined 25° forward, were fixed 0.60 m apart, resulting in an effective between-shank spacing of 0.30 m, with a maximum depth of 0.30 m. A clod-breaking roller was attached to break the biggest clods, decrease surface roughness and spare disking. Soybean was grown in summer in all plots. The crop sequence was repeated for three years. The soil was chiseled only once, that is, after the fall-winter crop harvest in the first year, and the chiseled plots were left fallow between the winter and summer crops thereafter. The experiment was evaluated in a complete randomized block design with a split-plot arrangement of treatments, with four replications. Triticale and sunflower were grown in the plots in the fall/winter with pearl millet, sorghum, sunn hemp, and chiseling in sub-plots. Plots were 8.0 x 32.0 m,and sub-plots 8.0 x 5.0 m, and blocks, plots and sub-plots were 4.0 m apart.

Table 1. Chemical and physical properties of the soil in the experimental area

Depth	Chemical properties								Physical properties						Sand	Clay	Silt
	pH $CaCl_2$ [(1)]	OM	P_{resin}	H + Al	K^+	Ca^{2+}	Mg^{2+}	CEC	SR [(2)]	Moisture [(3)]	Soil bulk density	Porosity					
												Total	Macro [(4)]	Micro			
m		g dm^{-3}	mg dm^{-3}	mmol$_c$ dm^{-3}					MPa	g g^{-1}	g cm^{-3}	m^3 m^{-3}			g kg^{-1}		
0–0.05	5.4	32	37	56	4.7	38	16	114	1.4	0.29	1.22	0.57	0.11	0.42	137	571	293
0.05–0.10	4.6	27	26	91	3.0	28	11	134	2.8	0.29	1.39	0.53	0.08	0.42	131	598	272
0.10–0.20	4.6	26	15	97	2.5	35	16	151	2.3	0.34	1.38	0.52	0.07	0.45	128	599	273
0.20–0.40	4.8	22	3	69	1.1	46	15	131	2.3	0.38	1.29	0.50	0.05	0.45	110	645	246
0.40–0.60	5.1	22	2	64	0.2	57	12	132	1.8	0.42	1.31	0.58	0.05	0.48	88	715	197

(1) pH determined in $CaCl_2$ 0.01 mmol L^{-1}. (2) Soil mechanical penetration resistance. (3) Soil gravimetric moisture and Db at the time of the penetration resistance test. (4) Macroporosity drained at a matric potential of -0.006 MPa.

Soybean fertilization with P and K followed specific recommendations for the crop according to Raij et al. (1996). Sunflower and triticale were not fertilized and the cover crops (in spring) received 40 kg ha^{-1} N as urea at planting.

Undisturbed soil samples were collected with volumetric rings (height 5.0 cm, internal diameter 4.8 cm), and 16 samples were taken per plot (8 from the center of the 0–20 cm and 8 from the center of the 20–40 cm layer) before starting the experiment to characterize the area, and after desiccating the cover crops in the first and third year of the experiment (just before soybean planting).

The LLWR was determined as described by Silva et al. (1994). The least limiting water range limits were associated to critical soil volumetric water content (θ) defined by the matric potential, soil penetration resistance, and air-filled porosity as follows: the soil water retention at field capacity (θ_{FC}), calculated at -0.01 MPa matric potential, the soil water retention at permanent wilting point (θ_{PWP}), -1.5 MPa matric potential, the soil water content (θ_{SR}) at which penetration resistance reaches 2.0 MPa, and the soil water content when the air-filled porosity (θ_{AFP}) equals 10 %.

In the laboratory, all samples were, at first, water-saturated (Embrapa, 1997) and submitted to the following tensions: 0.002, 0.004, 0.006, 0.01, 0.03, 0.1, 0.5, and 1.5 MPa. A tension table was used to obtain matric potentials (Ψ) of -0.002, -0.004 and -0.006 MPa. For Ψ of -0.01, -0.033, -0.1, -0.5, and -1.5 MPa samples were placed on a porous plate apparatus. When the samples reached equilibrium, penetration resistance was determined and samples were oven-dried at 105 °C for 24 h to determine gravimetric moisture and soil bulk density (Embrapa, 1997). The penetrograph (Marconi-model MA 933) consisted of a 6 mm diameter metal rod with a 30° half-angle conical tip and base area of 0.1256 cm^2 attached to a charge cell held by a mechanical arm driven by a cork screw-like axle. The vertical displacement speed of the rod was 1.0 cm min^{-1} to the depth of 4.0 cm. Data obtained from the sample surface to 1.0 cm deep were discarded, as recommended by Tormena et al. (1998). The volumetric moisture (θ) was obtained by multiplying gravimetric moisture by soil bulk density. The θ_{FC} and θ_{PWP} values were determined using equation 1 (Silva et al., 1994).

$$\theta = \exp(a + b\,Db)\,\Psi^{c} \qquad (1)$$

where θ = volumetric water content ($m^3\,m^{-3}$); Db = bulk density (g cm^{-3}); Ψ = matric potential (MPa); a, b, c = calibration coefficients.

The critical value of volumetric moisture below which SR is greater than 2.0 MPa (θ_{SR}) was obtained by the functional relationship between SR, θ and Db as in equation 2.

$$SR = d\theta^{e}\,Db^{f} \qquad (2)$$

where SR = Soil penetration resistance (MPa); θ = volumetric water content of the sample ($m^3\,m^{-3}$); Db = soil bulk density (g cm^{-3}); d, e, f = calibration coefficients.

Finally the θ_{PA} was obtained by equation 3.

$$\theta_{AFP} = \theta_{SAT} - 0.1 \qquad (3)$$

where θ_{AFP} = soil water content where aeration porosity is equal to 10 % (0.1 $m^3\,m^{-3}$); θ_{SAT} = (1-Db/2.65), and Db is the soil bulk density value (g cm^{-3}) and 2.65 (g cm^{-3}) is the assumed value of the mean particle density.

Thus, the upper limit (UL) of the LLWR is determined by the lower value of either θ_{FC} or $\theta_{AFP,}$ the lower limit (LL) of the LLWR equals the higher value of either θ_{SR} or $\theta_{PWP,}$ and LLWR is calculated as LLWR = UL – LL. After calculating the upper and lower LLWR limits, the critical soil bulk density (Db_c) was determined, i.e., the soil density at which LLWR equals zero, (Silva et al., 1994).

The statistical software Sigma Plot 8.0 was used to fit equations 1 and 2 and calculate the coefficients a, b, c, d, e, f (considered significant when $p < 0.05$) with individual data fit for each treatment and depth. The upper and lower LLWR limits as a function of soil bulk density were determined using a XML-based electronic spreadsheet, as described by Leão & Silva (2004).

RESULTS AND DISCUSSION

The determination coefficients of equations 1 and 2 had significant F values with $p < 0.01$ (Tables 2 and 3). In the first year of the experiment, differences in LLWR were small in all treatments and both soil layers (Figures 1 and 2) because the lower soil water content limit was very close to the upper limit in all samples. Chiseling led to a higher LLWR amplitude in the 0–20 cm layer (Figure 1d,h), which was not observed for the 20–40 cm layer (Figure 2d,h). According to Carter et al. (1999), the LLWR in NT is lower than in conventional tillage because SR reaches 2.0 MPa at higher moisture contents in the former system, due to the higher Db usually found in the conservation system. Betz et al. (1998) and Cavalieri et al. (2006) also observed greater LLWR in soil under conventional tillage and chiseling, resulting in a favorable physical environment for root growth. Regardless of soil depth, the water content bringing SR to 2 MPa (θ_{RP}) equaled the lower LLWR limit in all samples, and was higher than θPWP irrespective of Db in the first year. This result is typical of compacted soils that require high moisture to keep SR below the limiting value (Topp et al., 1994; Silva et al., 1994; Muller, 2002; Beutler et al., 2006).

Table 2. Estimation of regression coefficients for the soil penetration resistance (SR) as a function of volumetric water content (θ) and soil bulk density (Db), in the 0–0.20 and 0.20–0.40 m layers, in the first and third year of the experiment

Parameter	1° yr		3° yr		1° yr		3° yr	
	0 to 0.20 m	0.20–0.40 m	0 to 0.20 m	0.20–0.40 m	0 to 0.20 m	0.20–0.40 m	0 to 0.20 m	0.20–0.40 m
	Sunflower+millet				Triticale+millet			
a	0.0208	0.0120	0.0009	0.0605	0.0095	0.0080	0.0050	0.0444
b	-3.8393	-4.9700	-5.4453	-4.4275	-4.8718	-6.2081	-5.1608	-3.9762
c	5.3069	4.9007	10.3317	0.2948	4.4088	2.9771	4.3410	2.9643
R^2	0.84**	0.85**	0.81**	0.87**	0.81*	0.90*	0.92*	0.79*
	Sunflower+forage sorghum				Triticale+forage sorghum			
a	0.0171	0.0078	0.0028	0.0028	0.0091	0.0065	0.0031	0.0028
b	-4.0170	-5.1745	-5.2510	-5.6350	-4.8010	-5.9194	-4.9148	-6.4238
c	5.1657	6.7159	6.7007	8.8795	4.2352	4.8451	7.1206	5.4685
R^2	0.93**	0.82**	0.86**	0.77**	0.88**	0.93**	0.94**	0.87*
	Sunflower+sunn hemp				Triticale+sunn hemp			
a	0.0211	0.0486	0.0161	0.0558	0.0073	0.0208	0.0012	0.0155
b	-4.0888	-4.2293	-4.5999	-4.2660	-4.6910	-5.1226	-6.0335	-5.3065
c	4.4563	1.7524	1.2625	1.1131	5.7379	2.0039	6.0271	1.5950
R^2	0.85**	0.73**	0.78**	0.70**	0.90**	0.71**	0.93**	0.84**
	Sunflower+ chiseling				Triticale+ chiseling			
a	0.0110	0.0159	0.0007	0.0013	0.0111	0.0085	0.0034	0.0078
b	-4.5426	-4.8458	-5.6994	-5.9991	-4.6573	-5.7006	-4.6104	-5.1100
c	4.2021	3.8255	9.6695	9.1204	3.1960	4.1774	7.4610	4.8644
R^2	0.83**	0.82**	0.89**	0.89**	0.91**	0.76**	0.87**	0.87**

Significant at $p < 0.01$.

Table 3. Estimation of regression coefficients for the volumetric water content (θ) as a function of soil bulk density (Db) and matric potential (Ψ), in the 0–0.20 and 0.20–0.40 m layers, in the first and third year of the experiment

Parameter	1° yr		3° yr		1° yr		3° yr	
	0 to 0.20 m	0.20–0.40 m	0 to 0.20 m	0.20–0.40 m	0 to 0.20 m	0.20–0.40 m	0 to 0.20 m	0.20–0.40 m
	Sunflower+millet				Triticale+millet			
d	-1.5312	-1.2756	-2.0070	-1.0771	-1.6547	-1.2338	-1.4781	-1.0869
e	0.3207	0.2163	0.6669	0.0553	0.4294	0.2139	0.2341	0.0417
f	-0.0528	-0.0399	-0.0639	-0.0495	-0.0496	-0.0362	-0.0679	-0.0482
R^2	0.87**	0.85**	0.92**	0.87**	0.87**	0.87**	0.93**	0.87**
	Sunflower+forage sorghum				Triticale+forage sorghum			
d	-1.7213	-1.7044	-1.7031	-1.7735	-2.2712	-1.4422	-1.7660	-1.2889
e	0.4583	0.5974	0.4241	0.6139	0.9057	0.3703	0.4635	0.2285
f	-0.0581	-0.0326	-0.0618	-0.0481	-0.0531	-0.0412	-0.0640	-0.0462
R^2	0.92**	0.82**	0.93**	0.87**	0.84**	0.90**	0.96**	0.89**
	Sunflower+sunn hemp				Triticale+sunn hemp			
d	-1.4178	-1.3564	-1.5146	-0.9565	-1.5613	-1.2250	-1.4707	-0.9738
e	0.2512	0.2786	0.2714	-0.043	0.3530	0.1816	0.2376	-0.0432
f	-0.0462	-0.0396	-0.0613	-0.0451	-0.0487	-0.0356	-0.0604	-0.0397
R^2	0.89**	0.86**	0.83**	0.85**	0.90**	0.85**	0.94**	0.88**
	Sunflower+chiseling				Triticale+ chiseling			
d	-1.7061	-1.2481	-2.0005	-1.7712	-1.7619	-1.2702	-1.6950	-1.6238
e	0.4661	0.1823	0.6382	0.5558	0.4827	0.2363	0.4028	0.4524
f	-0.0524	-0.0442	-0.0646	-0.0503	-0.0603	-0.0372	-0.0599	-0.0491
R^2	0.89**	0.88**	0.83**	0.91**	0.91**	0.84**	0.86**	0.88**

Significant at $p < 0.01$.

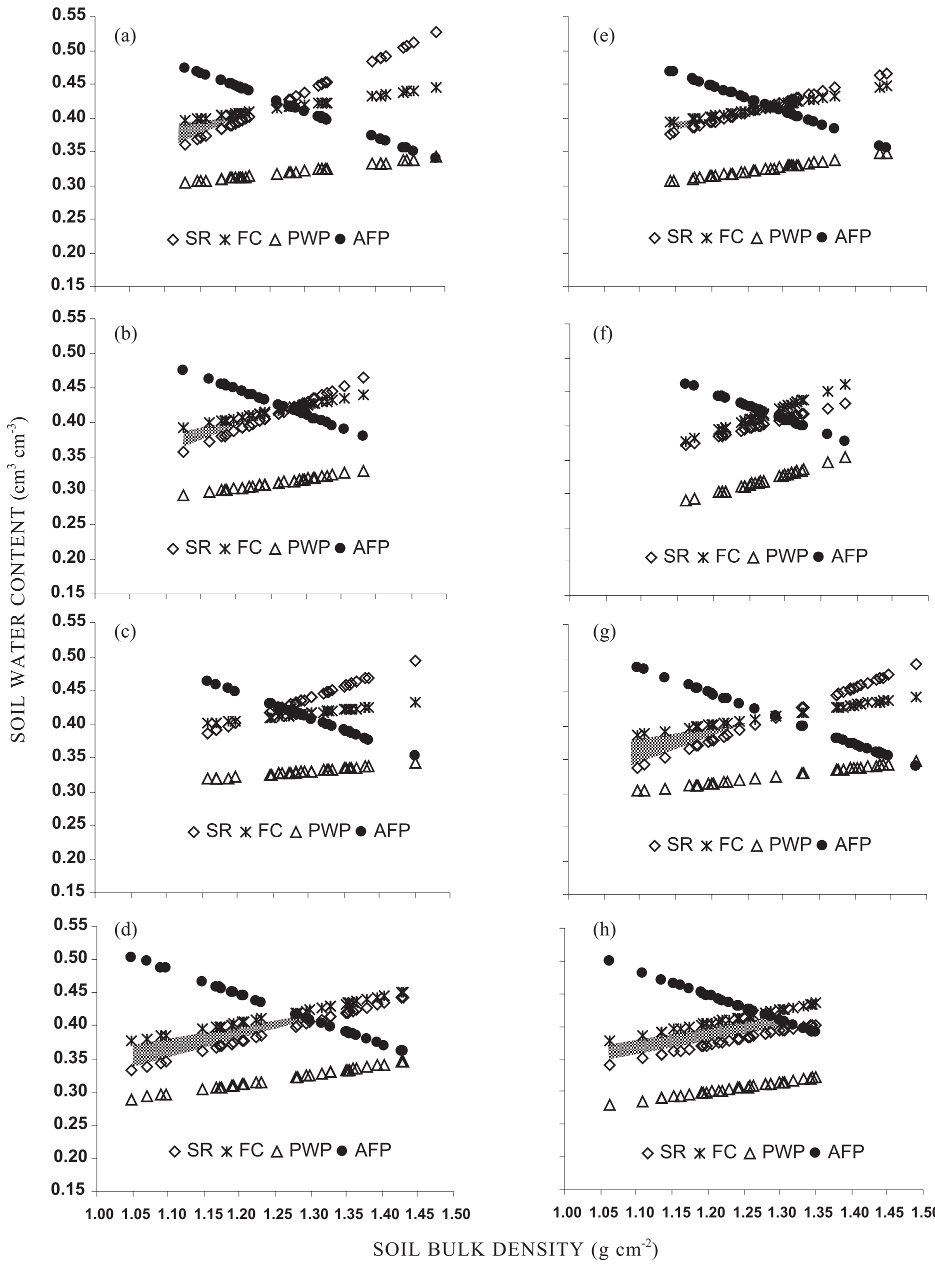

Figure 1. Soil water content (θ) as affected by soil bulk density, at the critical levels of field capacity (FC = -0.01 MPa), permanent wilting point (PWP = -1.5 MPa), air-filled porosity (AFP = 10 %) and soil penetration resistance (SR = 2MPa). Samples collected in the 0–20 cm layer, in the first year of the experiment. The shaded area represents the LLWR. (a) sunflower+millet; (b) sunflower+forage sorghum; (c) sunflower+sunn hemp; (d) sunflower+chiseling; (e) triticale+millet; (f) triticale+forage sorghum; (g) triticale+sunn hemp; (h) triticale+chiseling.

In all treatments and soil layers the available water content (AW = θ_{FC}–θ_{PWP}) was higher than LLWR in the first year of the experiment, which is typical of degraded soils (Letey, 1985). For this reason, Silva et al. (1994) suggested the LLWR as a more sensitive tool for soil structure analyses. According to Topp et al. (1994), the occurrence of very low, or even zero LLWR values is common in soils with heavy clay texture, as in this study (Table 1), which increases the probability of physical limitations for root growth (Kay, 1990). Tormena et al. (1998), when determining the LLWR in a Red Latosol with

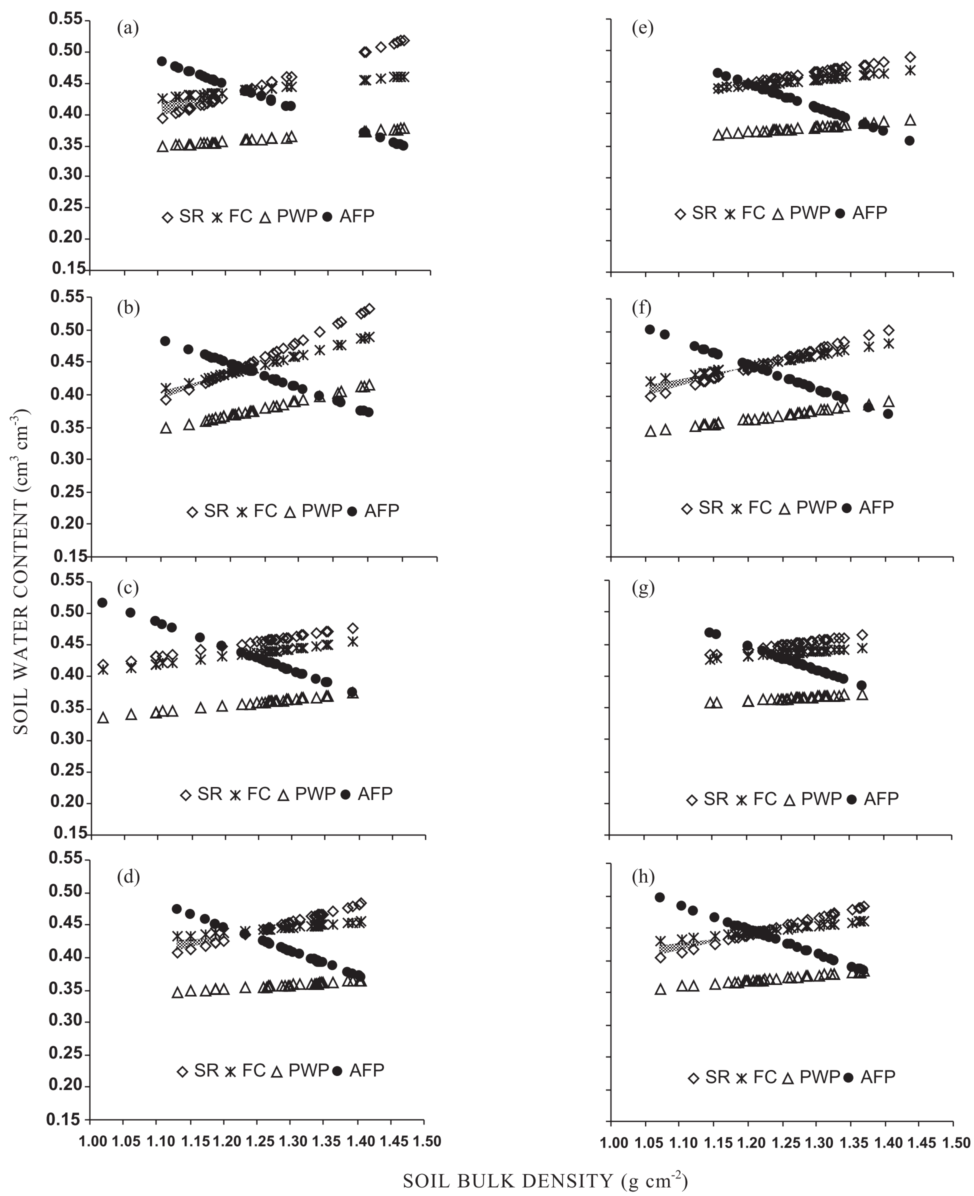

Figure 2. Soil water content (θ) as affected by soil bulk density, at the critical levels of field capacity (FC = -0.01 MPa), permanent wilting point (PWP = -1.5 MPa), air-filled porosity (AFP = 10 %) and soil penetration resistance (SR = 2MPa). Samples collected in the 20–40 cm layer, in the first year of the experiment. The shaded area represents the LLWR. (a) sunflower+millet; (b) sunflower+forage sorghum; (c) sunflower+sunn hemp; (d) sunflower+chiseling; (e) triticale+millet; (f) triticale+forage sorghum; (g) triticale+sunn hemp; (h) triticale+chiseling.

800 g kg^{-1} clay, observed that the θ_{SR} was the lower limit of soil available water, with Db > 1.10 g cm^{-3} and soil moisture over 0.24 cm cm^{-3}. This was not observed in the present experiment because in most treatments the lowest Db was higher than 1.10 g cm^{-3} and θ_{SR} higher than 0.34 g cm^{-3}, especially in the 20–40 cm layer, which contains more clay. Even in the chiseled treatments (Figure 1d,h), where the lowest Db were 1.05 and 1.06 g cm^{-3} under sunflower + chiseling and triticale + chiseling, respectively, the θ_{SR} represented the lower LLWR limit. Thus, it can be inferred that shortly after chiseling, this management was not efficient in increasing the LLWR to reach the values similar to those reported in the literature by Tormena et al.(1998), because at the same Db (of around 1.10 g cm^{-3}) the θ_{SR} was much higher, that is, 0.35 g cm^{-3}. However, after growing cover crops with vigorous, aggressive root systems under

NT the limiting SR for plant growth may be higher than under conventional systems. This is possible because when roots die they leave biopores within the soil profile allowing new root growth in depth (Silva & Rosolem, 2001b).

Regarding the upper limit of LLWR, the θ_{FC} was the maximum limit of soil water in all samples. Exceptions were the chiseling treatments in the 0–20 cm layer, where θ_{AFP} represented the upper limit of LLWR at Db values higher than 1.28 and 1.27 g cm^{-3} under sunflower and triticale, respectively. At these Db values the moisture for 10 % air-filled porosity (AFP) was approximately 0.42 cm cm^{-3}. The θ_{AFP} was the upper LLWR limit in 9 and 25 %, respectively, of the samples within the LLWR in the chiseled plots with triticale and sunflower as fall-winter crops. The replacement of θ_{FC} by the θ_{AFP} as the upper limit of IHO is common in clayey soils, due to the low soil macroporosity, as in this study (Table 1). Tormena et al. (1998) obtained similar results in a clayey soil, that is, the θ_{AFP} became the upper LLWR limit, substituting the θ_{FC}, with Db of 1.28 g cm^{-3}, with a soil volumetric moisture of around 0.42 cm cm^{-3}. However, Pereira et al. (2010) did not observe θ_{AFP} as the upper limit of LLWR for all Db values obtained, due to a high sand content (642 g kg^{-1}).

In the two chiseled treatments with sunflower or triticale in the fall-winter (Figure 1d,h), the Db_c were the highest in the first year, 1.31 and 1.33 g cm^{-3} respectively. This occurs due the large number of soil fractures, helping to maintain the pre-established condition of SR at 2.0 MPa, even with the increase of Db, increasing the Db_c. These Db_c values were similar to those reported by Müller (2002) in a Red Nitossol (Haplortox) with 590 g cm^{-3} clay in the 10–20 cm layer (Db_c = 1.33 g cm^{-3}), and higher than the 1.28 g cm^{-3} Db_c reported by Tormena et al. (1998) in a Red Latossol with 800 g cm^{-3} clay in the 0 to 10 cm layer. Cavalieri et al. (2006) observed critical Db in treatments with mechanical management, decreasing the percentage of samples with Db > Db_c. For Klein & Câmara (2007), sporadic sub-soiling in areas under no tillage result in favorable soil physical conditions for plant development, specifically by reducing the soil penetration resistance.

In the 20–40 cm layer LLWR was generally lower than in the 0–20 cm layer (Figure 2), due to the restrictive effect of the SR that reached the 2.0 MPa limit value at high moisture contents, even at the lowest Db ($\theta_{SR} \geq 0.40$ cm cm^{-3}). This effect supports findings by Tormena et al. (1998) who predicted a greater impact of SR on LLWR deeper in the soil profile. There was no effect of chiseling on LLWR in this layer, probably because it was the deepest limit of action of the equipment (20–40 cm layer) and therefore the de-compaction effect occurred only down to the tip of each shank. Araújo et al. (2004) also observed smaller differences in deeper Db in a comparison of NT with and without sub-soiling.

In the third year of the experiment, LLWR increased in the 0–20 cm layer in all treatments (Figure 3). However, the lowest LLWR limit was still represented by θ_{SR}, except under triticale + chiseling where, at the lowest Db values (1.02 and 1.04 g cm^{-3}), the LLWR was determined by the available water, that is, by θ_{FC} and θ_{PWP}, which is typical of a soil profile that is less restrictive to root development. In this layer, chiseling led to the greatest LLWR amplitude, especially in plots with winter triticale (Figure 3d,h), where the variation in Db values was greatest. The Db values were lowest under sunflower + chiseling and triticale + chiseling (1.09 and 1.02 g cm^{-3}, respectively), and Db values high (1.42 and 1.49 g cm^{-3}, respectively), which resulted in a higher coefficient of variation (7.15 and 10.08 %, respectively). Cavalieri et al. (2006) also observed the effect of mechanical implements on the increase of dispersion in Db values as soil mobilization increased.

In the 20–40 cm layer the LLWR amplitude was greater (Figure 4) under rotations involving forage sorghum (Figure 4b,f) and chiseling (Figure 4d,h). However, after three seasons, there was an increase in Db_c in most plots, both in the 0–20 cm (Figure 5a) and in the 20–40 cm layer (Figure 5b). The exceptions were triticale+chiseling in the 0–20 cm layer, where Db_c remained at 1.33 g cm^{-3} and sunflower + millet in the 20–40 cm layer where the LLWR equaled zero.

The highest Db_c was observed in the 0–20 cm layer after three years of sunflower as fall-winter crop and sunn hemp as cover crop preceding soybean (Figure 5a). This treatment resulted in a Db_c of 1.37 g cm^{-3}, since the increase required in soil volumetric water content to maintain SR at 2.0 MPa was low, due to an increase in the Db (Figure 3c). As Db_c was very high, 97 % of the samples collected to determine the LLWR had Db < Db_c (Figure 6a), i.e., a reduced probability of occurrence of highly restrictive conditions to plant growth (Silva & Kay, 1997).

Crop rotation of sunflower and sunn hemp for three consecutive years resulted in the highest soil organic matter (SOM) contents in the 0–20 cm layer (Calonego & Rosolem, 2008), with a beneficial influence on the soil structure (Mielniczuk, 1999; Zonta et al., 2006) and consequently on SR reduction. According to Sharma & Bhushan (2001), biomass addition to the soil increases θ_{AFP} and decreases θ_{SR}, resulting in a higher LLWR.

High frequencies of samples with Db < Db_c were also observed under triticale + millet and triticale + sunn hemp (94 and 91 %, respectively) in the 0–20 cm layer. Considering the Db_c values as a tool to assess treatment effects on soil structural quality, it can be stated that introduction of cover crops in the system led to higher Db_c increases in the 0–20 cm soil layer, with values similar to or even higher than those observed in plots with mechanical intervention (Figure 5a). Thus, it can be inferred that biological sub-soiling, rather than mechanical chiseling, would

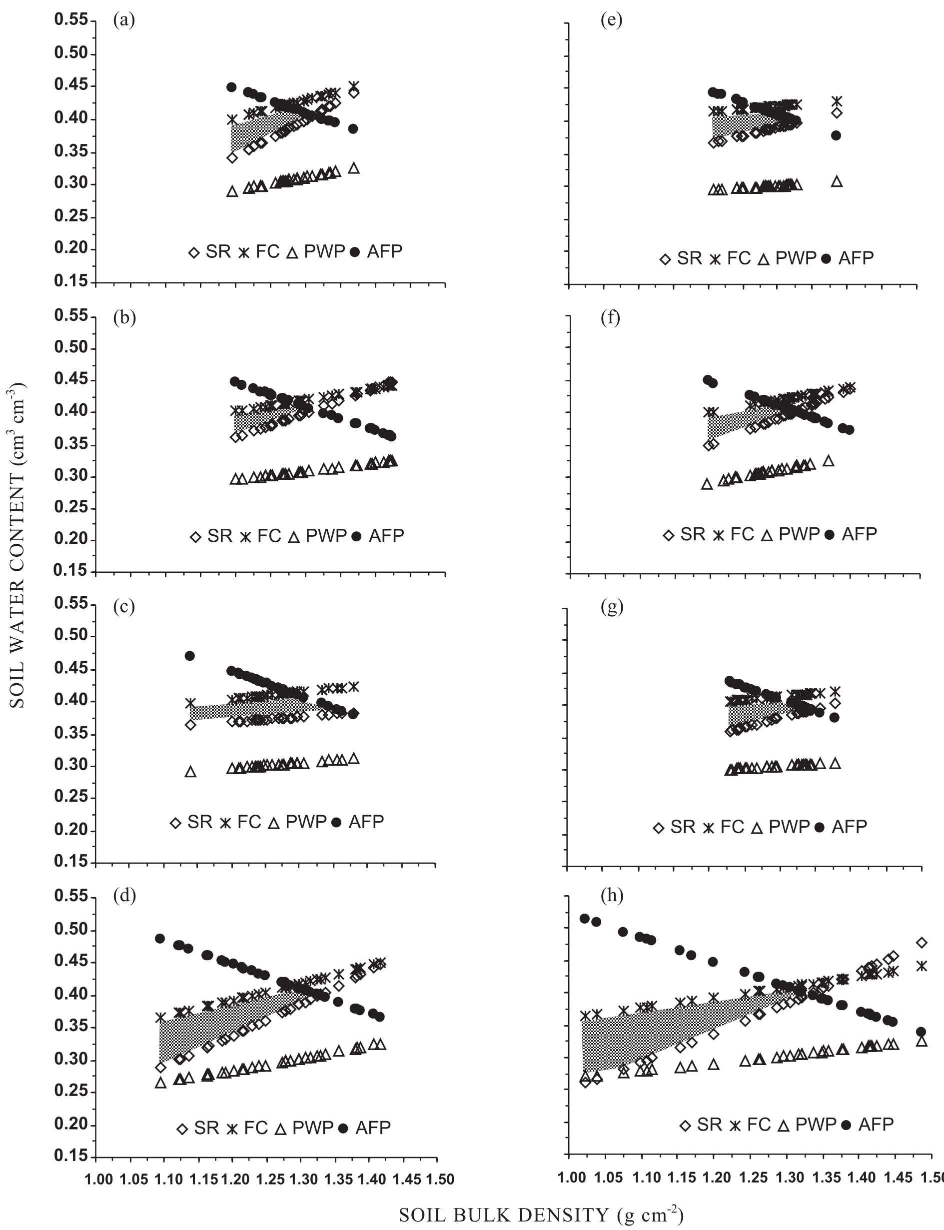

Figure 3. Soil water content (θ) as affected by soil bulk density, at the critical levels of field capacity (FC = -0.01 MPa), permanent wilting point (PWP = -1.5 MPa), air-filled porosity (AFP = 10 %) and soil penetration resistance (SR = 2MPa). Samples collected in the 0–20 cm layer, in the third year of the experiment. The shaded area represents the LLWR. (a) sunflower+millet; (b) sunflower+forage sorghum; (c) sunflower+sunn hemp; (d) sunflower+chiseling; (e) triticale+millet; (f) triticale+forage sorghum; (g) triticale+sunn hemp; (h) triticale+chiseling.

result in increasingly favorable soil physical characteristics in the future, mainly when soil organic matter is increased. To increase SOM the system must include not only grasses, but also legumes, such as sunn hemp in the present experiment, able to fix nitrogen. Moreover, similar results could be expected in other soils and regions with similar climate, although the time of response may be different, depending on the soil texture. However, a new chiseling in NT and fallow areas between the fall-winter and summer crops would be required. This is supported by the results presented in figure 6a in the triticale+chiseling treatment, where the percentage of samples with Db < Db_c in the 0–20 cm layer,

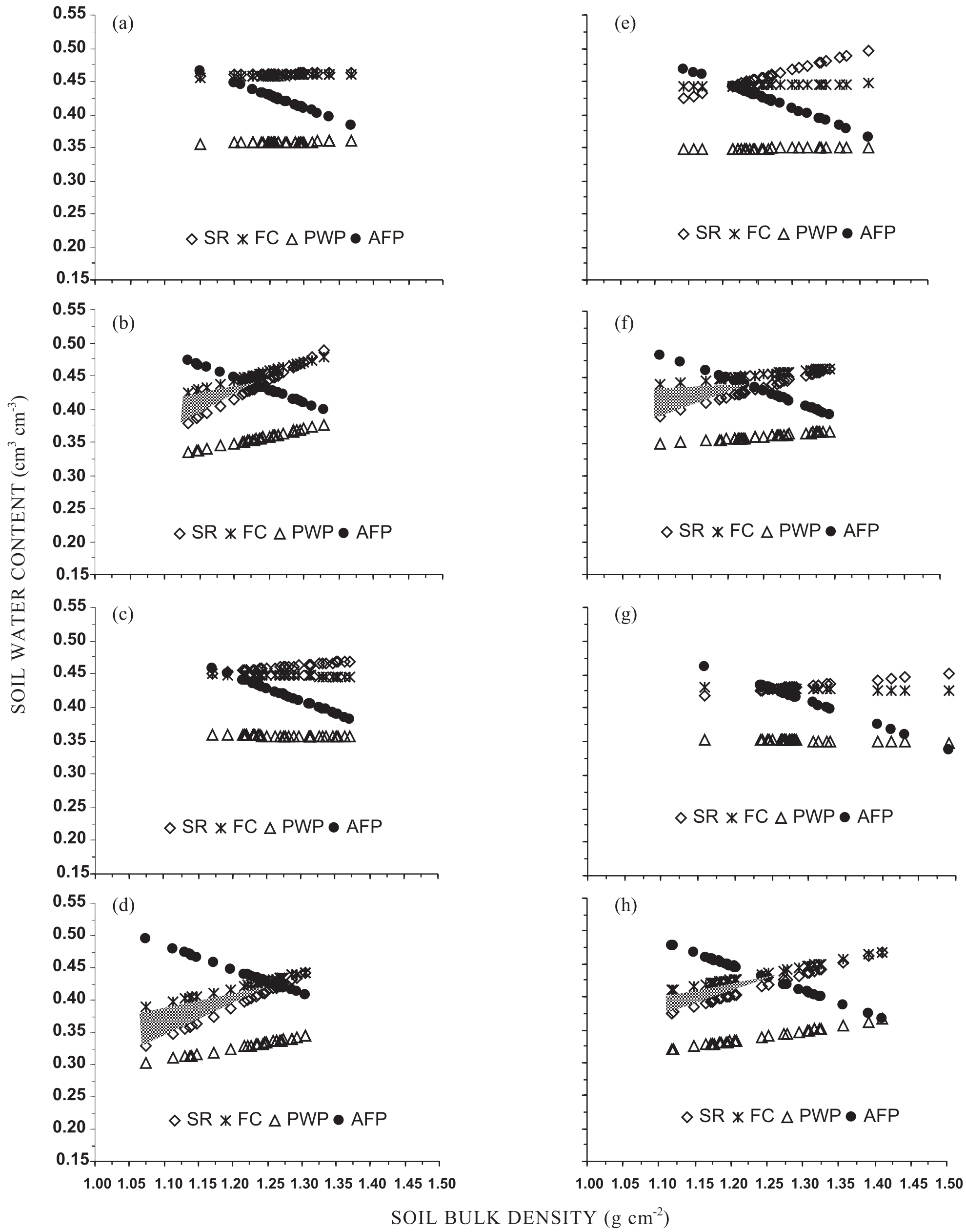

Figure 4. Soil water content (θ) as affected by soil bulk density, at the critical levels of field capacity (FC = -0.01 MPa), permanent wilting point (PWP = -1.5 MPa), air-filled porosity (AFP = 10 %) and soil penetration resistance (SR = 2MPa). Samples collected in the 20–40 cm layer, in the third year of the experiment. The shaded area represents the LLWR. (a) sunflower+millet; (b) sunflower+forage sorghum; (c) sunflower+sunn hemp; (d) sunflower+chiseling; (e) triticale+millet; (f) triticale+forage sorghum; (g) triticale+sunn hemp; (h) triticale+chiseling.

decreased from 88 to 56 % between the first and third year of the experiment. These results explain the decrease in soybean yield with this mechanical management, compared with plots under crop rotation (Calonego & Rosolem, 2010). In contrast, in the 20–40 cm layer, although the Db_c values increased in most treatments with cover crops, the values still remained lower than in chiseled plots (Figure 5b). For this reason, chiseling resulted in the highest frequency of samples (63 and 69 %) with $Db < Db_c$ (Figure 6), corroborating results of Cavalieri et al. (2006), who obtained a sample frequency of 56 % with $Db < Db_c$ in chiseled soils, against 25 % in treatments without mechanical intervention, in the 15–30 cm layer.

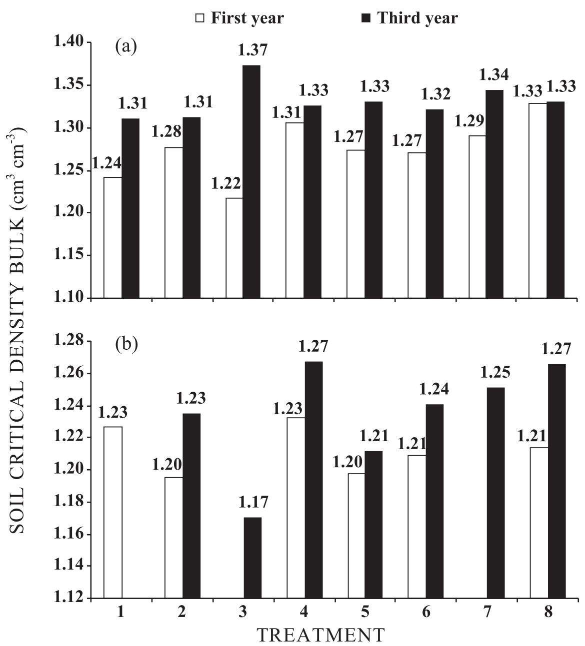

Figure 5. Soil critical bulk densities in the 0–20 (a) and 20–40 cm (b) layers, in the first and third year. Treatments: sunflower+millet (1); sunflower+forage sorghum (2); sunflower+sunn hemp (3); sunflower+chiseling (4); triticale+ millet (5); triticale+forage sorghum (6); triticale+ sunn hemp (7) and triticale+chiseling (8).

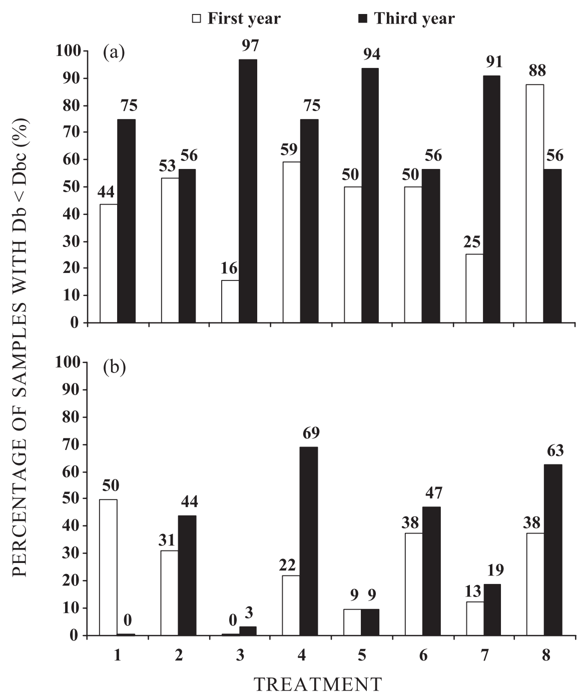

Figure 6. Percentage of samples with lower soil bulk density (Db) than the critical soil bulk density (Db_c), in the first and third year of the experiment in the 0–20 (a) and 20–40 cm (b) layers. Treatments: sunflower+millet (1); sunflower+forage sorghum (2); sunflower+sunn hemp (3); sunflower+ chiseling (4); triticale+ millet (5); triticale+forage sorghum (6); triticale+ sunn hemp (7) and triticale+ chiseling (8).

CONCLUSIONS

1. Chiseling decreases soil bulk density in the 0–20 cm soil layer, increasing the LLWR magnitude by lowering the soil water content at which penetration resistance reaches 2.0 MPa; this effect is measurable until the third year after chiseling, to a depth of 0.40 m.

2. Crop rotations with sunflower + sunn hemp, triticale + millet and triticale + sunn hemp for three years prevented soil bulk density from exceeding the critical bulk density in the 0–0.20 m layer. However, this effect is observed to a depth of 0.40 m,after three years of chiseling and crop rotations involving forage sorghum.

3. Chiseling and some crop rotations under no tillage are effective in increasing soil quality as assessed by the LLWR.

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