Soil compaction by machine traffic and least limiting water range related to soybean yield

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Abstract – The research aimed to evaluate machine traffic effect on soil compaction and the least limiting water range related to soybean cultivar yields, during two years, in a Haplustox soil. The six treatments were related to tractor (11 Mg weight) passes by the same place: T_0, no compaction; and T_{1*}, 1; T_1, 1; T_2, 2; T_4, 4 and T_6, 6. In the treatment T_{1*}, the compaction occurred when soil was dried, in 2003/2004, and with a 4 Mg tractor in 2004/2005. Soybean yield was evaluated in relation to soil compaction during two agricultural years in completely randomized design (compaction levels); however, in the second year, there was a factorial scheme (compaction levels, with and without irrigation), with four replicates represented by 9 m^2 plots. In the first year, soybean [*Glycine max* (L.) Merr.] cultivar IAC Foscarim 31 was cultivated without irrigation; and in the second year, IAC Foscarim 31 and MG/BR 46 (Conquista) cultivars were cultivated with and without irrigation. Machine traffic causes compaction and reduces soybean yield for soil penetration resistance between 1.64 to 2.35 MPa, and bulk density between 1.50 to 1.53 Mg m^{-3}. Soil bulk density from which soybean cultivar yields decrease is lower than the critical one reached at least limiting water range (LLWR = 0).

Index terms: *Glicine max*, soil management, soil physical quality.

Compactação do solo por tráfego de máquinas e intervalo hídrico ótimo na produtividade de soja

Resumo – O estudo objetivou a avaliação do efeito do tráfego de máquinas sobre a compactação do solo, e a avaliação do intervalo hídrico ótimo e sua relação com a produtividade de cultivares de soja, durante dois anos, em Latossolo Vermelho. Os seis tratamentos foram relativos a passadas de trator (peso de 11 Mg) pelo mesmo local: T_0, sem compactação; T_{1*}, 1; T_1, 1; T_2, 2; T_4, 4 e T_6, 6. No tratamento T_{1*}, a compactação foi realizada quando o solo estava seco, em 2003/2004, e com um trator mais leve – de 4 Mg – em 2004/2005. No primeiro ano, a soja [*Glycine max* (L.) Merr.] cultivar IAC Foscarim 31 foi cultivada sem irrigação e, no segundo ano, as cultivares IAC Foscarim 31 e MG/BR 46 (Conquista) foram cultivadas sem e com irrigação. O tráfego de máquinas compactou o solo e reduziu a produtividade de soja, a partir da resistência à penetração de 1,64 a 2,35 MPa e da densidade do solo de 1,50 a 1,53 Mg m^{-3}. A densidade do solo a partir da qual a produtividade de soja decresceu foi menor do que a densidade do solo crítica, obtida no intervalo hídrico ótimo (LLWR = 0).

Termos para indexação: *Glicine max*, manejo do solo, qualidade física do solo.

Introduction

Soil compaction can reduce root growth through physical processes associated with lower aeration and decreasing water and nutrients absorption, which causes significant yield decrease (Flowers & Lal, 1998; Beutler & Centurion, 2004; Czyz, 2004). In order to quantify the level of compaction and monitor the soil physical quality, many physical properties, such as soil bulk density (D_b), porosity, soil penetration resistance (PR) and preconsolidation pressure (σp) have been intensively studied. Adequate PR to the plants development, suitable levels of available water and aeration are required; these properties affect root growth and plant yield directly (Letey, 1985). For integrating these three properties in one parameter, Letey (1985) conceived a model, improved by Silva et al. (1994), which defines the water content where water limitation, aeration and PR to the root growth do not occur, determining the least limiting water range

(LLWR) (Silva et al., 1994). The superior limiting range of LLWR (high water content) is the lowest value between water content at 10% aeration porosity (Grable & Siemer, 1968; Engelaar et al., 2000) and the water content retained at field capacity (FC) (tension at 0.01 MPa) (Haise et al., 1955). The inferior limiting range is the highest value between water content retained at the permanent wilting point (at 1.50 MPa) (Richards & Weaver, 1944), and water content at which PR is limiting to root growth.

The least limiting water range has been effectively utilized in soil physics to monitor soil use and tillage systems, in three ways: to evaluate physical quality towards plant growth (Tormena et al., 1999; Wu et al., 2003); to establish relations between this indicator and the aerial part of plant growth (Silva & Kay, 1996); to investigate functional relationships between LLWR and grain yield (Benjamin et al., 2003; Lapen et al., 2004; Beutler et al., 2005; Collares et al., 2006).

The research aimed to evaluate machine traffic effect on soil compaction and the least limiting water range related to soybean cultivar yield, during two years, in a Haplustox soil.

Materials and Methods

The experiment was carried out during the agricultural years 2003/2004 and 2004/2005, in Jaboticabal county, in São Paulo State, Brazil (21º15'29"S e 48º16'53"E). According to Köppen's classification, the climate is defined as Aw (tropical wet-dry). The soil was classified as Haplustox, with sand, silt, and clay contents of 635, 35, and 330 g kg^{-1}, respectively, at 0–0.20 m depth. Particle density, determined by the pycnometer method, was 2.72 Mg m^{-3}.

The soybean yield was evaluated in relation to soil compaction, during two agricultural years in completely randomized design (compaction levels); in the second year, there was a factorial scheme (compaction levels, with and without irrigation), with four replicates represented by 9 m^2 plots. In the first year, soybean [(*Glycine max* (L.) Merr.)] cultivar IAC Foscarim 31 was cultivated without irrigation and, in the second year, IAC Foscarim 31 and MG/BR 46 (Conquista) cultivars were cultivated with and without irrigation.

In November 2003/2004, the soil was subsoiled down to 0.20 m and in 2004/2005, to 0.30 m depth, and leveled by harrowing. After a precipitation, when water content was near to field capacity (at 0.01 MPa), compaction treatments were applied in passes, as follows: T_0, no compaction; T_{1*}, one; T_1, one; T_2, two; T_4, four and T_6, six, with an 11-Mg tractor with double axle and four tires of equal width (0.40 m) and inflation pressure. The tractor traveled on the same place as described above. The treatment T_{1*}, in the first year, was performed with the heavier tractor, when the soil was dryer and, in the second year, with a 4-Mg tractor when water content was near to field capacity, to obtain the lowest compaction.

On December 5th, 2003, and November 22nd, 2004, seeds of a short cycle soybean cultivar (120 days) – IAC Foscarim 31 – and those of a medium cycle (131–140 days) – MG/BR 46 (Conquista) – were infected with *Bradyrhizobium japonicum* and sown at 0.05 m depth in rows and 0.45 m apart, in transversal direction of the tractor traffic and area's slope. In the second year, two irrigations were applied after the sowing to promote seed germination. After ten days, weeds were manually removed, and 20 soybean plants per meter were maintained.

Fertilization consisted of: 0.050 Mg ha^{-1} ammonium sulfate, 0.150 Mg ha^{-1} triple superphosphate, and 0.100 Mg ha^{-1} potassium chloride at sowing, in order to obtain the expected soybean yield of 3.5 to 4 Mg ha^{-1}.

In the second year, for the irrigated treatment, sprinkler irrigation was applied, when the water content was equivalent to that retained at the tension 0.05–0.15 MPa, with most irrigations being undertaken at 0.06 MPa. To control the water content, daily monitoring was done by collecting soil samples at 0–0.20 m depth and drying at 105^{o}C.

In January of both years, two replicates per treatment of six undisturbed soil samples were collected with cylinders of 0.030 m height and 0.048 m diameter (53.16×10^{-6} m^3) at 0.03–0.06, 0.08–0.11, 0.15–0.18 and 0.22–0.25 m depth. Then, one sample from each replicate was saturated for 24 hours and subjected to one of the following tensions: 0.006, 0.010, 0.033, 0.060, 0.100 and 0.300 MPa in Richards' pressure chambers. When equilibrated, the samples were weighted, and soil penetration resistance (PR) was determined in its intermediate layer of 0.006–0.023 m, with two replications per cylinder, and 100 readings on each replication were performed in order to obtain the average PR. The PR was determined with a static penetrometer with 30º semi-angle cone, constant penetration of 0.01 m min^{-1}, and a cone base area of 2.96x10^{-6} m^2.

Then, the samples were dried at 105–110°C to obtain the water content at each tension and the soil bulk density (D_b). Microporosity was the water content at 0.006 MPa (pores<50 µm), and macroporosity (pores>50 µm) was the difference between total porosity and microporosity.

In order to determine the least limiting water range (LLWR), the soil water retention curve was adjusted according to the model of van Genuchten (1980), and the water was estimated content at 1.5 MPa (θ_{WP}). The water content at 0.01 MPa (θ_{FC}) was adjusted by the nonlinear model used by Silva et al. (1994), by the linearized form:

$$\ln \theta = a + bD_b + c\ln \Psi \quad (1)$$

The PR curve was adjusted by the nonlinear model proposed by Busscher (1990), by the linearized form:

$$\ln PR = \ln d + e\ln \theta + f\ln D_b \quad (2)$$

in which: θ is the soil volumetric water content (m^3 m^{-3}); D_b is the soil bulk density (Mg m^{-3}); Ψ is the soil water tension (hPa); PR is the soil penetration resistance (MPa); a, b, c, d, e and f are the model-fitting parameters.

Assuming that water content at field capacity (FC) is equivalent to 0.01 MPa, the θ_{FC} were estimated by the equations (3) obtained by equation (1), as follows:

$$\theta_{FC} = \exp(a + bD_b)100^c \quad (3)$$

The water content at which PR is limiting was calculated by the equation (4), which was obtained from equation (2):

$$\theta_{PR} = PR_{lim}/(e^d(D_b^e))^{1/f} \quad (4)$$

in which: PR_{lim} is the value of PR determined at the water content retained at field capacity (0.01 MPa), from which the soybean yield started decreasing in this research.

The water content in which the aeration porosity equals 10% was calculated by equation (5), which follows:

$$\theta_{AP} = (1 - (D_b/D_p)) - 0.10 \quad (5)$$

Finally, the θ_{AP}, θ_{FC}, θ_{WP}, and θ_{PR} were fitted in function of D_b composing the LLWR, representative of the three layers 0.03–0.06, 0.08–0.11 and 0.15–0.18 m.

Soybean yield at harvest was evaluated in plots of 3.37 m^2.

The results were analyzed by ANOVA ($p \leq 0.05$). When significant, polynomial regressions were fitted between PR and D_b with soybean yield.

Results and Discussion

After the first tractor passes over the loose soil in treatment (T_{1*}), the macroporosity was greatly reduced and D_b increased (Table 1). As the number of tractor passes increased up to T_6, the changes in these properties, in both years, were progressively less at 0–0.20 m. It has been widely found that the first wheel pass promotes more compaction than subsequent passes (Horn et al., 1995). This effect is due to greater destruction of larger pores (pores>50 µm) with the initial traffic (T_0–T_{1*}). After that, the smaller pores, more numerous in compacted soil (T_{1*}–T_6), are more resistant to deformation and compaction, increasing the soil's ability to support applied loads (Horn et al., 1995).

Only one pass of a 11-Mg tractor (T_{1*}) over the soil, for four days (in 2003/2004), or a 4-Mg tractor for one day after rainfall (in 2004/2005), was enough to reach D_b values greater than 1.48 Mg m^{-3}, which was reported to be limiting for soybean yield by Beutler & Centurion (2004), in the same soil. Similarly, with one tractor pass (T_{1*}), soil PR reached values close to 2 MPa, considered to be restricting for root system growth.

Three aspects of the tractor traffic effects on soil have been established, namely: for T_{1*}, one 11-Mg tractor pass, four days after the rainfall of 13 mm (in 2003/2004), resulted in lower soil compaction than a single pass of a 4-Mg tractor, one day after the rainfall of 12 mm (in 2004/2005), which indicates traffic restriction, when the water content is low; at water content close to field capacity (0.01 MPa), one 11-Mg tractor pass at T_1 (weight equivalent to a harvester) was enough to compact the soil at levels considered limiting to plant yield; soil compaction by tractor traffic was generally most intense at depths down to 0.18 m, and there was little change in physical properties at 0.22–0.25 m depth (T_{1*}–T_6) (Table 1). However, it is common to find in literature that compaction by traffic with heavier machines may reach below 0.20 m (Hamza & Anderson, 2005).

Soybean yield was lower in 2003/2004 (Figure 1). This is attributed to low rainfall after sowing in December (Figure 2), which resulted in poor initial growth.

Excessive soil traffic reduced soybean yield with a maximum decrease of more than 18%, in both years, and in cultivation with and without irrigation in the second year (T_{1*}–T_6; $p \leq 0.05$, Figure 1).

A quadratic fitted function of PR and D_b with soybean yield, in both years, and cultivation with and without irrigation in the second year indicated that a small compaction value would result in greater yield ($p \leq 0.05$).

This study confirmed that a lack (T_0 – loose soil) or an excess (T_6) of soil compaction can cause a smaller plant growth, as reported by Czyz (2004). On loose soil (T_0), a maximum yield was not obtained, possibly due smaller root/soil contact, which reduces water and nutrient absorptions, as mentioned by Håkansson et al. (1998). On loose soils, unsaturated hydraulic conductivity is low (Richard et al., 2001), which reduces water and nutrient movements towards the roots, because of the greater space among soil particles (Lipiec & Hatano, 2003).

In addition, on heavily compacted soil (T_1–T_6), many adverse aspects of soil physical properties are damaging to plant growth and yield. In this condition, close proximity among soil particles, which favors water absorption, is not enough to compensate root growth reduction by mechanical restriction. A decrease in root density, surface and dry matter at 5–15 cm depth results in reduction of the available water to root and of its growth within the superficial soil layer with lowest available water content (Beutler & Centurion, 2004).

Table 1. Soil physical properties at different depths, after different number of tractor passes in 2003/2004 and 2004/2005 (n = 2).

Physical property	Depth (m)	Tractor passes[1]					
		T_0	T_{1*}	T_1	T_2	T_4	T_6
		2003/2004					
Macroporosity (m^3 m^{-3})	0.03–0.06	0.17±0.01	0.10±0.01	0.04±0.00	0.03±0.00	0.04±0.00	0.04±0.00
	0.08–0.11	0.18±0.06	0.12±0.01	0.05±0.01	0.04±0.00	0.04±0.00	0.05±0.00
	0.15–0.18	0.10±0.12	0.07±0.02	0.05±0.01	0.05±0.01	0.06±0.00	0.06±0.00
	0.22–0.25	0.06±0.01	0.08±0.02	0.08±0.00	0.08±0.01	0.08±0.00	0.08±0.01
Microporosity (m^3 m^{-3})	0.03–0.06	0.27±0.01	0.29±0.00	0.28±0.00	0.28±0.00	0.28±0.00	0.29±0.01
	0.08–0.11	0.26±0.01	0.29±0.00	0.28±0.00	0.30±0.01	0.28±0.00	0.29±0.01
	0.15–0.18	0.26±0.01	0.29±0.01	0.28±0.00	0.29±0.01	0.29±0.00	0.30±0.00
	0.22–0.25	0.29±0.01	0.30±0.02	0.29±0.01	0.28±0.00	0.30±0.00	0.30±0.00
Penetration resistance (MPa)[2]	0.03–0.06	1.09±0.01	1.31±0.01	2.72±0.03	3.80±0.15	4.01±0.08	4.54±0.02
	0.08–0.11	0.82±0.01	1.64±0.33	2.75±0.43	3.25±0.76	3.45±0.14	4.38±0.01
	0.15–0.18	1.56±0.13	2.18±0.40	2.47±0.00	2.93±0.13	3.43±0.63	4.34±0.01
	0.22–0.25	1.75±0.01	1.56±0.04	2.25±0.23	2.04±0.28	2.07±0.46	2.17±0.87
Soil bulk density (Mg m^{-3})	0.03–0.06	1.39±0.01	1.49±0.01	1.66±0.03	1.70±0.01	1.71±0.01	1.75±0.01
	0.08–0.11	1.31±0.01	1.58±0.03	1.68±0.01	1.70±0.01	1.71±0.02	1.69±0.01
	0.15–0.18	1.46±0.11	1.62±0.02	1.66±0.01	1.67±0.03	1.63±0.01	1.66±0.01
	0.22–0.25	1.60±0.01	1.54±0.02	1.57±0.01	1.60±0.02	1.54±0.01	1.53±0.05
		2004/2005					
Macroporosity (m^3 m^{-3})	0.03–0.06	0.26±0.00	0.09±0.01	0.07±0.01	0.05±0.01	0.05±0.01	0.03±0.01
	0.08–0.11	0.22±0.00	0.07±0.01	0.07±0.01	0.07±0.00	0.05±0.01	0.05±0.00
	0.15–0.18	0.18±0.06	0.10±0.01	0.08±0.01	0.08±0.01	0.07±0.00	0.07±0.01
	0.22–0.25	0.18±0.01	0.11±0.00	0.08±0.01	0.08±0.01	0.08±0.01	0.08±0.01
Microporosity (m^3 m^{-3})	0.03–0.06	0.26±0.00	0.30±0.00	0.30±0.01	0.29±0.01	0.28±0.01	0.29±0.00
	0.08–0.11	0.27±0.00	0.29±0.01	0.30±0.01	0.28±0.01	0.30±0.01	0.29±0.01
	0.15–0.18	0.28±0.02	0.29±0.01	0.30±0.01	0.29±0.01	0.29±0.00	0.29±0.00
	0.22–0.25	0.27±0.00	0.29±0.00	0.31±0.00	0.30±0.01	0.30±0.00	0.31±0.00
Penetration resistance (MPa)	0.03–0.06	0.83±0.13	2.07±0.02	2.71±0.09	3.57±0.32	5.03±0.01	6.75±1.52
	0.08–0.11	1.23±0.44	2.38±0.03	2.15±0.04	2.75±0.23	3.99±0.23	4.62±0.10
	0.15–0.18	1.43±0.40	2.17±0.14	2.23±0.02	3.01±1.10	3.02±0.49	3.06±0.49
	0.22–0.25	1.08±0.19	1.96±0.09	1.71±0.03	2.36±0.14	2.68±0.19	2.48±0.35
Soil bulk density (Mg m^{-3})	0.03–0.06	1.24±0.02	1.58±0.01	1.67±0.01	1.75±0.02	1.79±0.01	1.81±0.01
	0.08–0.11	1.32±0.02	1.66±0.01	1.66±0.01	1.71±0.01	1.74±0.01	1.75±0.01
	0.15–0.18	1.41±0.02	1.62±0.01	1.64±0.01	1.67±0.01	1.68±0.01	1.69±0.01
	0.22–0.25	1.42±0.07	1.57±0.00	1.62±0.01	1.63±0.02	1.59±0.05	1.56±0.02

[1] T_0, 0; T_1, 1; T_2, 2; T_4, 4 and T_6, 6 – are passes of an 11-Mg tractor over the same spot, near to the field capacity water content 0.01 MPa; in 2003/2004, in T_{1*}, the soil was passed over when it was dryer; in the second year, in T_{1*}, the soil was passed over by a 4-Mg tractor to obtain smaller compaction level. [2] Determined at field capacity water content at 0.01 MPa.

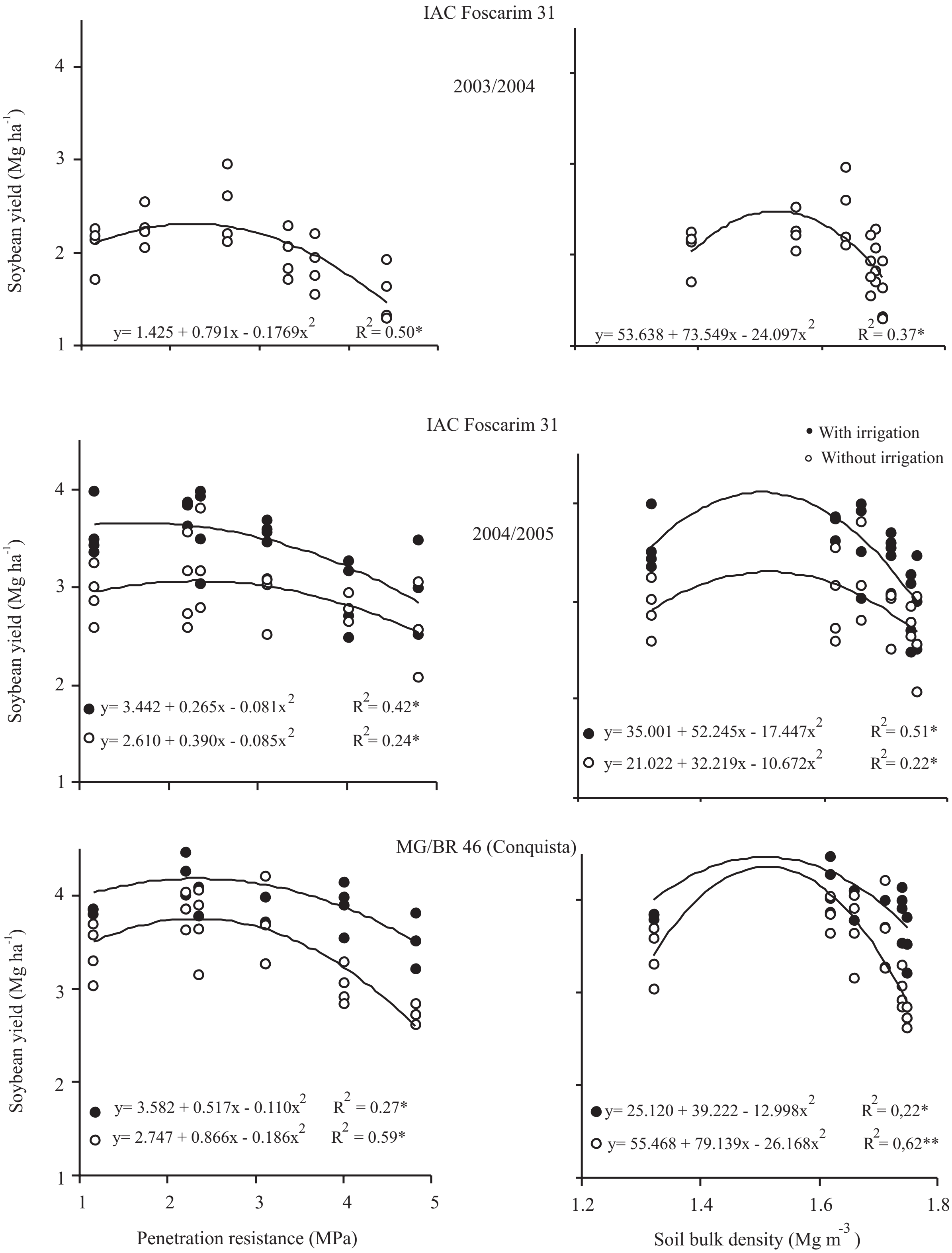

Figure 1. Regression between soil penetration resistance and soil bulk density, at 0.0–0.20 m depth, with yield of soybean cultivar IAC Foscarim 31, in 2003/2004, and cultivars IAC Foscarim 31 and Conquista, in 2004/2005. * and **Significant at 5 and 1%, respectively, by F test.

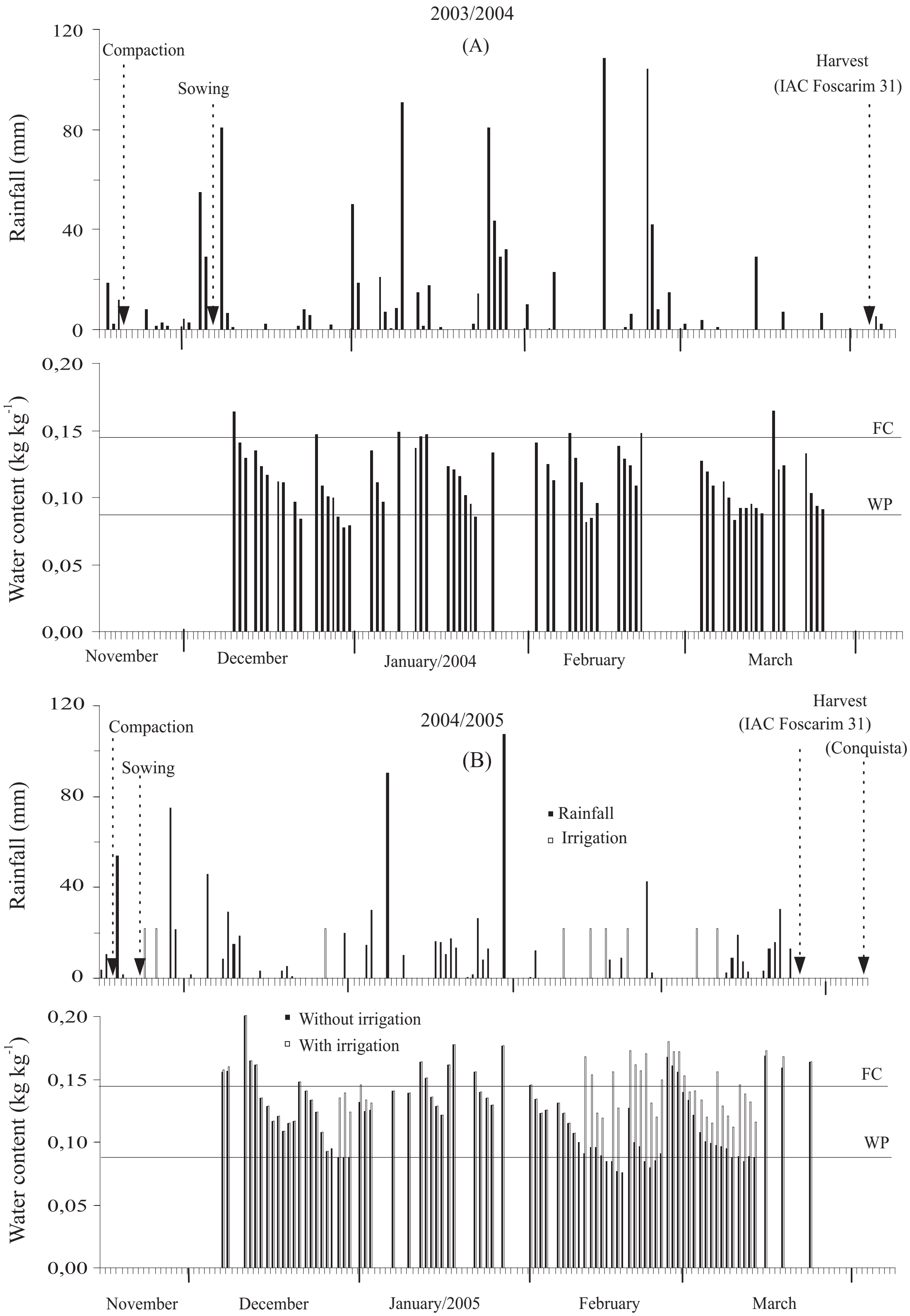

Figure 2. Rainfall and water content, during soybean cultivation in 2003/2004 (A) and 2004/2005 (B) with and without irrigation. FC, field capacity (0.01 MPa); WP, permanent wilting point (1.5 MPa).

In addition, on compacted soils there is a greater production and concentration of abscisic acid (ABA) in roots, which is sent to aerial part and acts as a chemical message to induce reduced plant growth (Mulholland et al., 1996).

An increase on soybean yield was obtained with a small increase in soil compaction (T_0–T_1), verified between PR values from 1.84 to 2.35 MPa and D_b from 1.50 to 1.53 Mg m^{-3}, in both years, and in the second year with and without irrigation (Figure 1 A and B). From those values, yield decreased, which means that these values were limits and could be used in modeling of the least limiting water range. However, these limiting values must be analyzed with caution, when decisions should be taken about physical or biological actions to increase soil loosening. In imperfectly drained tropical soil in Bolivia, it was noticed that soybean yield (cultivar IAC 8) decreased at PR values from 2 to 3 MPa, determined at water content equal to FC, with smaller values in years with more rainfall, as a consequence of reduction in internal drainage and aeration deficiency in compacted soil (Barber, 1994).

In the second year, soybean showed a greater yield, when irrigation was applied at the grain filling stage (February and March), in comparison to soybean without irrigation (Figure 1 B and Figure 2) ($p \leq 0.01$), as was found by Garside et al. (1992). Furthermore, in soybean cultivated without irrigation, the water content remained below the WP (0–0.20 m depth) for many days (Figure 2 B), which caused senescence of few plants at the end of December.

The values of PR and D_b at which soybean yield began to decrease were near, whether with or without irrigation (Figure 1 B), implying that soybean cultivated under irrigation increased yield and did not reduce the limiting values of PR and D_b. However, Barber (1994), Flowers & Lal (1998) and Czyz (2004) emphasized that changes in limiting values of PR and D_b were a function of water content. These observations were related to an experimental area location, which favors good internal drainage, with few aeration deficiencies, in irrigated cultivation. In the present work, it is verified in Figure 2 B: e.g. on December 11th, 2004, when the soil had high water content due to rainfall (0.20 kg kg^{-1}). This value multiplied by D_b of 1.24 (T_0) and 1.58 Mg m^{-3} (T_{1*}) (0.03–0.06 m) (Table 1) results in values of 0.25 and 0.32 m^3 m^{-3}, respectively, of volumetric water content. When subtracted from total porosity 0.52 and 0.39 m^3 m^{-3} (Table 1) results in an aeration porosity of 0.27 (T_0) and 0.07 m^3 m^{-3} (T_{1*}), respectively. Since soybean yield decreased from the 1.51 Mg m^{-3} D_b (smaller than 1.58 Mg m^{-3} – T_{1*}), there is no aeration deficiency, if it is adopted 0.10 m^3 m^{-3} as limiting value to plant growth, suggested by Grable & Siemer (1968). On the following day (December 12th), the water content was reduced to 0.17 kg kg^{-1}, showing a quick drainage of this soil.

Besides, the highest water content after irrigation was 0.18 kg kg^{-1} (Figure 2 B), which indicates that water added to soil through irrigation did not cause aeration deficiency until D_b limiting to soybean yield reached 1.51 Mg m^{-3} (Figure 1 B). Thus, there was no aeration or water deficiency in the irrigated cultivation. However, the values of PR and D_b, from which soybean yield decreases occurred, were similar with and without irrigation. So, yield decreasing occurred due to soil mechanical impediment to root growth, in fact, soil physical quality to plant growth is related to aeration, water content, PR, and temperature function (Letey, 1985). This was confirmed, when a proportional soybean yield decreasing, with and without irrigation, was observed in compacted soil (T_1–T_6) (Figure 1 B).

The PR value has an inverse relation with the water content (Letey, 1985; Lipiec & Hatano, 2003). This way, the PR of irrigated soils was lower than without irrigation. If the PR was smaller in irrigated cultivation and yield decreased at the same compaction level as in cultivation without irrigation, we can suppose that another factor, beyond PR and water content, was responsible for the maintenance of the same D_b limiting level with and without irrigation.

This factor is possibly the aeration deficiency, for short periods after irrigation, which among other factors, reduces the availability and absorption of some nutrients. Besides, aeration porosity of 0.10 m^3 m^{-3} is adopted as critical to root growth (Grable & Siemer, 1968; Engelaar et al., 2000). Some studies show reduced plant growth at greater values of aeration porosity, and that negative effects are intensified in 0.10 m^3 m^{-3} (Silva et al., 2004). In the present study, we can infer that a small amount of aeration deficiency occurred with the occurrence of the same D_b limiting levels with and without irrigation. Aeration deficiency is widely reported in poorly drained soils, in which PR and D_b limiting to yield is smaller, in years with high rainfall amount, compared to dryer years (Barber, 1994; Czyz, 2004). This way, benefits of lower PR in irrigated cultivation were possibly minimized by poor aeration, compared to cultivations without irrigation, related to limiting values. From that, we can infer that the water content out the LLWR, above FC (poor aeration) or below (PR) is damaging to plant growth in compacted soils (Figure 3).

From the physical properties determined for the 288 samples, the models that compose the LLWR were fitted. The LLWR has as superior limiting the lowest value between θ_{AP} and θ_{FC}, and as inferior limiting the highest value between θ_{PR} and θ_{WP} (Figure 3 A and B). In the θ_{PR} limiting, PR values were used from which the soybean yield began to decrease in (0–0.20 m depth) (Figure 1), to establish functional relation of LLWR with soybean yield.

According to Tormena et al. (1999) and Beutler et al. (2005), the upper limiting value of LLWR in tropical soils was θ_{FC} and the lower limit was θ_{PR}. The factor that reduces the range of LLWR, with compaction increasing (D_b), was θ_{PR}, in inferior limiting up to the end of LLWR (LLWR = 0), when it reached the critical bulk density (D_{bc}) to soybean yield, which changed from 1.52 to 1.60 Mg m^{-3}, in both years (Figure 3 A

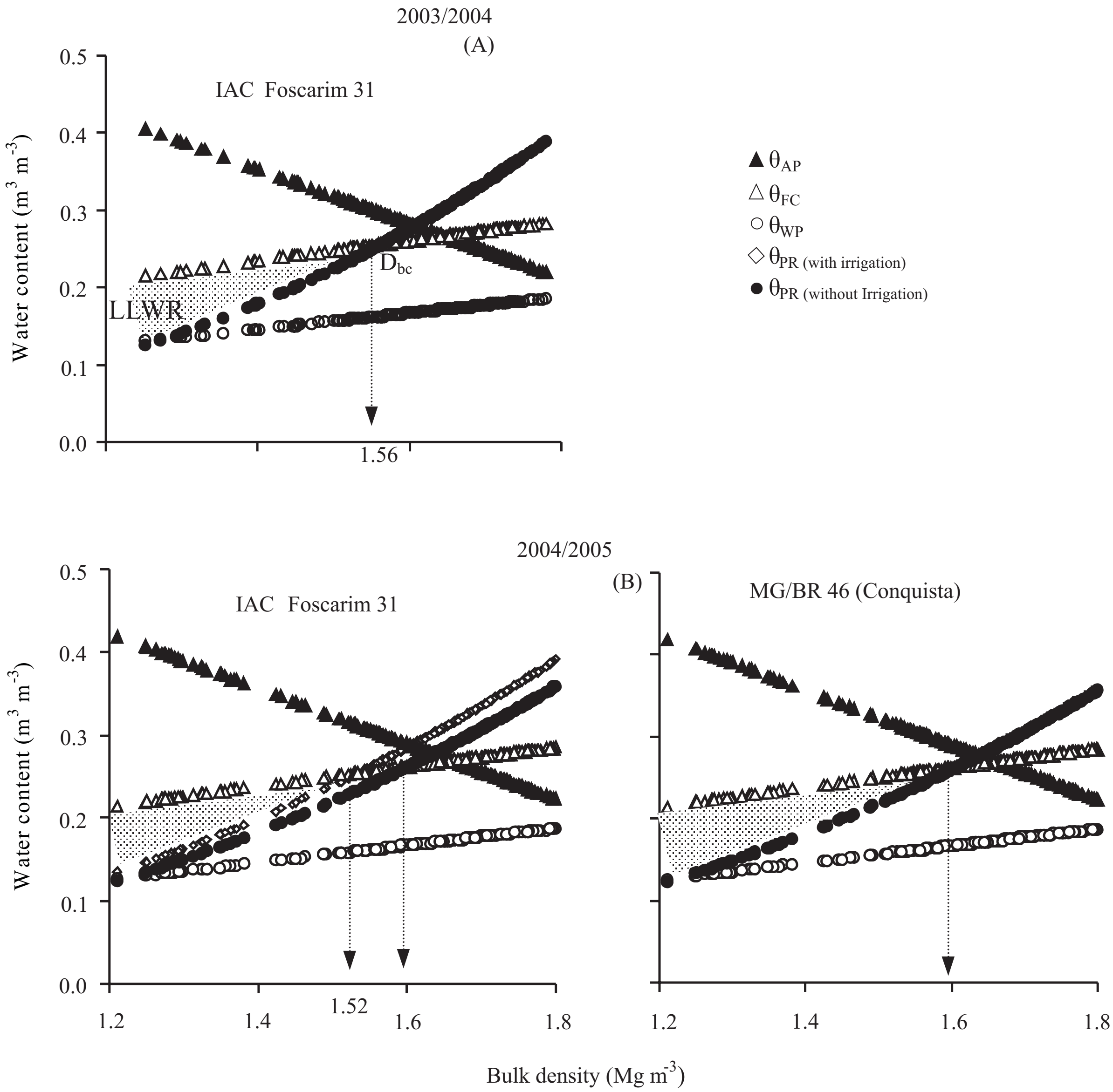

Figure 3. Variation of water content (θ) with D_b, to critical limits of aeration porosity (θ_{AP}), field capacity (θ_{FC}), soil penetration resistance (θ_{PR}) and permanent wilting point (θ_{WP}), in 2003/2004 (A) and 2004/2005 (B), at 0.0–0.20 m depth. LLWR, least limiting water range; D_{bc}, critical soil bulk density.

and B). At values of D_b over 1.65 Mg m^{-3}, beside the θ_{PR}, the θ_{AP} also reached critical levels to root growth (<0.10 m^3 m^{-3}), which together were responsible for soybean yield decreasing (T_1–T_6; Figure 1), as a function of compaction.

Penetration resistance (θ_{PR}) was the physical property that reduced the LLWR extent, from soil without traffic (T_0), because of the direct relation between PR and D_b, and the inverse one with θ. When water content was below θ_{PR} limiting to yield, plants were exposed to adverse conditions to growing by excessive PR, e.g. lower water content than at 0.01 MPa (θ_{FC}), in D_{bc} (LLWR = 0). In addition, above the D_{bc}, the water content greater to θ_{FC} was also damaging to plants, due to poor aeration, according to the model.

The D_{bc} values were slightly greater than D_b obtained in field, from which soybean yield decreases, when yield was fitted as a function of D_b. Nevertheless, decreases in yield were found until D_b reached 1.60 Mg m^{-3} (Figure 1) equivalent to the highest D_{bc} in LLWR (Figure 3), which indicates that the LLWR is a model that can be used to monitor soil physical quality for soybean yield, according to Beutler et al. (2005). These authors, in the same soil, in 2002/2003, verified that the D_b value from which soybean yield began to decrease was 1.48 Mg m^{-3}, similar to D_{bc} in LLWR, even though it had the lowest PR limiting. Collares et al. (2006) verified that black bean yield was smaller, when D_b was equal to D_{bc} at 0.10 to 0.20 m depth.

The use of D_{bc} (LLWR = 0), as indicated in the present work, is a possible form to monitor soil compaction and establish its relations with plants, and its use as soil physical indicator, since Benjamin et al. (2003) found little correlation of LLWR>0 with corn and wheat yield.

Conclusions

1. Machine traffic causes compaction and reduces soybean yield, from soil penetration resistance between 1.64 and 2.35 MPa and bulk density between 1.50 and 1.53 Mg m^{-3}.
2. Soil bulk density from which soybean cultivar yield decrease is lower than the critical bulk density reached at least limiting water range (LLWR = 0).

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