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Physiological and agronomic response of soybean cultivars to soil compaction in the Brazilian Cerrado

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ABSTRACT: Soil compaction negatively impacts soil physical functions, affecting root growth and crop yield. This study aimed to evaluate different soybean cultivars' agronomic and physiological performance as a function of compaction in Rhodic Ferralsol under no-tillage (NT) with a clay loam texture in the Brazilian Cerrado biome. The experiment was implemented in Rio Verde, Goias state, central Brazil. The experimental design was a randomized block with a 3x2 factorial scheme with six replications. The first factor corresponded to three soybean cultivars from different maturity groups (MG) identified as super-early (MG = 6.2); early (MG = 6.8), and medium (MG = 7.9). The second factor was the cultivation in compacted and uncompacted soil. The experiment evaluated the soil physical properties: bulk density, total porosity, water content at matric potential -6 kPa, aeration capacity and water and air holding capacity in 0.0-0.1 and 0.1-0.2 m layers, agronomic and physiological traits (gas exchange). Soil compaction negatively affected the agronomic traits of soybean cultivars, with better performance of the medium cycle cultivar. Net photosynthesis, stomatal conductance, and transpiration rates were reduced up to 50% under compaction and were not influenced by cultivars. Our findings suggest that soil compaction negatively affected the performance of soybean cultivars with lower maturity groups reflecting in lower plant height, shoot and root dry mass, number of pods and grain yield. The choice of soybean cultivars with a longer cycle can be an alternative to minimize the adverse effects of soil compaction.

Key words: *Glycine max*, penetration resistance, photosynthesis, grain yield.

INTRODUCTION

The intensification of production systems in Brazil, with two annual harvests involving mainly soybean and corn crops, requires intensive operations with increasingly larger and heavier machines under limited operating time, resulting in soil compaction (Peixoto et al. 2020). The soil compaction promotes deleterious changes in its functions, compromising the flow, air, and water storage in the soil, as well as crop root elongation rates, reducing access to water and nutrients in the soil profile, which reflects in decreasing rates of plant transpiration and photosynthesis (Colombi and Keller 2019, Keller et al. 2019). Soil compaction exposes plants to multiple stresses and is considered one of the biggest challenges to soil fertility, agronomic productivity, and food security (Colombi and Keller 2019). Concomitantly with the harmful effects of compaction on soil quality, climate forecasts and projections indicate a systematic increase in temperature in different world regions, increasing the frequency and severity of water deficit (Kirtman et al. 2013). In this context, soil compaction can be exacerbated by increasing soil penetration resistance, reducing root growth rates, and delaying access to water and nutrients in deeper layers of the profile, enhancing the effect of water deficit on crops (Keller et al. 2019).

Soil compaction and its impacts on soil quality have been widely studied worldwide (Siczek et al. 2015, Kahlon and Chawla 2017, Moraes et al. 2018, Ferreira et al. 2021). It is well recognized that, once compacted, the soil's return to its initial state is slow, and its recovery can take decades (Schjønning et al. 2015), primarily in the subsurface. However, few works still point out practical solutions to reverse or minimize the problems caused by compaction (Bluett et al. 2019). In this sense, the development of strategies to alleviate the impacts of soil compaction on crop yield plays a significant role in food security (Peixoto et al. 2019).

Studies show stagnation in the productivity of most crops in recent years, motivated by soil compaction (Keller et al. 2019), which has contributed to the limited crop yield increases in Brazil. Grain production in Brazil involves sowing and harvesting at least two crops in a single agricultural year, which intensifies the soil mechanical stress induced by field machinery. For soybean, breeding has prioritized the development of early cultivars with phytosanitary objectives and to anticipate the implantation of another crop in succession due to water restrictions in the fall/winter period, when corn is grown in warmer regions or wheat in colder areas. However, with the shortening of the crop cycle, plants are losing the ability to recover from abiotic stresses, especially in soil with physical restrictions associated with increased soil compaction.

In Brazilian intensive agricultural production systems, the adoption of soybean cultivars with a super-early cycle (approximately 100-days cycle) and with high productive potential has been increasingly adopted by producers. However, under a no-till system (NT), soybean and corn production areas in the Brazilian Cerrado have been subjected to soil compaction. Longer maturity cycle of the soybean cultivar promoted lower soybean sensitivity to soil compaction and associated with the longer time of cultivation and greater capacity of adaptation (Ferreira et al. 2021), which allows for greater production stability. One of the alternatives to minimize the effects of soil compaction on crop yield is cultivars with longer maturity. However, information about the response of cultivars with varying groups of maturity on compacted soil is still scarce or lacking our knowledge.

Thus, the hypothesis raised in this study was that cultivars belonging to longer maturity promote better performance in physiological and agronomic terms in compacted soil compared to early cycles. The objective was to evaluate the influence of soil compaction on physiological parameters, soil physical properties, and yield of soybean cultivars from different maturity groups in a Rhodic Ferralsol under NT in the Cerrado biome in the Central-West region of Brazil.

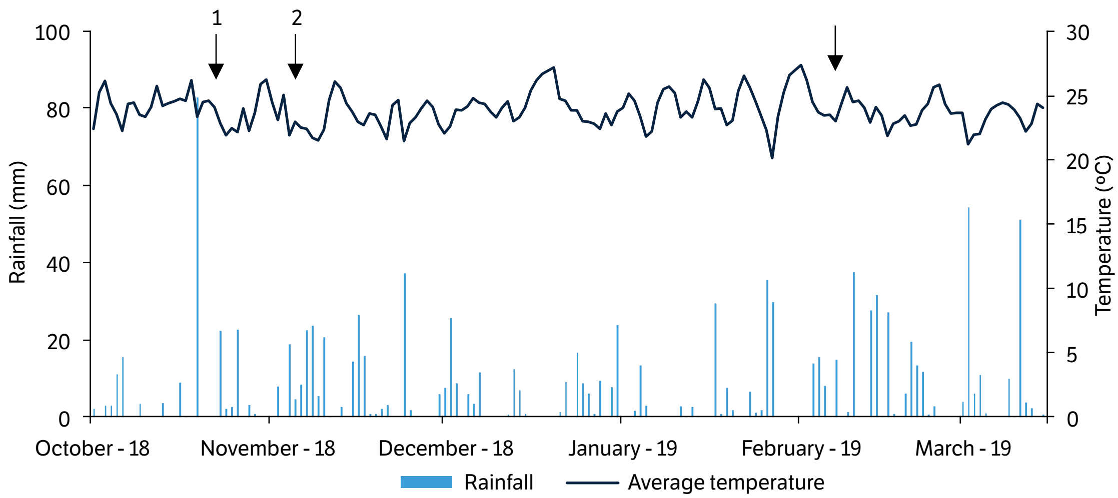
MATERIALS AND METHODS

Area characterization and experimental design

The experiment was carried out in the 2018/19 growing season in Rio Verde, Goias state (17º46'52.03"S; 50º58'13.46"W; and 789 m altitude), Central-West region of Brazil. Before the experimental set up, the soil was sampled in the 0.0-0.2 m layer, showing the following physical and chemical properties: pH ($CaCl_2$) = 5.10; 0 $cmol_c·dm^{-3}$ = exchangeable Al^{3+}; 4.28 $cmol_c·dm^{-3}$ Ca^{+2}; 2.09 $cmol_c·dm^{-3}$ Mg^{+2}; 0.59 $cmol_c·dm^{-3}$ K^{+}; 16.08 $mg·dm^{-3}$ available P (Mehlich-1); 18.35 $g·dm^{-3}$ organic carbon (Walkley-Black); 495, 50 and 455 $g·kg^{-1}$ of sand, silt and clay, respectively. The mineralogical composition of this soil is iron and aluminum oxides. The experimental area is conducted in an NT for over ten years, with soybean cultivated in the spring/summer crop and corn in succession in the second or fall/winter crop. The prevailing climate in the region is Aw (tropical climate with a well-defined dry season) according to the Köppen classification (Alvares et al. 2013). The soil is classified as Rhodic Ferralsol, according to the World Reference Base (WRB 2006), or Latossolo Vermelho distrófico, according to the Brazilian classification system (Santos et al. 2018), with a clay loam texture. The average air temperature and rainfall data during the experimental period are illustrated in Fig. 1.

The experimental design was a randomized block with a 3x2 factorial scheme with six replications. The first factor was composed of three soybean cultivars with indeterminate growth habits, with differences in cycle duration:

- Super-early: M6210 IPRO®, maturity group 6.2, with about 100 days and population 400,000 $plants·ha^{-1}$;
- Early: M7110 IPRO®, maturity group 6.8, with about 110 days and population 400,000 $plants·ha^{-1}$;
- Medium: IPRO® bonus, maturity group 7.9, with cycle longer than 121 days and population 266,667 $plants·ha^{-1}$.



1: soil compaction; 2: soybean sowing; 3: super-early cultivar harvest; 4: early cultivar harvest; 5: medium cycle cultivar harvest; 6: soil sampling.
Source: Instituto Nacional de Meteorologia (INMET), Climatological Station of the Universidade do Rio Verde.

Figure 1. Air temperature and rainfall during the experimental period. Rio Verde, Goiás state, Brazil, 2018/19.

The second factor consisted of the presence or absence of soil compaction. Each plot was formed by eight rows of 5 m in length, spaced at 0.45 m (18 m^2). The useful area in which the evaluations were carried out was constituted by the four central rows, excluding 1 m from each end (5.4 m^2).

The soil was compacted on October 20, one day after an 85-mm rain (Fig. 1). The tractor used was a John Deere 5403, with a total mass of 4,510 kg, diagonal tire, front/rear tire measures 14.9/28" and 23.1/30", inflation pressure of 85 and 60 kPa, respectively. Before sowing soybeans, penetration resistance was evaluated in the field using a Falker® PLG 1020 penetrometer, in which the penetration resistance (PR) data were obtained every 0.01 m up to 0.40 m in depth. Measurements were taken two days after the rain so that the soil water content was close to the field capacity of 0.26 $kg \cdot kg^{-1}$ (measured moisture = 0.24 ± 0.03 $kg \cdot kg^{-1}$).

Soybean cultivars were sown on November 5th using a four-row vacuum seeder, equipped with a front cutting disc for cutting the straw and double discs for depositing seeds and fertilizers. Seeds were treated, and inoculant was applicated according to cultivars recommendations. Fertilization was carried out in the sowing furrow with 170 $kg \cdot ha^{-1}$ mono ammonium phosphate (MAP), and 140 $kg \cdot ha^{-1}$ potassium chloride (KCl) was applied as a top dressing.

Crop evaluations

Agronomic traits analyzed in the soybean crop were initial population 20 days after emergence (DAE) of plants, counting the number of plants. To complement the assessment of plant development by soil compaction, the canopy closure at 38 DAE was evaluated according to the methodology proposed by Heiffig et al. (2006), assigning scores from 0 to 100%, 100% represents the completely closed interrow. The shoot and dry root mass were evaluated by collecting three plants per plot, oven-dried for 72 h at 65 °C. Roots were considered to a depth of 0.25 m using a shovel to contain the material, sieved, and washed before being taken to the oven.

To check the effect of soil compaction on soybean cultivars' gas exchange, net photosynthesis, internal CO2 concentration, transpiration rate, and stomatal conductance in the third fully expanded trifoliate between 9 and 11 a.m. at 38 DAE. In these evaluations, a portable infrared gas analyzer IRGA, model CI-340-CID (Biosciences Inc., Camas, WA, United States of America). In addition to these parameters, the efficiency of water use was evaluated through the ratio of net photosynthesis to transpiration, according to Xu and Hsiao (2004).

Upon soybean harvest, in three random plants per plot, plant height and first pod height (measurement of the stem until the insertion of the last trifoliate and the first pod, respectively), the total number of pods per plant (counting the number of pods on the primary and secondary stems), 1,000-grain-mass (measuring and weighing a thousand grains with moisture corrected to 13%), and grain yield were determinate by weighting the grains of the harvested plants with subsequent water converted to 13%.

Soil sampling and physical analysis

Soil samples were taken in March 2019 in layers from 0.0 to 0.1 and 0.1 to 0.2 m in depth. Small trenches (0.25 × 0.25 m) were opened, and two undisturbed samples (one in the row and one in the interrow of the soybean crop) were collected using stainless steel rings 0.05 m in diameter and 0.05 m in height (volume of 10-4 m3) in each layer of treatments, totaling 144 samples. Soil samples were wrapped in aluminum foil and carefully transported to the laboratory, kept at 4 °C to avoid interference from biological activity.

Afterwards, samples were placed in trays and saturated with water by capillary action for 48 h. Once saturated, samples were weighed and subjected to a potential of -6 kPa, using a tension table similar to that described by Ball and Hunter (1988). Upon reaching equilibrium, indicated by the absence of water drainage on the tension table, samples were again weighed and oven-dried at ± 105 °C for 24 h. Bulk density (BD) was calculated by the ratio of dry soil mass to total sample volume, as described by Grossman and Reinsch (2002). Total porosity (TP) was determined by Eq. 1.

$$TP = 1- (BD/Dp) \quad (1)$$

in which: TP = total porosity ($m^3{\cdot}m^{-3}$); BD = soil bulk density ($Mg{\cdot}m^{-3}$); Dp = particle density, obtained according to the methodology described in Brazilian Agricultural Research Company (Embrapa 2017) with the mean value of 2.60 ± 0.03 $Mg{\cdot}m^{-3}$.

Water content at matric potential -6 kPa (WC) was obtained indirectly from the soil water content retained in the matric potential of -6 kPa, according to Severiano et al. (2011). Soil aeration capacity (SAC) or drained pore volume after the equilibrium of the sample soil at the potential of -6 kPa was determined by the difference between the total porosity and water content at matric potential -6 kPa.

The other physical indices were obtained according to Reynolds et al. (2002):

- The soil water holding capacity indicator (WHC, dimensionless) was calculated by the ratio of the water content at the potential of -6 kPa to total soil porosity;
- The soil air holding capacity indicator (AHC, dimensionless) was calculated by the ratio of soil aeration capacity at the potential of -6 kPa to total soil porosity.

When taking undisturbed soil samples, soil PR was measured using a Falker® PLG 1020 penetrometer. The measurements were taken two days after sufficient rain to saturate the sampled profile so that the soil water content was close to the field capacity and the water content was 0.24 ± 0.02 $kg{\cdot}kg^{-1}$. Four PR sampling points were performed in each repetition.

Statistical analysis

Analysis of variance was run for all soil and plant parameters using the SAS software. When the significance between the factors interaction or between the levels of each factor was detected in the F test ($p < 0.05$), the LSD-Fisher Test was applied ($p < 0.05$). To check the dependence of the analyzed variables, Pearson correlation analysis was performed between the soil and plant variables through the PROC CORR routine.

RESULTS AND DISCUSSION

Soil physical condition indicators

Soil penetration resistance measured before soybean sowing was significantly higher in compacted soil throughout the profile evaluated, with PR values up to three times greater than in uncompacted soil (Fig. 2). In the compacted soil profile, PR values were above the critical limit of 2.5 MPa (Girardello et al. 2014), reducing root growth. The results of Girardello et al. (2014) indicated that PR > 2.5 MPa negatively affects crop growth, development, and productivity, with more substantial effects under water-limited conditions (Colombi and Keller 2019).

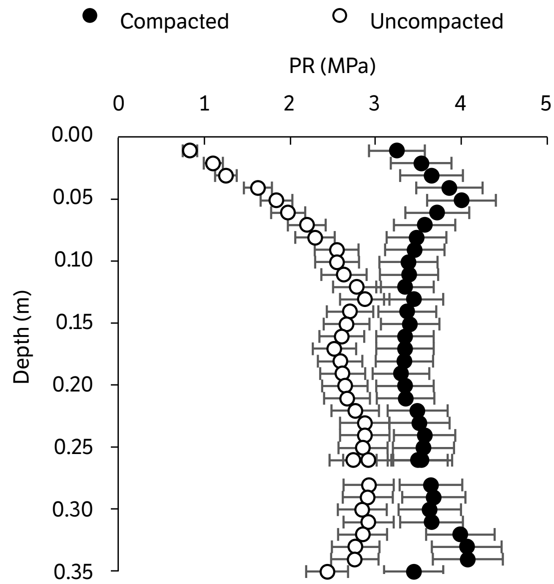


Figure 2. Before the experiment implementation, soil penetration resistance (PR) at compacted and uncompacted treatments. Bars refer to the confidence interval of the mean, and the overlapping of the confidence intervals indicates the absence of differences between means ($p > 0.05$). Rio Verde, Goiás state, Brazil, 2018/19.

BD values of the compacted treatment were significantly higher than that of the uncompacted soil for both evaluated layers (Table 1), causing reduction in soil porosity, promoting an unfavorable physical environment for crop root growth (Siczek et al. 2015). Observing the interaction effect of soybean cultivars and soil condition, in the 0.0-0.1 m layer for both soil conditions, the lowest BD was found for the medium cycle soybean cultivar, differing by up to 0.14 $Mg{\cdot}m^{-3}$ in the uncompacted soil (Table 1). The results of soil porosity follow the same behavior, with the highest values in the soil for the medium cycle cultivar. These results are related to the greater mass of soybean roots due to the medium cycle cultivar's larger maturity group and rusticity than the early cultivar (Tables 2 and 3).

In the 0.1-0.2 m layer, for the interaction effect, in the compacted treatment, there were no differences in bulk density and soil porosity among the soybean cultivars associated with the possible effects of soybean cultivars on the soil. On the other hand, lower values of BD and TP were also found for the medium cycle cultivar in uncompacted soil, probably related to the growth of the root system that may have reached this layer, as shown in Fig. 3 and Table 3. These results suggest that plants with longer cycles improve the soil's physical environment, especially in NT soils, in which the compacted layers are located at 0.07 to 0.20 m depth (Nunes et al. 2015). It is essential to highlight that the root systems of crops in production systems are demonstrably considered crucial strategies in the physical improvement of the soil (Calonego et al. 2017), and the longer the permanence time of these crops in the field, the greater the root growth and effectiveness in soil physical improvement.

In the 0.0-0.1-m layer, soil compaction did not affect water contents at matric potential -6 kPa neither the soil water and air holding capacity (WHC and AHC, respectively), only with significant effect of the isolated factor cultivars. On the other hand, aeration capacity was lower in the compacted soil (Table 1). Similar results were reported by Severiano et al. (2011) in Ferralsol in the same region of this study, which indicated a decline in aeration porosity with an increase in soil compaction, contributing to the increase in BD.

Figure 3. Soybean cultivars in (left) compacted and (right) uncompacted soil within the same cultivar. Rio Verde, Goiás state, Brazil, 2018/19.

For the 0.1-0.2-m layer, only the water content at matric potential -6 kPa and soil PR was not affected by soil compaction (Table 1). In compacted soil, the soil water holding capacity exceeded the limit of 0.66 proposed by Reynolds et al. (2002), indicating that the soil may be subjected to restrictions of aeration to microbial and root respiration under more extended wet periods in this region (Tubeileh et al. 2003), common in the Central-West region of Brazil in summer. Thus, it would be necessary to dry the soil to moisture values below the water content at matric potential -6 kPa for an adequate oxygen supply to the root zone. These results agree with Anghinoni et al. (2019), who also reported restrictive values of water holding capacity in a Ferralsol under Cerrado conditions.

In the 0.0-0.1-m layer, with the early cycle cultivar, lower water content values at matric potential -6 kPa, more deficient aeration and air holding capacity, and higher water holding capacity were verified (Table 1). Higher aeration capacity and air storage values are justified by this cultivar's lower root production and performance in compacted soil (Table 3). In the 0.1-0.2-m layer, regardless of soil compaction, the medium cycle soybean cultivar, soil water, and air holding capacity values were found (Table 1), closer to those proposed by Reynolds et al. (2009). The physical improvement provided by plant roots resulted in more significant dry mass accumulation, even in a compacted soil condition, which contributes to an increase in grain yield (Table 3). The more substantial root and shoot dry mass, the higher total number of pods, and yield shows the stability of production promoted by this cultivar even under compacted soil conditions.

Table 1. Soil physical properties (BD; WC at matric potential -6 kPa; SAC; WHC; AHC; TP; and PR) in layers from 0.0 to 0.1 and 0.1 to 0.2 m in SE, E and M cycle soybean cultivars in C and NC soil. Rio Verde, Goiás State, Brazil, 2018/19.

	Soybean cultivars	0.0 to 0.1 m			0.1 to 0.2 m		
		C	NC	Mean	C	NC	Mean
BD (Mg·m^{-3})	SE	1.46 Aab	1.37 Bab	1.42 ab	1.58 Aa	1.55 Aa	1.56 a
	E	1.52 Aa	1.42 Ba	1.47 a	1.57 Aa	1.55 Aa	1.56 a
	M	1.42 Ab	1.28 Bb	1.35 b	1.55 Aa	1.48 Bb	1.52 b
	Mean	1.47 A	1.36 B		1.57 A	1.52 B	
WC (m^3·m^{-3})	SE	0.42 Aa	0.44 Aa	0.43 a	0.37 Aa	0.37 Ab	0.37 b
	E	0.36 Ab	0.37 Ab	0.36 b	0.37 Aa	0.38 Aa	0.38 a
	M	0.40 Aa	0.42 Aa	0.41 a	0.34 Ab	0.34 Ac	0.34 c
	Mean	0.39 A	0.41 A		0.36 A	0.36 A	
SAC (m^3·m^{-3})	SE	0.11 Aab	0.12 Aab	0.12 a	0.10 Ab	0.11 Ab	0.10 b
	E	0.08 Ab	0.10 Ab	0.09 b	0.08 Ab	0.09 Ac	0.08 c
	M	0.12 Aa	0.13 Aa	0.12 a	0.12 Ba	0.15 Aa	0.13 a
	Mean	0.10 B	0.12 A		0.10 B	0.12 A	
WHC	SE	0.79 Aa	0.80 Aa	0.79 ab	0.79 Aa	0.77 Ab	0.78 b
	E	0.81 Aa	0.79 Aa	0.80 a	0.82 Aa	0.80 Aa	0.81 a
	M	0.78 Aa	0.76 Aa	0.77 b	0.74 Ab	0.70 Bc	0.72 c
	Mean	0.78 A	0.80 A		0.78 A	0.76 B	
AHC	SE	0.20 Aa	0.21 Ab	0.21 ab	0.21 Ab	0.23 Ab	0.22 b
	E	0.19 Aa	0.21 Ab	0.20 b	0.18 Ab	0.19 Aa	0.19 c
	M	0.22 Aa	0.24 Aa	0.23 a	0.26 Ba	0.30 Ac	0.28 a
	Mean	0.20 A	0.22 A		0.22 B	0.24 A	
TP (m^3·m^{-3})	SE	0.44 Aab	0.47 Ab	0.45 ab	0.39 Aa	0.41 Ab	0.40 b
	E	0.41 Bb	0.46 Ab	0.43 b	0.40 Aa	0.40 Ab	0.40 b
	M	0.45 Ba	0.51 Aa	0.48 a	0.40 Ba	0.43 Aa	0.42 a
	Mean	0.43 B	0.48 A		0.39 B	0.41 A	
PR (MPa)	SE	3.12 Aa	2.30 Bb	2.71 a	2.88 Aa	2.91 Aa	2.90 a
	E	2.99 Aa	2.59 Ba	2.79 a	2.91 Aa	2.89 Aa	2.90 a
	M	3.07 Aa	2.29 Bb	2.68 a	2.77 Aa	2.83 Aa	2.80 a
	Mean	3.06 A	2.39 B		2.85 A	2.88 A	

*Mean values followed by different uppercase letters in the same row and lowercase letters in the same column are significantly different by the LSD-Fisher test ($p < 0.05$); BD: bulk density; WC: water content; SAC: soil aeration capacity; WHC: water holding capacity; AHC: air holding capacity; TP: total porosity; PR: penetration resistance; SE: super-early; E: early; M: medium; C: compacted soil; NC: uncompacted soil.

In compacted soil, the penetration resistance of the soil at the 0.0-0.1-m layer was 28% higher than in the uncompacted soil (Table 1), whose values are above the critical limit of 2.5 MPa, impacting plant development as highlighted by Grzesiak et al. (2013). Thus, the plant response to compaction differences is justified by the increase in resistance to root penetration in compacted soil, limiting root growth in the soil profile and reducing carbon assimilation rate (Tubeileh et al. 2003). Under these conditions, the higher concentration of roots in the soil surface layer can lead to faster depletion of available water, generating increases in resistance that confine the roots to this layer. Consequently, the growth of roots in deeper layers is reduced and harms plant growth (Colombi et al. 2018).

In the 0.0-0.1-m layer in the treatment with compaction, a difference was observed between cultivars for PR, with lower values with the super-early and medium cycle soybean cultivar (Table 1). In the 0.1-0.2-m layer, there were no differences in PR (Table 1) between treatments. This is due to before soybean sowing. The PR differences between uncompacted and compacted soils were not as pronounced as in the 0.0-0.1-m layer (Fig. 2). Also, there is temporally more significant moisture at a depth of 0.1 to 0.2 m, which reduces PR (Colombi and Keller 2019).

Physiological characteristics

The adverse effects of soil compaction can be seen in variables related to gas exchange in soybean leaves. However, no differences were observed among soybean cultivars (Table 2). Independently of cultivars, considerable reductions were observed in net photosynthesis, internal CO_2 concentration, transpiration, and stomatal conductance (Table 2). Net photosynthesis of soybean plants decreased by 48% in compacted soil. Our results corroborate Grzesiak et al. (2013), who reported a significant reduction in photosynthesis in corn and triticale crops grown in compacted soil. The decrease in photosynthetic rate results from the drop in stomatal conductance in 50% of plants that grew in compacted soil. This is attributed to a chemical message, mainly abscisic acid (ABA), produced in stressed roots and carried to the shoot through the xylem (Tubeileh et al. 2003).

Table 2. Physiological characteristics (PN; IC; TRANS; C; and WUE) of SE, E, and M cycle soybean cultivars in C and NC soil. Rio Verde, Goiás state, Brazil, 2018/19.

Soybean cultivars	C	NC	Mean
	PN (µmol CO_2 $m^{-2} \cdot s^{-1}$)		
SE	7.63 Ba	17.45 Aa	12.54 a
E	9.92 Ba	16.18 Aa	13.05 a
M	9.95 Ba	19.30 Aa	14.62 a
Mean	9.17 B	17.64 A	
	CO_2 IC (mmol $m^{-2} \cdot s^{-1}$)		
SE	205.67 Ba	276.00 Aa	240.83 a
E	167.17 Ba	244.33 Ab	205.75 a
M	208.67 Ba	272.00 Aa	240.33 a
Mean	193.83 B	264.11 A	
	TRANS (mmol $m^{-2} \cdot s^{-1}$)		
SE	1.98 Ba	4.45 Aa	3.22 a
E	2.32 Ba	3.83 Aa	3.07 a
M	2.52 Ba	4.50 Aa	3.51 a
Mean	2.27 B	4.26 A	
	C (mmol $m^{-2} \cdot s^{-1}$)		
SE	67.67 Ba	241.67 Aa	154.67 a
E	69.83 Aa	185.50 Aa	127.67 a
M	100.67 Ba	258.83 Aa	179.75 a
Mean	103.39 B	204.67 A	
	WUE		
SE	3.86 Aa	3.96 Aa	3.91 a
E	4.45 Aa	4.36 Aa	4.41 a
M	3.90 Aa	4.42 Aa	4.16 a
Mean	4.07 A	4.29 A	

*Mean values followed by different uppercase letters in the same row and lowercase letters in the same column are significantly different by the LSD-Fisher test ($p < 0.05$); PN: net photosynthesis; IC: internal concentration; TRANS: transpiration; C: stomatal conductance; WUE: water use efficiency; SE: super-early; E: early; M: medium; C: compacted soil; NC: uncompacted soil.

Reductions in photosynthetic rates of soybean cultivars in compacted soil are related to lower stomatal conductance, water losses by transpiration, and lower internal CO2 concentration (Alameda and Villar 2012), which drastically affect the photosynthesis rates of cultivars in a compacted soil environment. Soil compaction affects plant root morphologically and physiologically; these modifications harm shoot development, reducing the photosynthetic area in the plant (Ramos et al. 2010). Effects of soil compaction on the photosynthetic metabolism of wheat were found by Masle and Passioura (1987), with expressive decreases in transpiration in wheat plants with an increase in soil penetration resistance. Photosynthetic products accumulate in leaves and return to the photosynthetic mechanism, which leads to a drop in plant net photosynthesis (Grzesiak et al. 2013). Nevertheless, physiological parameters measured were not dependent on the soybean cultivars (Table 2), suggesting that soil compaction by degrading soil physical quality strongly influenced the physiological responses of plants, as highlighted by Carminati and Javaux (2020).

Water use efficiency was the only physiological variable not affected by soil compaction (Table 2). The relationship between the amount of water absorbed and the accumulated dry mass was similar in compacted and uncompacted soils. Furthermore, it is known that plants with C3 photosynthetic metabolism, such as soybean, have a lower capacity to increase the efficiency of water use under conditions of abiotic stress than C4 plants (Way et al. 2014).

Phytotechnical characteristics

Soil compaction reduced the height and dry mass of shoots and roots of soybean plants when observed the isolated effect of soil condition (Table 3), agreeing with Tubeileh et al. (2003). High levels of PR reduce plant growth (Bengough et al. 2011), reducing the root absorption capacity of water and nutrients (Singh et al. 2019). Consequently, growth is limited due to the low photosynthetic rate of the plant and stomatal conductance (Masle and Passioura 1987). The importance of root growth is that the phytohormones like cytokinins are synthesized in the root tips and transported to the leaves via the xylem, causing less development of both the lateral and apical meristems.

Table 3. Agronomic traits (POPi and POPf; PH; SDM and RDM; CC; FPH; TNP; TGM; and GY) of soybean cultivars in C and NC soil. Rio Verde, Goiás state, Brazil, 2018/19.

Soybean cultivars	C	NC	Mean	C	NC	Mean
	POP$_i$ (thousand plants·ha^{-1})			POP$_f$ (thousand plants·ha^{-1})		
SE	316.6 Aa	331.5 Aa	324.0 a	315.8 Aa	327.8 Aa	321.8 aA
E	261.1 Bb	300.0 Ab	280.4 b	251.8 Bb	301.8 Aa	276.9 b
M	198.2 Bc	242.6 Ac	220.4 c	224.0 Ab	234.2 Ab	229.1 c
Mean	258.6 B	291.3 A		263.8 B	288.0 A	
Soybean cultivars		**PH (cm)**			**SDM (g)**	
SE	67.6 Bb	71.1 Ac	69.4 c	13.2 Ba	21.8 Ab	17.5 b
E	70.5 Bb	75.1 Ab	72.8 b	12.1 Ba	32.3 Aa	22.2 ab
M	86.1 Ba	93.9 Aa	89.9 a	16.7 Ba	30.8 Aa	23.8 a
Mean	74.7 B	79.9 A		14.0 B	28.3 A	
Soybean cultivars		**RDM (g)**			**CC (%)**	
SE	1.9 Ab	2.6 Ab	2.3 b	89.7 Ba	94.7 Aa	92.2 a
E	1.4 Bb	3.1 Aab	2.2 b	78.0 Ab	81.7 Ab	79.8 b
M	2.5 Ba	4.1 Aa	3.3 a	76.2 Bb	82.2 Ab	79.2 b
Mean	1.9 B	3.3 A		81.3 B	86.2 A	
Soybean cultivars		**FPH (cm)**			**TNP**	
SE	13.95 Ab	13.8 Ab	13.9 b	34.4 Ab	43.0 Ab	38.7 b
E	12.1 Ac	12.5 Ac	12.3 c	34.7 Bb	52.0 Ab	43.3 b
M	17.9 Aa	17.5 Aa	17.7 a	64.2 Aa	69.0 Aa	66.6 a
Mean	14.65 A	14.60 A		44.42 B	54.7 A	
Soybean cultivars		**TGM (g)**			**GY (kg·ha^{-1})**	
SE	165.0 Ab	170.4 Ab	167.7 b	3,593.9 Ab	3,835.1 Ab	3,714.5 b
E	131.6 Ac	137.3 Ac	134.5 c	3,427.2 Bb	3,927.2 Ab	3,690.8 b
M	187.0 Aa	186.8 Aa	186.9 a	4,406.5 Aa	4,701.8 Aa	4,554.1 a
Mean	161.2 A	164.8 A		3,818.25 B	4,154.7 A	

*Mean values followed by different uppercase letters in the same row and lowercase letters in the same column are significantly different by the LSD-Fisher test ($p < 0.05$); POP$_i$: initial plant population; POP$_f$: final plant population; PH: plant height; SDM: shoot dry mass; RDM: root dry mass; CC: canopy closure; FPH: first pod height; TNP: total number of pods; TGM: 1,000-grain-mass; GY: grain yield; C: compacted soil; NC: uncompacted soil.

The initial and final plant populations were also affected by compaction (Table 3), which can be attributed to the effects of soil compaction in promoting less uniformity in seed distribution during sowing, either in depth or between seeds in the seed furrow. Thus, compaction resulted in germination and emergence failures, affecting the establishment of the crop, as observed by Logsdon and Karlen (2004) and Altikat and Celik (2011). The super-early cycle cultivar showed the lowest stand losses in the compacted treatment. Regardless of compaction, the medium cycle cultivar showed better growth and development patterns, such as higher plant height, first pod height, shoot and root dry mass, compared to the other cultivars (Table 3). These differences are due to the intrinsic genetic characteristics of each cultivar.

About the interaction effect of soil condition and soybean cultivars, the soil compaction negatively influenced canopy closure of super-early and medium cycle cultivars (Table 3). Effects of compaction in canopy closure in these cultivars are associated with limited plant growth due to the reduction in the volume of soil explored by roots (Shah et al. 2017). Less canopy closure causes more excellent weed infestation, increased soil temperature, and soil water evaporation, negatively affecting crop yield (Raimondi et al. 2014). Regardless of the compaction, the super-early cycle cultivar showed more significant interrow closure, which can be explained by the short cycle of the cultivar.

Although compaction did not affect the 1,000-grain mass, the grain yield of the early-cycle cultivar was reduced (Table 3) by 12% in compacted soil compared to uncompacted. There were no differences in soybean yield between the other cultivars (Table 3). These results suggest soybean cultivars with a longer cycle (larger maturity group) in compacted soils, which allows for greater production stability, as highlighted by Ferreira et al. (2021).

About the soil condition effect, soil compaction reduced grain yield by 8%, corroborating other studies evaluating soybean yield performance in compacted soils (Beutler et al. 2006, Ferreira et al. 2021). These effects may be associated with plant growth and development (smaller plant population, height, and number of pods) as consequences of soil and physical degradation (Siczek et al. 2015).

When evaluating the yield of cultivars, higher values were observed in the medium cycle cultivar, regardless of soil compaction (Table 3) due to higher plant height, number of pods, and 1,000-grain mass. It is worth noticing that the medium cycle cultivar produced 812.58 and 979.29 $kg{\cdot}ha^{-1}$ more than the super-early and early cycle cultivars, respectively. Figure 3 illustrates the effects of soil compaction on the studied cultivars. During plant development, both the volume and even rainfall distribution were verified (Fig. 1), not registering prolonged periods of water deficit that could further impair the development of soybean cultivars in compacted soil (Keller et al. 2019).

Relationship between soil properties and soybean crop

The visual evaluation of the soybean crop made it possible to notice the influence of compaction on the growth and yield components of the soybean crop. In general, there was a significant correlation between the physical properties of the soil in the 0.0-0.1 and 0.1-0.2-m layer with the agronomic and physiological traits of soybean (Table 4). The most significant effects of soil compaction were observed on plant height and first pod height, root dry mass, the total number of pods, 1,000-grain mass, and grain yield. Beutler et al. (2006) highlight that the soybean crop grown in compacted soils has root morphological changes due to physical limitation, characterized by having less continuity, number, and diameter of pores. Soil compaction did not only influence the aerial part of the soybean plant: the dry mass of the roots was also negatively affected by BD and PR and positively by soil porosity in the 0.0 to 0.1-m layer, which did not occur in the 0.1 to 0.2-m layer. Similar effects of root growth with PR were reported by Moraes et al. (2018). Under compacted soil conditions, the first effect on the plant is on the root system, which in turn induces morphophysiological changes throughout the plant (Tardieu et al. 2010).

The soybean crop yield responses are consequences of several factors, which significantly correlated with almost all soil physical properties in the layers from 0 to 0.1 and 0.1 to 0.2 m (Table 4). The decrease in root growth, imposed by higher BD and lesser soil aeration, reduces plant access to water and nutrients, leading to plant metabolism and growth (Bengough et al. 2006, Benjamin and Karlen 2014, Colombi and Keller 2019, Yadav et al. 2019). The negative effects of soil compaction could be verified in the gas exchange ratios of soybean cultivars. The greater soil PR under compacted soil in the topsoil (0.0 to 0.1 m) significantly decreased metabolic processes essential to crop growth, such as net photosynthesis (r = -0.80), internal CO_2 concentration (r = -0.61), transpiration rates (r = -0.75), and stomatal conductance (r = -0.78), all with strong negative correlation. It is known that the greater the soil PR, the greater the difficulty for plants to absorb water and nutrients. Gas exchanges are directly affected, negatively affecting crop productivity (Colombi and Keller 2019).

Table 4. Pearson linear correlation of soil physical properties in the 0.0 to 0.1 and 0.1 to 0.2 m layers versus agronomic traits (POP_i and POP_f; PH; SDM and RDM; CC; FPH; TNP; TGM; and GY) and physiological characteristics (PN; IC; TRANS; C; and WUE). Rio Verde, Goiás State, Brazil, 2018/19*.

		Agronomic traits										Physiological characteristics				
(m)		POP_i	POP_f	PH	CC	RDM	SDM	FPH	TNP	TGM	GY	PN	CO_2CI	TRANS	C	WUE
0.0-0.1	Water content at -6 kPa	0.21	0.14	0.07	**0.54**	0.22	0.07	0.28	0.05	**0.48**	0.07	0.23	**0.33**	0.21	0.32	0.01
	Soil aeration capacity	-0.05	0.02	**0.39**	0.27	0.21	0.21	**0.45**	0.27	**0.59**	**0.50**	0.12	0.23	0.09	0.19	-0.06
	Bulk density	0.06	0.21	**-0.54**	-0.21	**-0.46**	**-0.49**	**-0.43**	**-0.41**	**-0.45**	**-0.43**	**-0.45**	**-0.35**	-0.29	**-0.44**	-0.24
	Total porosity	-0.06	-0.21	**0.54**	0.21	**0.46**	**0.49**	**0.43**	**0.41**	**0.45**	**0.43**	**0.45**	**0.35**	0.29	**0.44**	0.24
	Water holding capacity	0.11	0.05	**-0.37**	-0.08	-0.14	-0.22	**-0.36**	-0.26	**-0.44**	**-0.49**	-0.05	-0.12	-0.02	-0.09	0.08
	Air holding capacity	-0.11	-0.05	**0.37**	0.04	0.15	0.23	**0.36**	0.26	**0.46**	**0.51**	0.04	0.12	0.01	0.08	-0.07
	Penetration resistance	-0.21	0.29	-0.31	**-0.34**	**-0.48**	**-0.63**	-0.08	-0.28	-0.19	-0.31	**-0.80**	**-0.61**	**-0.75**	**-0.78**	-0.11
0.1-0.2	Water content at -6 kPa	**0.43**	-0.01	**-0.66**	0.31	**-0.39**	-0.13	**-0.67**	**-0.49**	**-0.74**	**-0.53**	-0.14	-0.11	-0.05	-0.18	-0.17
	Soil aeration capacity	-0.24	-0.15	**0.64**	-0.11	**0.56**	0.29	**0.52**	**0.56**	**0.71**	**0.50**	**0.38**	**0.33**	0.26	**0.37**	0.18
	Bulk density	0.13	**0.35**	**-0.56**	0.10	**-0.45**	**-0.41**	-0.29	**-0.50**	**-0.38**	**-0.38**	**-0.60**	**-0.43**	**-0.50**	**0.57**	-0.18
	Total porosity	-0.13	**-0.35**	**0.56**	-0.10	**0.45**	**0.41**	0.29	**0.50**	**0.38**	**0.38**	**0.60**	**0.43**	**0.50**	**-0.57**	0.18
	Water holding capacity	0.28	0.11	**-0.67**	0.15	**-0.54**	-0.27	**-0.57**	**-0.56**	**-0.75**	**-0.54**	**-0.34**	**-0.31**	-0.23	**-0.36**	-0.17
	Air holding capacity	-0.28	-0.11	**0.67**	-0.15	**0.54**	0.27	**0.57**	**0.56**	**0.75**	**0.54**	**0.34**	**0.31**	0.23	**0.36**	0.17
	Penetration resistance	**0.66**	-0.14	**-0.68**	**0.47**	-0.23	-0.02	**-0.76**	**-0.54**	**-0.68**	**-0.56**	0.11	0.01	0.11	0.07	0.07

*In bold, significant Pearson correlation coefficients ($p < 0.05$); POPi: initial plant population; POPf: final plant population; PH: plant height; SDM: shoot dry mass; RDM: root dry mass; CC: canopy closure; FPH: first pod height; TNP: total number of pods; TGM: 1,000-grain-mass; GY: grain yield; PN: net photosynthesis; IC: internal concentration; TRANS: transpiration; C: stomatal conductance; WUE: water use efficiency; C: compacted soil; NC: uncompacted soil.

Our results confirmed that soil compaction caused by machine traffic reduces soil physical quality and negatively impacts the physiological responses of soybeans. Thus, plants are more susceptible to abiotic stresses, whether due to excess or lack of water, causing damage to the agricultural production system. The choice of soybean cultivars of a larger maturity group, i.e., with a longer cycle, can be an alternative to minimize the adverse effects of soil compaction. Despite this, it is necessary to further improve the tolerance of plants to physical stresses in the development of new cultivars (Schneider and Lynch 2020), prioritizing the growth of the root system in a compacted soil environment. Thus, there are the mitigation of crop yield reductions and the recovery of the soil structure (Keller et al. 2019). As plant roots are considered one of the main foundations of soil structure, the increase in root growth can provide significant productive stability for crops and recover soil quality.

Despite all these findings, the choice of soybean cultivar should not be used only as an isolated strategy to mitigate soil compaction problems. The combination with soil management practices that prioritize better conditions for root growth and crop practices such as crop rotation has already proven to effectively mitigate soil compaction problems in tropical regions under a no-till system (Anghinoni et al. 2019, Anghinoni et al. 2021). And finally, it should be considered that actions to prevent soil compaction are still the most effective practices to minimize damage to the agricultural production system.

CONCLUSION

The maturity stage of plants was affected by soil compaction. The medium cycle cultivar contributes to improving the soil physical condition and reflects in better vegetative growth, metabolism and yield (up to 980 $kg \cdot ha^{-1}$) than other cultivars.

Soil compaction negatively affect the plant function that reflect in decrease of soybean yield (up to 12%).

The negative effects of soil compaction could be verified in the gas exchange ratios (net photosynthesis, internal CO_2 concentration, transpiration, and stomatal conductance) of soybean cultivars.

AUTHORS' CONTRIBUTION

Conceptualization: Ferreira, C. J. B. and Silva, A. G.; **Methodology:** Ferreira, C. J. B., Silva, A. G. and Tormena, C. A.; **Validation:** Ferreira, C. J. B., Paiva Filho, S. V. and Braz, G. B. P.; **Formal Analysis:** Ferreira, C. J. B., Tormena, C. A. and Tavares, R. L. M.; **Investigation:** Ferreira, C. J. B., Silva, A. G., Severiano, E. C. and Braz, G. B. P.; **Data Curation:** Ferreira, C. J. B.; **Writing – Original Draft:** Ferreira, C. J. B., Severiano, E. C. and Braz, G. B. P.; **Writing – Review and Editing:** All authors; **Visualization:** Ferreira, C. J. B. and Tormena, C. A.; **Supervision:** Ferreira, C. J. B. and Braz, G. B. P.; **Funding Acquisition:** Ferreira, C. J. B. and Silva, A. G.

DATA AVAILABILITY STATEMENT

All dataset were generated and analyzed in the current study.

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