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LEAST LIMITING WATER RANGE IN ASSESSING COMPACTION IN A BRAZILIAN CERRADO LATOSOL GROWING SUGARCANE[1]

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SUMMARY

In the south-central region of Brazil, there is a trend toward reducing the sugarcane inter-harvest period and increasing traffic of heavy harvesting machinery on soil with high water content, which may intensify the compaction process. In this study, we assessed the structural changes of a distroferric Red Latosol (Oxisol) by monitoring soil water content as a function of the Least Limiting Water Range (LLWR) and quantified its effects on the crop yield and industrial quality of the first ratoon crop of sugarcane cultivars with different maturation cycles. Three cultivars (RB 83-5054, RB 84-5210 and RB 86-7515) were subjected to four levels of soil compaction brought about by a differing number of passes of a farm tractor (T_0 = soil not trafficked, T_2 = 2 passes, T_{10} = 10 passes, and T_{20} = 20 passes of the tractor in the same place) in a 3 × 4 factorial arrangement with three replications. The deleterious effects on the soil structure from the farm machinery traffic were limited to the surface layer (0-10 cm) of the inter-row area of the ratoon crop. The LLWR dropped to nearly zero after 20 tractor passes between the cane rows. We detected differences among the cultivars studied; cultivar RB 86-7515 stood out for its industrial processing quality, regardless of the level of soil compaction. Monitoring of soil moisture in the crop showed exposure to water stress conditions, although soil compaction did not affect the production variables of the sugarcane cultivars. We thus conclude that the absence of traffic on the plant row maintained suitable soil conditions for

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plant development and may have offset the harmful effects of soil compaction shown by the high values for bulk density between the rows of the sugarcane cultivars.

Index terms: *Saccharum* sp., soil physical degradation, monitoring soil water content, industrial quality.

RESUMO: *INTERVALO HÍDRICO ÓTIMO NA AVALIAÇÃO DA COMPACTAÇÃO EM UM LATOSSOLO DO CERRADO BRASILEIRO CULTIVADO COM CANA-DE-AÇÚCAR*

Na região centro-sul do Brasil, há a tendência de redução do período de entressafra canavieira, condicionando tráfego de máquinas para colheita em condições de elevados conteúdos de água do solo, o que pode contribuir para a intensificação do processo de compactação. Os objetivos deste estudo foram avaliar as alterações estruturais de um Latossolo Vermelho distroférrico por meio do monitoramento do conteúdo de água do solo em razão do Intervalo Hídrico Ótimo (IHO) e quantificar seus efeitos sobre o rendimento agrícola e o industrial da primeira soqueira de cultivares de cana-de-açúcar, com diferentes ciclos de maturação. Foram avaliados três cultivares de cana-de-açúcar (RB 83-5054; RB 84-5210; e RB 86-7515) submetidos a quatro níveis de compactação do solo, atingidos pelo número de passadas de um trator agrícola, correspondendo a T_0 = solo não trafegado; T_2 = 2; T_{10} = 10; e T_{20} = 20 passadas do trator no mesmo lugar, em esquema fatorial 3 × 4, com três repetições. Os efeitos deletérios causados na estrutura do solo pelo tráfego de maquinário agrícola ficaram limitados à entrelinha de cultivo das soqueiras, na camada superficial do solo. O IHO foi reduzido a valores próximos de zero com 20 passadas do trator, nas entrelinhas de cultivo da cana-de-açúcar. Foi detectada diferença entre os cultivares estudados, com destaque para o RB 86-7515, quanto à qualidade tecnológica da matéria-prima, independentemente dos níveis de compactação do solo a que estiveram sujeitos. O monitoramento da umidade do solo indicou exposição da cultura a condições hídricas estressantes, embora a compactação do solo não tenha influenciado as variáveis produtivas dos cultivares de cana. Concluiu-se então que a inexistência de tráfego sobre as linhas de cultivo, mantendo o solo desses locais em condições adequadas ao desenvolvimento das plantas pode ter compensado os efeitos prejudiciais da sua compactação, evidenciada pelos elevados valores de sua densidade, presentes nas entrelinhas de cultivo dos cultivares de cana-de-açúcar.

Termos de indexação: Saccharum *sp., degradação física do solo, monitoramento hídrico do solo, qualidade industrial.*

INTRODUCTION

The combination of increasing global demand for ethanol, public policies for low-cost financing of the sugar-alcohol sector and development of new cultivars adapted to regional growing conditions has been responsible for the steady expansion of sugarcane cultivation in Brazil in recent years. In the search for greater operational productivity, mechanization has increased throughout the steps of the production process (Paulino et al., 2004), resulting in increasing use of heavy vehicles, especially during harvest (Severiano et al., 2008).

In the south-central region of Brazil, there is a trend toward reducing the inter-harvest period (Severiano et al., 2009), which increases machinery traffic at times of unfavorable soil moisture conditions, leading inevitably to soil compaction (Iaia et al., 2006), considered one of the main factors of soil physical degradation (Mosaddeghi et al., 2007). Soil compaction may increase through mechanized harvesting procedures, while soil preparation operations during field renewal eliminate soil stress (Severiano et al., 2010). Therefore, mitigation of soil compaction is fundamental to maintain the productivity and longevity of sugarcane fields (Braunbeck & Oliveira, 2006; Araújo et al., 2013), avoiding yield loss from increased soil bulk density and penetration resistance arising from traffic at harvest (Braunack et al., 2006).

In assessing soil structural quality, monitoring the Least Limiting Water Range (LLWR) has proven to be a useful technique. The LLWR represents the range of soil moisture levels under which physical limitations to plant growth are minimized. It indicates the restrictions imposed by water potential, aeration and mechanical resistance to root penetration in a single parameter (Silva et al., 2006). These factors are responsible for degradation of soil structure in sugarcane under heavy machine traffic, especially during harvest operations, which may restrict the development of subsequent cycles of ratoon cane at any level of soil water content (Severiano et al., 2008).

The LLWR concept is increasingly applied to sugarcane cultivation, and recent studies that modeled soil compaction in cane fields have helped to minimize the impacts of compaction on the structure of soils planted to sugarcane (Severiano et al., 2009; Silva et al., 2009; Cavalieri et al., 2011; Roque et al., 2011). However, there has been little study of the effects of soil structural degradation on the yield and quality for industrial processing of subsequent crops as well as its effect on the growth of sugarcane cultivars with different maturation cycles.

Therefore, monitoring temporal variation of soil water content during crop cycles through quantification of the critical limits of the LLWR is a useful tool for making inferences regarding the optimal number of crop cycles and the periods of phenological development during which plants are more or less subject to stress in terms of water availability, aeration and resistance to root penetration (Blainski et al., 2009; 2012).

In this context, we assessed the structural changes of a distroferric Red Latosol (Oxisol) in the Brazilian Cerrado by monitoring soil water content as a function of the critical limits of the Least Limiting Water Range and quantified its effects on the crop yield and industrial quality of the first ratoon crop of sugarcane cultivars with different maturation cycles.

MATERIALS AND METHODS

The experiment was conducted on the experimental farm of the Rio Verde Campus of the Federal Institute of Education, Science and Technology of Goiano (Instituto Federal de Educação, Ciência e Tecnologia de Goiano - IF Goiano) located in Rio Verde, Goiás, Brazil, at 17° 48' 22" S, 50° 53' 59" W, and an elevation of 725 m. Local climate is Aw on the Köppen scale, with dry winters and rainy summers, average annual temperature from 20 °C to 25 °C and an average annual rainfall greater than 1,500 mm. Soil in the area is a distroferric Red Latosol in the Brazilian classification system (Embrapa, 2013) [corresponding to Oxisol in USA Soil Taxonomy, Soil Survey Staff (2010); Ferralsol in the World Reference Base for Soil Resources, IUSS Working Group - WRB (2006)].

The experiment was performed in a 2,300 m^2 field that had been dedicated to citrus production for 10 years followed by one year of fallow. First, lime was applied for amendment of soil acidity based on previous analysis of its fertility (Table 1). Then, the area was planted to sunn hemp (*Crotalaria juncea* L.) as a green manure crop, after which the soil was prepared by crossed direction subsoiling to a depth of 40 cm, followed by one plowing and two disk harrowings. Furrows were then opened to a depth of 30 cm and fertilized for planting sugarcane, following the recommendations of Sousa & Lobato (2004) for an expected yield of more than 120 Mg ha^{-1}.

The sugarcane cultivars were planted in March 2010 in 4.5 × 7.5 m plots composed of 6 rows spaced at 1.5 m, with 5-m-wide paths between blocks. The experiment was performed in a 3 × 4 factorial design with three sugarcane cultivars (RB 83-5054, RB 84-5210 and RB 86-7515), defined according to their maturation period (early, medium and late, respectively), and four degrees of soil compaction, obtained through passing a tractor (Agrale model 4230) (Caxias do Sul, RS, Brazil) with a tare of 1.9 Mg, corresponding to the following traffic intensities: T_0 = 0 passes, T_2 = 2 passes, T_{10} = 10 passes and T_{20} = 20 passes in the same place.

The treatments were performed in three replications, for a total of 36 plots (3 × 4 × 3), which were distributed in randomized blocks. The tractor passes were only carried out directly after the first harvest, when the ratoons had not yet begun the budding process.

After the first year of cultivation, the plants of each cultivar were harvested according to the maturation index (MI) (Cesnik & Miocque, 2004), which was determined with an Atago model PAL-1 portable digital refractometer (Tokyo, Japan). The plants were harvested manually and cut at ground level using cane knives. An 80-mm water layer was then applied to maintain the viability of the ratoons for sprouting (Oliveira et al., 2012). Maintenance fertilizer was applied for nutrition of the new tillers over the growth cycle of the ratoons for an expected yield greater than 80 Mg ha^{-1} (Sousa & Lobato, 2004) through the addition of 60, 40 and 120 kg ha^{-1} of N, P_2O_5 and K_2O, respectively.

Subsequently, the tractor passed over the entire length of the inter-row space, leaving a 20 cm width of the plant row undisturbed. The straw, which had previously been removed, was then replaced to simulate the conditions of mechanized harvest without burning.

Approximately one month after applying the treatments for each harvest cycle, soil samples were collected from each plot at paired points, in the row (R) and in the inter-row (IR) positions along parallel transects. In these positions, 144 undisturbed soil samples were collected from the 0-10 and 10-20 cm layers using sampling rings of 6.4 cm diameter and 5.0 cm height. The samples were covered with paraffin to maintain the water content.

The undisturbed samples were prepared by removing excess soil from their edges. This excess material was used to physically characterize the soil (Table 2) and to determine the permanent wilting point (matric potential of -1.5 MPa) using a Richards extraction chamber (Embrapa, 2011).

The undisturbed samples were first saturated and subjected to a matric potential of -0.006 MPa to determine microporosity and field capacity (Severiano et al., 2011; Embrapa, 2011). The samples were then adjusted to water content levels ranging from 0.05 to 0.43 $dm^3 dm^{-3}$ for the penetration test using a Marconi model MA 933 penetrometer (Piracicaba, SP, Brazil) equipped with an electronic speed control and data-recording system, as described by Tormena et al. (1998).

After that, the samples were dried in a laboratory oven at 105 °C for 48 h to determine bulk density (Bd) according to Embrapa (2011). Total porosity (TP) was determined by the expression TP = (1-Bd/Pd), where Pd is particle density. The macroporosity of the soil samples was determined by the difference between the TP and the microporosity according to Embrapa (2011).

The penetration resistance curve was obtained by plotting penetration resistance (PR) as a function of the volumetric water content (θ) and the Bd according to the nonlinear model that was proposed by Busscher (1990), as shown in equation: $PR = 0.5545\ Bd^{4.6924}\ \theta^{-0.5576}$; $r^2 = 0.75^{**}$

Available Water ($AW = \theta_{FC}-\theta_{PWP}$) was determined by the difference between the volumetric water content at field capacity (θ_{FC}) and at the permanent wilting point (θ_{PWP}). The Least Limiting Water Range (LLWR) was determined according to the procedures that were described by Silva et al. (2006), considering the upper limit to be the lowest value among the water content retained in the soil at a matric potential of -0.006 MPa, corresponding to field capacity (θ_{FC}) or the value at which the air-filled porosity (θ_{AFP}) was 10 %, which was calculated for each sample by the expression θ_{AFP} = TP-0.1. In turn, the lower limit was considered to be the greatest value among the retained water contents at a matric potential of -1.5 MPa in relation to the permanent wilting point (θ_{PWP}), and/or the water content corresponding to a penetration resistance of 2.5 MPa (θ_{PR}).

Soil water content (θ) was monitored weekly during the rainy season, as of September 2011 for the early and medium-maturing cultivars, and October 2011 for the late-maturing cultivar. These measurements continued until the harvest of each cultivar according to an adaptation of the method proposed by Blainski et al. (2009).

The 0 -20 cm layer was assessed using a Saci model S-20 semiautomatic electric soil sampler (Santa Bárbara d'Oeste, SP, Brazil). The samples were packed and taken to the laboratory to measure the gravimetric moisture content according to Embrapa (2011). The LLWR was used as a reference parameter to determine the frequency of θ within the available water range during the growing cycle (Fwithin), according to Silva & Kay (1997). The monitoring period was divided into the crop vegetative phase (VPh) and the maturation phase (MPh), according to Diola & Santos (2012).

At the end of the ratoon cycle of each cultivar (maturation), the sugarcane was harvested in May, June and September 2012 for the early, medium and late cycle cultivars, respectively. At the time of each

Table 1. The sorption complex of the distroferric Red Latosol before cultivation of sugarcane in the Brazilian Cerrado

Ca	Mg	Al	H+Al	P	K	V(1)	m(2)	O.M. (3)	$pH(H_2O)$
$cmol_c\ dm^{-3}$				$mg\ dm^{-3}$		%		$g\ kg^{-1}$	
				0-20 cm					
4.2	1.6	0.1	3.6	22.0	254.5	64.3	2.0	46.0	6.5
				20-40 cm					
1.6	0.6	0.1	4.0	3.7	98.0	38.9	4.0	34.0	6.2

(1) V: base saturation; (2) m: aluminum saturation; (3) O.M.: organic matter; P: determined by Mehlich-1 extractor.

Table 2. Physical and chemical characterization of a distroferric Red Latosol planted to sugarcane in the Brazilian Cerrado

Bd	Pd	VCS	CS	MS	FS	VFS	Silt	Clay	SiO_2	Al_2O_3	Fe_2O_3	Ki	Kr
$kg\ dm^{-3}$		$g\ kg^{-1}$											
						0-20 cm							
0.91	2.80	0.0	17.0	190.0	146.0	43.0	237.0	367.0	40.5	203.6	204.0	0.34	0.21
						20-40 cm							
1.02	2.82	0.0	16.0	183.0	142.0	42.0	150.0	468.0	38.8	200.5	214.7	0.33	0.20

Bd: bulk density, determined before application of the machine traffic treatments. Pd: particle density by the volumetric flask method. VCS: very coarse sand. CS: coarse sand. MS: medium sand. FS: fine sand. VFS: very fine sand. Ki: molecular relationship SiO_2/Al_2O_3. Kr: molecular relationship $SiO_2/(Al_2O_3 + Fe_2O_3)$. Particle size was determined by sieving and the pipette method.

harvest, the stalks from the two central rows of each plot were weighed, and the value was extrapolated to kg ha^{-1}.

Ten additional stalks were also collected from the two central rows to determine the industrial quality variables, according to the method described by Consecana (2006). The parameters measured were Brix (B), Pol in the juice (S), Pol in the cane (PC), purity of the juice (Q), total recoverable sugars (TRS), cane fiber (F), reducing sugars in the juice (RS) and reducing sugars in the cane (CRS).

Mean monthly temperature and rainfall were also monitored during the experiment. The results are shown in figure 1.

The results of the soil physical properties and moisture levels and the cane quality variables were subjected to analysis of variance according to a randomized block design, and the mean values were compared by the Tukey test at 5 % probability.

RESULTS AND DISCUSSION

Analysis of variance of the soil physical properties indicated differences in the inter-row samples only for the variation of the number of tractor passes (N) in the layer from 0-10 cm (Table 3). In this regard, it is noted that bulk density (Bd) and soil total porosity (TP), as well as soil macro- and microporosity, have been modified by increasing the number of tractor passes over the soil. For the in-row samples, there was no change in the physical or moisture properties, with average bulk densities (Bd) of 1.00 and 1.05 kg dm^{-3} at depths of 0-10 cm and 10-20 cm, respectively, similar to the findings of Correchel et al. (1999). The other sources of variation (Cultivar [C] and N x C interaction) did not have a significant effect on the physical properties at either depth (Table 3).

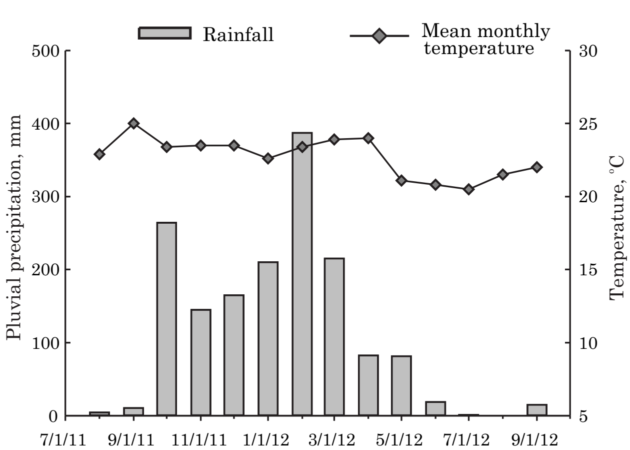

Figure 1. Rainfall and mean monthly temperature during sugarcane cultivation in the Brazilian Cerrado.

Analysis of the LLWR as a function of Bd (Figure 2) shows increasing amplitude of the LLWR until Bd = 1.15 kg dm^{-3} (Bd_{PR}), after which the magnitude begins to decrease until Bd = 1.23 kg dm^{-3} (Bdc). Considering the position of each treatment within the LLWR for the soil layer where the physical changes were greatest (0-10 cm), the compaction levels of 0 and 2 tractor passes (Bd = 1.08 and 1.13, respectively) did not cause any physical restrictions. Conversely, the T_{10} (Bd = 1.17) and T_{20} (Bd = 1.22) treatments exposed the cane to water limitations due to the high θ_{PR}. Though low, these values for critical bulk density are similar to those observed by Tormena et al. (1998) and Lima et al. (2012) working with clay Oxisols.

The Available Water (AW) value had a weak positive correlation with increasing Bd (Figure 2), indicating that the AW parameter is not as sensitive as the LLWR to structural changes in the soil (Tormena et al., 2007). The positive effect of Bd on AW is due to the redistribution of pores by size, especially through an increase in microporosity, which increases soil water retention (Leão et al., 2004).

The results of monitoring soil water content as a function of the critical limits of the LLWR are shown in figures 3 and 4 for the inter-row (IR) and in-row (R) sampling points, respectively, highlighting the phenological division corresponding to the vegetative and maturation phases of the stalks. Sugarcane responds differently to water deficit depending on its growth stage; this environmental stress is harmful during the vegetative phase but desirable during ripening since it stimulates accumulation of sucrose in the stalks.

For the IR position at the 0-10 cm depth (Figure 3), the amplitude of the LLWR was reduced and soil moisture was outside the LLWR limit as of 10 tractor passes (T_{10}). This behavior worsened with 20 tractor passes over the same location (T_{20}). There was substantial occurrence of moisture points outside the LLWR limits at T_{20} during the vegetative phase, a period when the stalks are extremely sensitive to water deficit.

In the treatments with less traffic intensity, there was only a brief water deficit, particularly during September and October (Figure 3) in the vegetative phase of the early and medium-maturing cultivars. This result may be explained by the fact that these months are at the end of the dry season, when water availability in the soil is naturally low. On the other hand, the late-maturing cultivar underwent water deficit at all traffic levels during the final maturation phase. This stress promotes sucrose accumulation according to sugarcane physiology (Segato et al., 2006).

Table 3. Analysis of variance, overall mean values and coefficients of variation for the physical properties of a distroferric Red Latosol in the inter-row of sugarcane in the Brazilian Cerrado

Source of variation	Mean square							
	Bd(1)	TP(2)	Micro(3)	Macro(4)	Bd	TP	Micro	Macro
	0-10 cm				10-20 cm			
Tractor passes (N)	0.0329**	0.0057**	0.0008**	0.0097**	0.0021^{NS}	0.0004^{NS}	0.0003^{NS}	0.0001^{NS}
Cultivar (C)	0.0032^{NS}	0.0001^{NS}	0.0001^{NS}	0.0005^{NS}	0.0037^{NS}	0.0005^{NS}	0.0002^{NS}	0.0009^{NS}
N x C	0.0019^{NS}	0.0002^{NS}	0.0002^{NS}	0.0002^{NS}	0.0030^{NS}	0.0005^{NS}	0.0003^{NS}	0.0012^{NS}
Block	0.0026	0.0003	0.0001	0.0008	0.0056	0.0007	0.0001	0.0011
Residue	0.0019	0.0002	0.0001	0.0002	0.0039	0.0005	0.0004	0.0013
Means	1.1511	0.5872	0.4144	0.1725	1.1397	0.5925	0.3994	0.1947
CV (%)	3.78	2.37	2.33	8.24	5.46	3.80	4.88	18.33

(1) Bulk density; (2) Soil total porosity; (3) Microporosity; (4) Macroporosity. NS Not Significant and ** significant at 1 % probability by the F test.

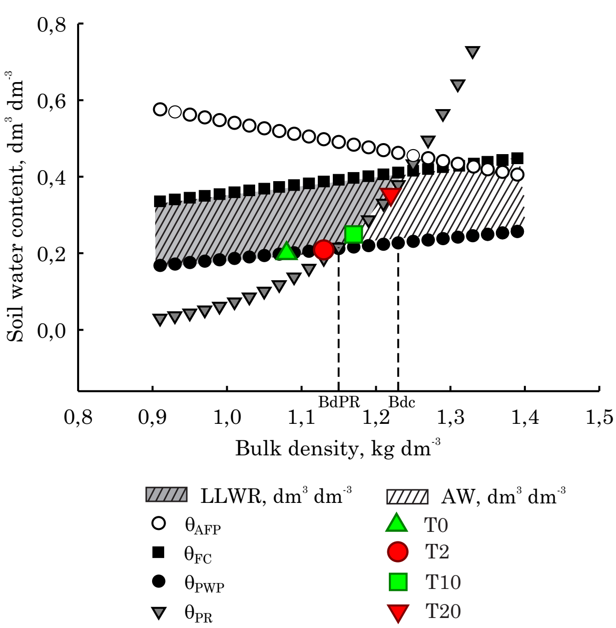

Figure 2. Variation in the Least Limiting Water Range (LLWR) and Available Water (AW) as a function of bulk density (Bd) observed in a distroferric Red Latosol planted to sugarcane in the Brazilian Cerrado. T_0 = 0, T_2 = 2, T_{10} = 10 and T_{20} = 20 tractor passes in the same place. Bd_{PR}: Bd at the lower limit of the LLWR as limited by θ_{PR}. Bdc: bulk density critical for plant development.

Moreover, for the lower soil layer that was studied (10-20 cm) in the IR position, points outside the LLWR were only detected for the months of lowest rainfall (Figure 3). This finding confirms the small changes in the Bd in the layers deeper than 10 cm (Table 3), which did not cause any change in the magnitude of the LLWR.

Similar behavior was observed in the soil from within the crop rows (position R) in all the treatments assessed because as there were no tractor passes and therefore no deleterious effects of soil compaction, the LLWR remained at adequate levels (Figure 4). In the rows, maintaining θ within the limits of the LLWR provided suitable conditions for growth; this water content range is less restricted in terms of available water, penetration resistance and oxygen supply (Silva et al., 1997). These results are similar to the observations of Souza et al. (2012) regarding the conservation of structural quality in the region of the ratoon and its positive impact on the sugarcane development.

The frequency percentages of the soil water content within the LLWR limits (Fwithin) are shown in table 4. According to figures 3 and 4, the Fwithin values in the 0-10 cm layer decreased in treatment T_{10} and worsened in T_{20} when assessing the IR position. Under these conditions, the LLWR was reduced by 16 and 69 % for 10 and 20 passes, respectively, compared to the treatment without traffic.

Although the early and medium-maturing cultivars showed an Fwithin of approximately 40 % during the vegetative phase when the soil was most compacted (T_{20}), this effect may not be deleterious since soil moisture monitoring for these two cane hybrids began in September 2011, a period after the sprouting phase, which is when cane is most sensitive to water deficit in view of the harvest dates (April and June 2011, respectively). We therefore suggest that the irrigation applied after the harvest assured the sprouting and initial development of the cultivars in question.

This irrigation did not occur for the late-maturing cultivar, which showed an Fwithin value of approximately 60 % during the vegetative phase in treatment T_{20} at the 0-10 cm depth. It should be noted that these conditions reflect the water deficit that was aggravated by the excessive PR for almost half of the vegetative phase, as the harvest of the previous cycle occurred at the beginning of the rainy season.

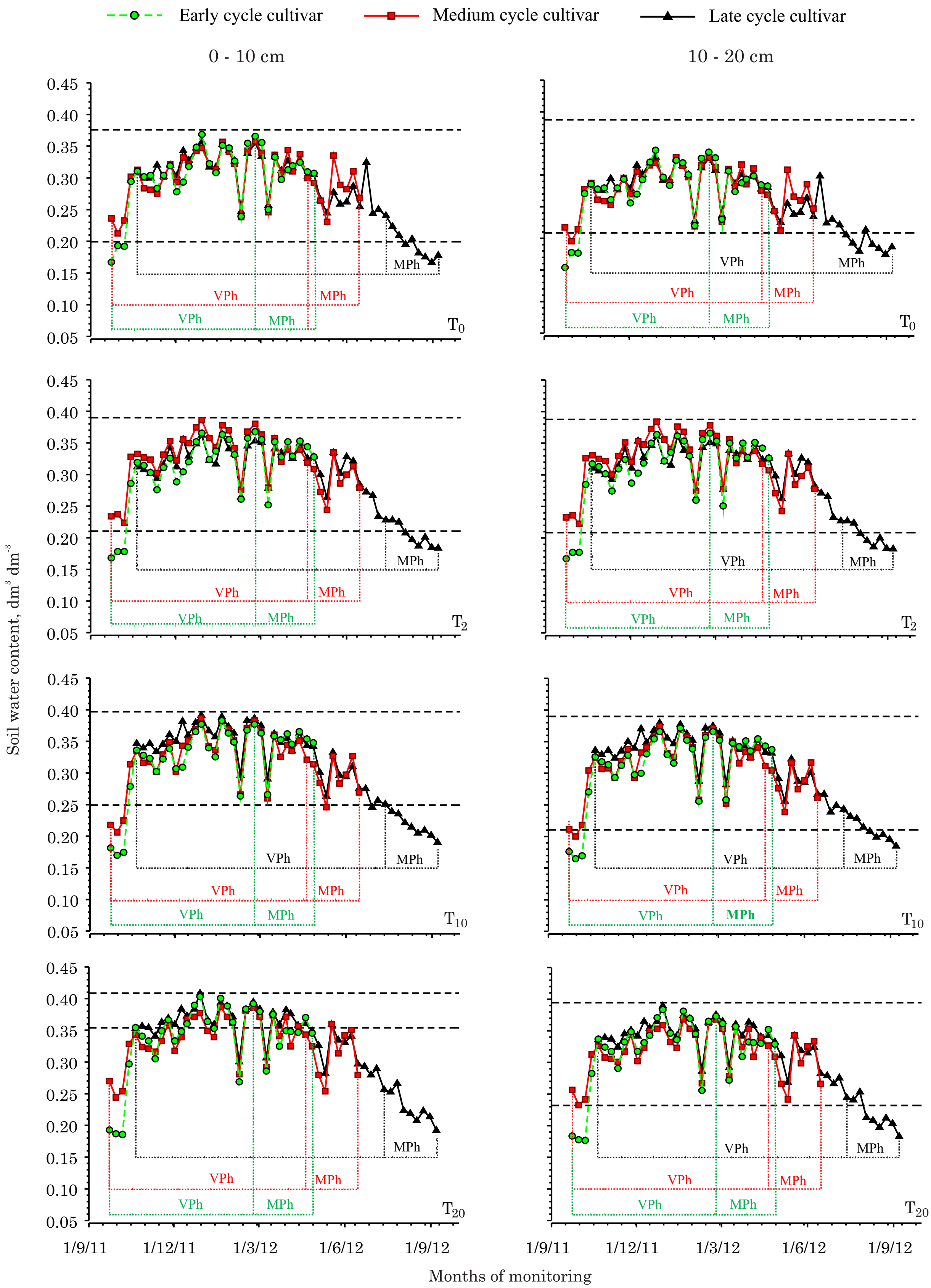

Figure 3. Temporal variation of soil water content in relation to the critical limits of the Least Limiting Water Range for samples from the inter-row of sugarcane (IR) in the Brazilian Cerrado. VPh: vegetative phase. MPh: maturation phase. T_0 = 0, T_2 = 2, T_{10} = 10 and T_{20} = 20 tractor passes in the same place.

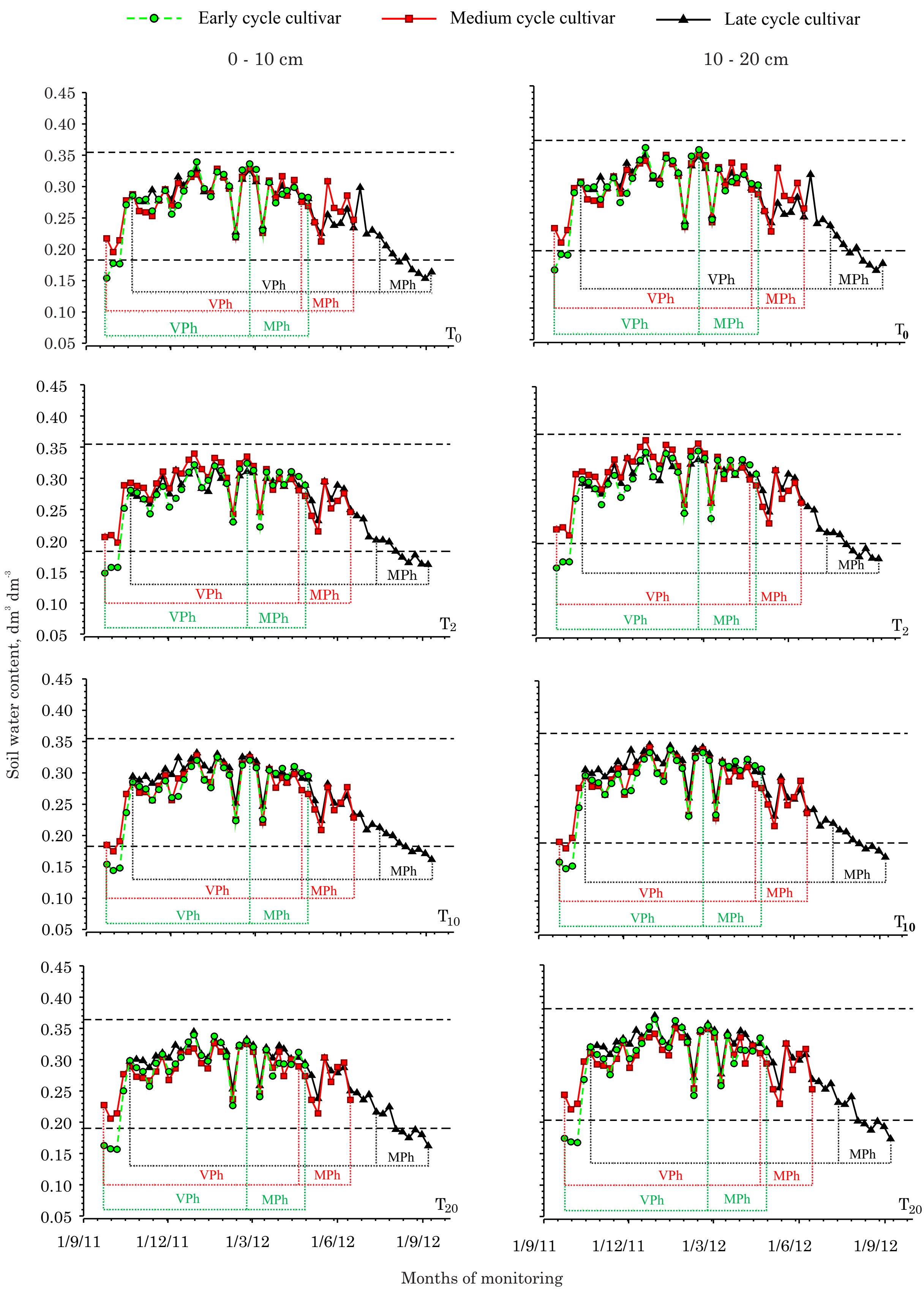

Figure 4. Temporal variation of soil water content in relation to the critical limits of the Least Limiting Water Range for samples from within the rows of sugarcane (R) in the Brazilian Cerrado. VPh: vegetative phase. MPh: maturation phase. T_0 = 0, T_2 = 2, T_{10} = 10 and T_{20} = 20 tractor passes in the same place.

Table 4. The Least Limiting Water Range and frequency analysis of θ for soil from the rows and inter-rows of sugarcane within the bounds of the LLWR (Fwithin) during the plant cycle for different levels of traffic in a distroferric Red Latosol in the Brazilian Cerrado

Number of passes	Sampling position	LLWR[(1)]	Fwithin					
			VPh[(2)]			MPh[(3)]		
			E[(4)]	M[(5)]	L[(6)]	E[(4)]	M[(5)]	L[(6)]
		$dm^3\ dm^{-3}$	%					
			0-10 cm					
0	IR[(7)]	0.177	84.2	100.0	100.0	100.0	100.0	44.4
	R[(8)]	0.172	84.2	100.0	100.0	100.0	100.0	44.4
2	IR	0.179	84.2	100.0	100.0	100.0	100.0	33.3
	R	0.172	84.2	100.0	100.0	100.0	100.0	44.4
10	IR	0.148	84.2	90.0	97.4	100.0	88.9	11.1
	R	0.172	84.2	96.7	100.0	100.0	100.0	44.4
20	IR	0.055	42.1	43.3	63.2	46.2	11.1	0.0
	R	0.174	84.2	100.0	100.0	100.0	100.0	33.3
			10-20 cm					
0	IR	0.178	84.2	96.7	100.0	100.0	100.0	22.2
	R	0.174	84.2	100.0	100.0	100.0	100.0	44.4
2	IR	0.178	84.2	100.0	100.0	100.0	100.0	33.3
	R	0.175	84.2	100.0	100.0	100.0	100.0	33.3
10	IR	0.179	84.2	96.7	100.0	100.0	100.0	44.4
	R	0.174	84.2	96.7	100.0	100.0	100.0	44.4
20	IR	0.163	84.2	100.0	100.0	100.0	100.0	33.3
	R	0.177	84.2	100.0	100.0	100.0	100.0	33.3

(1) Least Limiting Water Range. (2) Vegetative phase of sugarcane. (3) Maturation phase of sugarcane. (4) Early cycle cultivar. (5) Medium cycle cultivar. (6) Late cycle cultivar. (7) Inter-row of the crop. (8) In the crop row.

During the maturation phase in the IR position and at a depth of 0-10 cm, the early-, medium- and late-maturing cultivars were subjected to stressful conditions (T_{20}) for 54, 89 and 100 % of the sucrose accumulation phase, respectively. Under the lower traffic levels, only the late-maturing cultivar had Fwithin values that were less than or equal to 45 %. These low Fwithin values during the maturation phase of the late-ripening cultivar, regardless of the traffic levels, are a consequence of the water regime in the region (Figure 1), not the structural degradation of the soil. We reach this conclusion by observing similar values for Fwithin in the rows and the inter-rows of the crop as well as in the layers deeper than 10 cm, where the structural condition of the soil is preserved.

Conversely, there was no significant modification of the Fwithin values at any of the traffic intensities up to a depth of 10 cm in the plant rows, except during the maturation phase of the late-ripening cultivar. The reason for this is that some of the assessments were performed during the dry season (July to September 2012).

Analyses of the production variables and technological quality variables of the cane cultivars of the first ratoon are shown in table 5. Only the cultivar source of variation (C) differed and then only for the parameters of Pol in the juice (S), Pol in the cane (PC), total recoverable sugars (TRS), fiber (F) and Brix (B). Soil compaction, which is represented by the number of tractor passes (N), and the interaction of the factors (N × C), did not affect the productive and industrial quality of the cane stalks.

The overall average weight of the stalks was 186.6 Mg ha^{-1}, a figure far above (119 %) average (85 Mg ha^{-1}) for Brazil (Brasil, 2010). Adequate water availability during the vegetative phase of all the cultivars at both depths that were assessed (Table 4) helps to explain the absence of differences in stalk yields, as the accumulation of mass in the aerial part is a result of good soil water conditions during this phase. In contrast, the relative lack of water during the maturation phase determines the quality of the material that is produced.

In this respect, juice purity (Q) achieved the minimum value of 85 % proposed by Ripoli & Ripoli (2004). According to Consecana (2006), the sugar mill can refuse to receive loads of cane with Q <75 %. The reducing sugar levels were within the recommended limits (Ripoli & Ripoli, 2004).

For the variables where the F-test showed significance, we applied the Tukey test ($p<0.05$). The results are shown in table 6. The values of apparent sucrose in the juice and cane (S and PC, respectively) for all the cultivars achieved the 14 % minimum proposed by Ripoli & Ripoli (2004). The S and PC values were higher in the late-maturing cultivar than in the other two, in agreement with the findings of Hoffmann et al. (2008), denoting the high production capacity of late-cycle sugarcane for accumulating sucrose. This capacity is a physiological characteristic that is inherent to this cultivar.

Only the late-maturing cultivar presented TRS levels that were greater than the average of 137.5 kg t^{-1} in the south-central region of Brazil for the 2011-2012 season (UNICA, 2012). This cultivar differs from other hybrids in regard to the quantity of TRS per ton of cane, corroborating its high productive potential and quality as proposed by Hoffmann et al. (2008). In addition, the water stress that was quantified during the maturation of this cultivar (Figures 3 and 4) may have contributed to its superior performance in comparison to the other cultivars in regard to quality of the juice (Table 6).

The fiber contents of the early and late-maturing cultivars were between 11 and 13 %, the same range that was reported as adequate by Ripoli & Ripoli (2004). Stalk fiber for the medium-cycle cultivar was lower than that proposed by Ripoli & Ripoli (2004) and smaller than that of the other cultivars (Table 6), which predisposes the plant to lodging and difficulty in harvesting. Finally, the level of Brix in the juice (B) of the late-maturing cultivar was 29 % greater than in the other two, which did not differ from one another. This higher sugar accumulation was expected due to the characteristics of high industrial quality of the late-cycle cultivar (Hoffmann et al., 2008).

The absence of a response of the productive and industrial quality variables to the traffic levels and to the narrowing of the LLWR may be associated with the critical limits that were used to determine the LLWR, especially in regard to the penetration resistance (PR) of 2.5 MPa. In this respect, according to Silva et al. (2009), the critical limits of the LLWR need to be adjusted for different soil and management conditions and species. For example, the critical limit for PR may need to be increased for Latosols under low mechanical movement, as in the case of sugarcane, for which the average renewal cycle in Brazil is currently five years (Brasil, 2010). Furthermore, according to Silva et al. (2009), although the soil in cane fields persists for long periods without tillage, accumulating historic stress, the bioporosity resulting from successive crops can provide preferential pathways for root growth, offsetting greater soil resistance.

Table 5. Analysis of variance, overall mean values and coefficients of variation for the technological and production variables of cane cultivars that were grown in a distroferric Red Latosol in the Brazilian Cerrado

Source of variation	Mean square								
	Weight of the stalks	S(1)	Q(2)	PC(3)	TRS(4)	F(5)	RS(6)	CRS(7)	B(8)
Number of tractor passes (N)	$1.139 \cdot 10^{9}$ NS	0.121NS	3.477NS	0.100NS	7.517NS	0.084NS	0.005NS	0.003NS	0.077NS
Cultivar (C)	$2.017 \cdot 10^{9}$ NS	72.875**	14.298NS	49.695**	4367.784**	9.460**	0.017NS	0.015NS	79.547**
N × C	$6.122 \cdot 10^{8}$ NS	1.283NS	1.922NS	0.991NS	85.081NS	0.342NS	0.023NS	0.002NS	1.319NS
Block	$4.395 \cdot 10^{9}$	0.442	4.459	0.188	12.312	0.394	0.005	0.004	0.113
Residue	$6.331 \cdot 10^{8}$	1.126	6.361	0.793	62.754	0.284	0.008	0.006	0.739
Means	$1.866 \cdot 10^{5}$	16.736	87.887	14.487	142.926	10.681	0.626	0.543	19.012
CV (%)	13.48	6.34	2.87	6.15	5.54	4.99	14.08	14.12	4.52

(1) Pol in the juice. (2) Purity of the juice. (3) Pol in the cane. (4) Total recoverable sugars. (5) Cane fiber. (6) Reducing sugars in the juice. (7) Reducing sugars in the cane. (8) Brix or percentage of soluble solids in the juice. NS not significant. ** significant at 1 % probability by the F test.

Table 6. Mean values for the technological variables of samples collected during the first ratoon harvest of sugarcane grown in a distroferric Red Latosol in the Brazilian Cerrado

Cultivar cycle	S(1)	PC(2)	TRS(3)	F(4)	B(5)
Early	15.32 B	13.14 B	130.31 B	11.24 A	17.62 B
Medium	15.31 B	13.49 B	133.60 B	9.66 B	17.44 B
Late	19.58 A	16.83 A	164.87 A	11.15 A	21.98 A

(1) Pol in the juice. (2) Pol in the cane. (3) Total recoverable sugars. (4) Cane fiber. (5) Brix or percentage of soluble solids in the juice. For each technological variable of sugarcane, mean values followed by the same letter do not differ by the Tukey test (p<0.05).

Another important factor in explaining the results of this study is the absence of traffic over the plant rows. With a width of 0.2 m, furrowing depth of 0.3 m and length of 27 m for the rows in each plot, there was a volume of 483 m^3 ha^{-1} of structurally adequate soil, covering 16 % of the total area and allowing the root system to grow in compartmented form.

However, because there was no water deficit during nearly the entire vegetative phase and because the demand for nutrients was most likely adequately met in the crop rows where the soil remained structurally preserved (Figure 4), we believe that the adverse environment caused by soil compaction within the furrows was compensated for. This compensation is called the "pot effect" and involves crowding of the plant root system into a reduced volume of soil due to the deformation of the soil between the plant rows or elsewhere below the surface.

CONCLUSIONS

1. The deleterious effects of soil compaction were limited to the area between the crop rows and only in the surface layer (depth < 10 cm).

2. The LLWR was altered by an increasing number of tractor passes, which reduced the LLWR to almost zero in the treatment with 20 passes between the rows.

3. Monitoring of the Fwithin indicated the incidence of stressful conditions to sugarcane in terms of water availability, notably under the heaviest traffic conditions (10 or more passes).

4. The absence of traffic over the crop rows, which maintained the soil in the adequate condition for plant development established in preparing the soil for planting, may have offset the harmful effects of soil compaction on the development of the sugarcane cultivars.

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