

Gas exchanges and growth of soybean as affected by irrigation depths and soil compaction

Jodean Alves da Silva¹, Luiz Gonsaga de Carvalho¹, and Fabrício Ribeiro Andrade^{2*}

¹Universidade Federal de Lavras (UFLA), Departamento de Engenharia Agrícola, Lavras, Minas Gerais, Brasil.

²Instituto Federal de Educação, Ciência e Tecnologia de Mato Grosso (IFMT), Juína, Mato Grosso, Brasil.

*Corresponding author (fabricio.andrade@ifmt.edu.br).

Received: 18 January 2022; Accepted: 29 April 2022; doi:10.4067/S0718-58392022000300502

ABSTRACT

The availability of water above compacted soil layer improves the performance of soybean (*Glycine max* (L.) Merr.) gas exchanges. However, studies do not address the responses of the photosynthetic process of soybean in compacted soil. The objective of this study was to evaluate the dynamics of gas exchange, growth and performance of soybean in compacted soil with poor irrigation. The experiment was conducted in a greenhouse with a completely randomized design in a 3 × 4 split plot for three soil densities (1.0 ± 0.013, 1.15 ± 0.022 and 1.30 ± 0.035 Mg m⁻³) and four daily water depths (4.0, 5.0, 6.0 and 7.0 mm d⁻¹) with three replicates. Net photosynthesis rate (A), transpiration rate (E), stomatal conductance (g_s), water use efficiency (WUE), instantaneous water use efficiency (iWUE), net assimilation rate, growth rate of shoot and root, relative growth rate of shoot and root, shoot biomass, root biomass at different layers (upper, compacted and lower), total root biomass and pod biomass were evaluated. The 4.0 and 5.0 mm d⁻¹ water depths provided higher WUE and iWUE, but not soybean biomass accumulation; with these water depths and 1.15 Mg dm⁻³, gas exchange and accumulation of shoot biomass improved. From 45 to 65 d after emergence (DAE), shoot growth rate had a maximum peak at 7.0 mm d⁻¹ in compacted soil. The growth rate and relative growth rate of soybean roots had smaller increases in biomass at 65 DAE. Daily water depths of 4.0 and 5.0 mm d⁻¹ provided the best results in terms of WUE, however, it did not reflect an accumulation in soybean biomass. In these depths, soil compaction at 1.15 Mg m⁻³ provided an increase in g_s, E, and A.

Key words: Growth, photosynthesis, resistance penetration, transpiration, water deficit.

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) production reached 136 million tons in the 2020/2021 harvest, being one of the most important commodities for Brazilian agribusiness (Conab, 2020). The success of the agricultural production of this crop depends on climatic conditions, where a low availability of water in the soil limits the production of plant biomass and potential productivity, as it needs between 450 and 800 mm water (Oliveira et al., 2021).

Reduction in soil water content alters the growth of soybean. This alteration varies depending on the intensity and duration of the water deficit at each phenological stage, with underdeveloped plants, since the roots send chemical signals to the shoot, changing the physiological processes in different metabolic pathways (Rahnama et al., 2011). Several authors in their studies report the reduction in leaf area, growth and development of shoots and roots of soybeans as a consequence of water stress (Tian et al., 2010; Selim and El-Nady, 2011; Hossain et al., 2014; Nosalewicz and Lipiec, 2014; Machado Júnior et al., 2017).

Greater concentration and proliferation of secondary soybean roots are placed in the superficial layer of the soil where the water deficit is more intense, and which can be minimized in soils with a physical impairment. However, studies do not assess the gas exchange of soybean leaves in compacted soil, which deserves attention, as leaf gas exchange can be

benefited by the greater availability of water between the interfaces of the soil particles above the compacted layer, at temporal scale, contributing to the minimization of the effect of severe water stress in soybeans, even with a deficient water depth, by prolonging the dehydration of leaf tissues, delaying leaf rolls, since soil compaction causes water retention in the soil (Moraes et al., 2020).

In this sense, deficient irrigation can improve water use efficiency and conserve water levels in the soil through this condition management. However, it is noteworthy that the compacted soil layer increases the soil resistance to root penetration with a reduction in total porosity, contributing to the reduction of water flow in the soil as a result of its availability (Bengough et al., 2011; Troldborg et al., 2013; Moraes et al., 2014; 2016) with greater proliferation of secondary roots above the compacted layer (Correa et al., 2019) which limits the depth and volume of soil explored by the roots in search of water and nutrients (Valentine et al., 2012). These modifications, resulting from the effect of soil compaction, have been evidenced in studies on the potential yield of soybeans (Calonego and Rosolem, 2010; Sato et al., 2015).

Given this and given the importance of evaluating gas exchange during the growth and development phases of soybeans to identify the effect of water stress in compacted soil, research is needed to elucidate the behavior of soybeans in function of this management. Thus, we start from the hypothesis that gas exchange in soybean crops can be positively affected by the management of crops with poor irrigation in compacted soil and that this effect on the transpiration and photosynthetic rate can elucidate the productive behavior of soybean under these conditions. Therefore, this study was conducted to evaluate the effect of water stress on physiological parameters, agronomic performance and growth analysis of soybean in compacted soil.

MATERIALS AND METHODS

Experimental site and soil

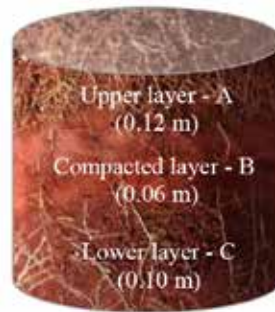
The experiment was conducted in a greenhouse, located at the Water and Soil Engineering Center of the Engineering Department (DEG) of the Federal University of Lavras (UFLA), Lavras, Minas Gerais, Brazil, from November 2016 to January 2017. During the study, the temperature, humidity and solar radiation inside the greenhouse was 26.9 ± 2.1 °C, $58.22 \pm 5.1\%$ and 663.2 ± 104.3 W m², respectively.

Soil used in this study was a very clayey Oxisol (Latossolo Vermelho Distroférico, Brazilian classification; Rhodic Eutrudox, USDA classification) collected from the 0.0-0.2 m layer in cattle pasture, air-dried and sieved to a 2 mm mesh. Before the experiment, the physical and chemical characterization of soil was carried out: 150, 180 and 670 g kg⁻¹ sand, silt and clay, respectively; pH (H₂O) = 6.3; H + Al³⁺ = 3.27 cmol_c dm⁻³; Al³⁺ = 0.0 cmol_c dm⁻³; P (Mehlich-1) = 1.13 mg dm⁻³; K = 58.0 mg dm⁻³; Ca²⁺ = 2.8 cmol_c dm⁻³; Mg = 0.6 cmol_c dm⁻³; CEC = 6.82 cmol_c dm⁻³; base saturation = 52% and, organic matter = 25.5 g dm⁻³.

Based on the chemical analysis of the soil, liming was performed to increase the base saturation to 60%, using dolomitic limestone. After incubation of the soil for 30 d, with humidity close to 60% of the total pore volume (TPV), the planting fertilization was carried out, according to recommendations of Malavolta (1980) with the following applications (mg kg⁻¹): 80 N, 250 P, 200 K₂O and 50 S, using monobasic ammonium phosphate (NH₄H₂PO₄), monopotassium phosphate (KH₂PO₄) and magnesium sulfate (MgSO₄·7H₂O). Fertilization with micronutrients (mg kg⁻¹) consisted of the application of 0.5 B, 1.5 Cu, 0.1 Mo and 5.0 Zn, provided in the form of boric acid (H₃BO₃), copper sulphate (CuSO₄·5H₂O), ammonium molybdate [(NH₄)₆Mo₇O₂₄·4H₂O] and zinc sulfate (ZnSO₄·7H₂O), respectively. At 25 and 40 d after planting (DAP), topdressing fertilization was carried out with the application of 55 mg K₂O, using potassium chloride as a source.

Each experimental plot consisted of a pot of 0.296 m in height and 0.262 m of internal diameter in the compacted layer, divided into three layers: the upper with 0.12 m and the lower with 0.10 m, filled with sieved soil with a soil density of 1.00 Mg m⁻³ (control), and compacted layer was variable depending on the treatments of levels of soil density. The volume of compacted layer was determined based on the volume of the metallic ring [(0.054 m² × 0.06 m) = 0.00324 m³]. Soil was moistened and homogenized until reaching the optimum moisture for compaction, according to the methodology of Santos et al. (2005) for typical Oxisol, made with the aid of a hydraulic press. To avoid deformation or rupture of the pots due to the compression of the soil in the compacted layer, a metallic ring (steel plate 0.06 m high and 0.012 m thick) of the same dimensions as the pot was placed inside (Figure 1). For the fit between the compacted layer and the pot's wall, a finish with cold asphalt waterproofing was performed to prevent the preferential flow of water and root growth.

Figure 1. Diagram representing the layout of the pots with the upper, lower and compacted layers.



Experimental design and treatments

Experimental design used was completely randomized in a 3×4 split-plot scheme, with the factors consisting of three levels of soil density (1.0 ± 0.013 ; 1.15 ± 0.022 and $1.30 \pm 0.035 \text{ Mg m}^{-3}$) and four daily water depths (4.0 , 5.0 , 6.0 and 7.0 mm d^{-1}), with three replicates. This compaction was defined as critical according to Torres and Saraiva (1999).

Before sowing, seeds of the indeterminate growth soybean (*Glycine max* (L.) Merr.) 'RK 8115 IPRO' were treated with pyraclostrobin + methyl thiophanate + fipronil at a dose of $2 \text{ mL commercial product kg}^{-1}$ seed, inoculated with *Bradyrhizobium japonicum*, SEMIA strains 5079 and 5080 (5.0×10^9 viable cells mL^{-1}), at a dose of $4 \text{ mL commercial product kg}^{-1}$ seed. Sowing was carried out on 15 November 2016, by distributing five seeds per pot at a depth of 0.02 m and they were thinned 15 d after sowing leaving three seedlings. In order to maintain the health of the plants, insecticide and fungicide recommended for this crop were preventively applied.

From 35 d after emergence (DAE), the replacement of the pre-established daily irrigation of 4 , 5 , 6 and 7 mm d^{-1} , was manually maintained from 09:00-10:00 h. The lowest daily water depth of 4.0 mm d^{-1} applied is half of the critical amount ($7\text{-}8 \text{ mm d}^{-1}$) required by soybeans in the phases of higher transpiration demand between flowering and grain filling under normal growing conditions.

Gas exchange measurements

At 45, 55, 65 and 75 DAE, gas exchange was determined using a portable infrared gas analyzer (IRGA-LICOR 6400, LiCOR, Lincoln, Nebraska, USA), carried out between 09:00-10:30 h, in two plants per pot using the third fully expanded leaf from top to bottom, photosynthetically active and without lesions, located in the third trefoil from top to bottom. Photosynthetically active radiation was standardized in artificial saturating light of $1000 \mu\text{mol m}^{-2} \text{ s}^{-1}$ (equivalent to natural light) and ambient CO_2 concentration (Silva et al., 2020). We measured stomatal conductance rate (g_s , $\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$), transpiration rate (E , $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$), internal CO_2 concentration (C_i , $\mu\text{mol CO}_2 \text{ mol}^{-1}$), as well as the net photosynthesis rate (A , $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), leaf temperature (T_l) and vapor pressure deficit (VPD). With these data, the water use efficiency (WUE) was quantified as (A/E) ($[\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}] [\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}]^{-1}$) calculated relating it to net photosynthesis with transpiration, the instantaneous water use efficiency (iWUE) (A/g_s) ($[\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}] [\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}]^{-1}$) calculated relating it to net photosynthesis with stomatal conductance and instantaneous carboxylation efficiency (A/C_i) ($[\mu\text{mol m}^{-2} \text{ s}^{-1}] / [\mu\text{mol mol}^{-1}]^{-1}$) calculated relating it to net photosynthesis with the internal concentration of CO_2 .

Biometric and growth measurements

At 45, 55, 65 and 75 DAE, the plants were sectioned at the base of the collar, taken to the laboratory and the leaf area was determined using a leaf area meter (LI-3100, LI-COR). Having the leaf area, the total area of leaves in the sample was determined and, subsequently, the leaf area index (LAI) (leaves $\text{m}^2/\text{plant density per pot area}$) were determined. Subsequently, stems, leaves and pods were dried in an oven with forced air circulation at $65 \text{ }^\circ\text{C}$ for 72 h to determine the biomass on a precision scale (± 0.001).

After removing the aerial part of the plants at 55 DAE, root dry biomass was determined in the upper layer (A), compacted layer (B) and below the compacted layer (C). The dry biomass of the roots was dried in a forced air circulation oven at $65 \text{ }^\circ\text{C}$ for 72 h in order to be determined with a precision scale (± 0.001).

The crop growth rate (CGR) of shoot and root ($\text{g plant}^{-1} \text{d}^{-1}$) was calculated by the equation $\text{CGR} = (\text{BSt}_2 - \text{BSt}_1) / (t_2 - t_1)$, where BSt_2 is the total current dry biomass (g plant^{-1}), BSt_1 is the total initial dry biomass (g plant^{-1}), and $t_2 - t_1$ is the time interval between two collections. The relative growth rate (RGR) of shoot and root ($\text{g g}^{-1} \text{d}^{-1}$) was calculated by the equation $\text{RGR} = (\ln \text{BSt}_2 - \ln \text{BSt}_1) / (t_2 - t_1)$, where BSt_1 and BSt_2 represent dry biomass at times t_1 and t_2 . The net assimilation rate (NAR, $\text{g plant}^{-1} \text{d}^{-1}$), was calculated by the formula $\text{NAR} = [(\text{BSt}_2 - \text{BSt}_1) \times (\ln \text{LAI}_2 - \ln \text{LAI}_1)] / [(\text{LAI}_2 - \text{LAI}_1) \times (t_2 - t_1)]$, in which LAI_2 is the total current LAI (cm^2) and LAI_1 is the total initial LAI of the shoot (cm^2). The dry biomass of the pod (DBP, g plant^{-1}) was calculated at 55, 65 and 75 DAE.

Statistical analysis

The data were submitted for comparison of standard errors of the mean. For growth analysis, an ANOVA is not recommended, as it does not comply with its basic assumptions (Banzatto and Kronka, 2013). Means, standard errors and behavioral graphs were performed using SigmaPlot 12.5 statistical software (Systat Software, San Jose, California, USA).

RESULTS AND DISCUSSION

Gas exchange in soybean crops, relating net photosynthesis with transpiration

After evaluating the stomatal conductance (g_s), transpiration rate (E) and net photosynthesis rate (A), it was found that, regardless of the soil density, they were significantly influenced by the daily water depths, with higher values observed in the largest water depth (Figure 2). The greatest differences due to the water depths were verified at 45 and 55 DAE, with higher values of g_s , E and A in the daily water depth of 7.0 mm d^{-1} , differing from 4 mm d^{-1} , however at 65 and 75 DAE this same response was not verified. At the first evaluation, g_s was approximately 4.3, 2.2 and 1.99 times higher in the highest daily water depth, when compared to 4.0 mm d^{-1} for densities of 1.0, 1.15 and 1.30 Mg m^{-3} , respectively (Figures 2A-2C).

These results corroborate those obtained by Hossain et al. (2014), who found similar behavior in different soybean cultivars with lower g_s values under water deficit without compaction. This greater variation of g_s in soil without compaction, at 45 DAE, from the smallest to the largest water depth, is due to the greater flow of water on the soil to the deeper layers of the soil; which contributes to the soil drying faster in the surface layer where most of the soybean roots were, causing them to absorb little water, even though it is a phase of rapid growth and development of the root system in a soil with less soil resistance to root penetration.

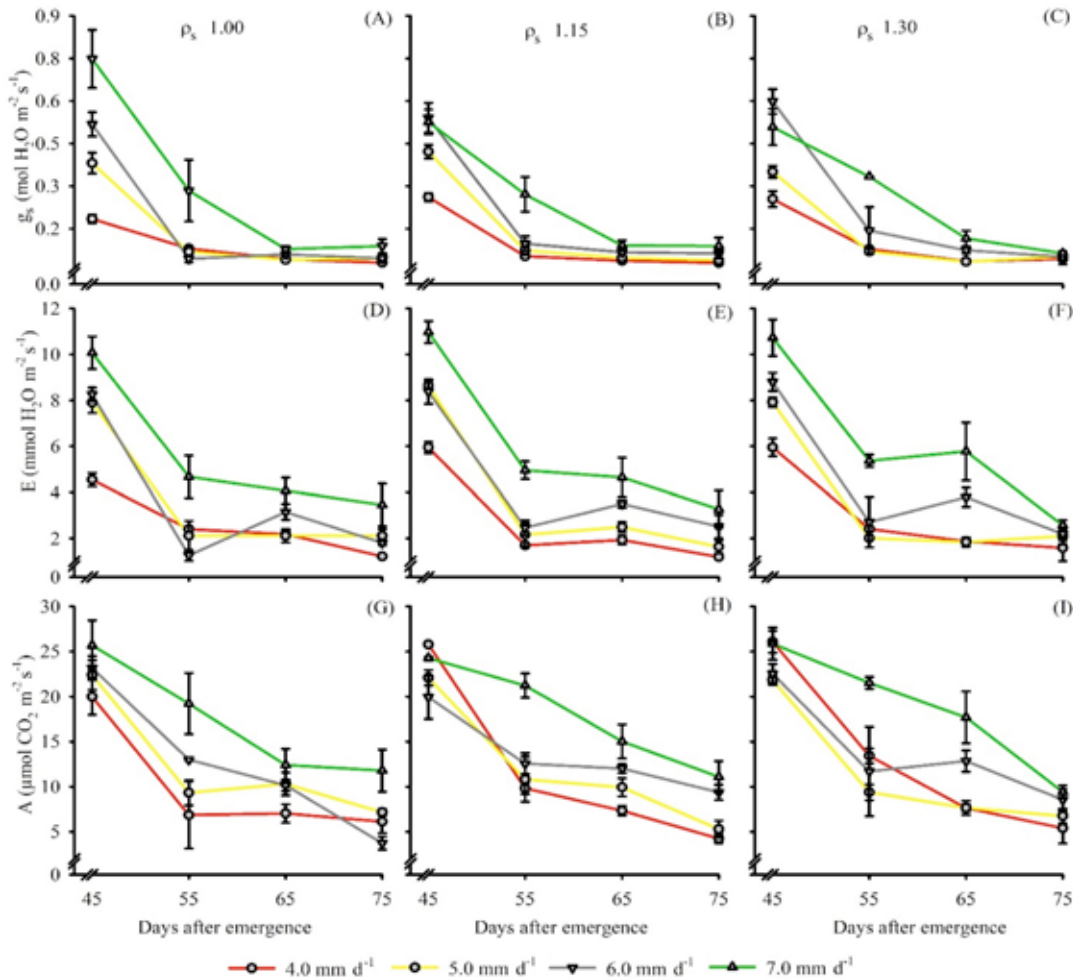
From 45 DAE onwards, the amplitudes of E values due to the water depths were reduced until 75 DAE, when differences were no longer observed, regardless of soil density (Figures 2D-2F). This plant response can be explained by the small leaf area at the beginning of soybean development due to the low transpiration demand and a good water availability in the soil, thus increasing the water potential in the xylem. However, as the soybean develops, the leaf area expands and, consequently, the transpiratory demand increases, which ends up reducing the difference of E amongst the water depths until 65 DAE, especially in the daily depth of 7.0 mm d^{-1} . This caused the plants to remain stable from 65 to 75 DAE.

Reduction of water partition to the atmosphere by stomatal closure is one of the plant's responses to maintain a high-water potential in the leaves while the water deficit intensifies (Ohashi et al., 2006). Thus, stomatal conductance causes a reduction in the intercellular influx of CO_2 and, consequently, a decrease in the photosynthetic rate, as observed in this study (Figures 2G-2I). Although it reduces the intercellular influx of CO_2 , this reduction is not so severe as to cause deleterious effects to photosystems under severe water deficit. According to Tanaka and Shiraiwa (2009) the indeterminate-growing soybean cultivars have higher stomatal density and, consequently, higher g_s .

Largest WUE and iWUE were verified in the smallest water depths applied, however, this difference was significant up to 55 and 65 DAE for WUE and iWUE, respectively (Figure 3). Except for 7.0 mm d^{-1} , the other depths provided WUE above 4 ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) ($\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$) $^{-1}$ (Figures 3A-3C) and iWUE of 170 ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) ($\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$) $^{-1}$ (Figures 3D-3F).

Daily water depths applied changed the net assimilation rate (NAR) throughout the growth cycle of the soybean plants, with a daily water depth of 7.0 mm d^{-1} at 45 DAE being approximately 1.7, 2.2 and 1.9 times higher when compared to 4.0 mm d^{-1} , regardless of soil density (Figures 3G-3I). This behavior is due to the greater weight gain with the expansion of the leaves' surface in the largest water depths due to the increase in g_s and E, associated with the increase in A.

Figure 2. Stomatal conductance (g_s) (A, B, C), transpiration rate (E) (D, E, F), and photosynthesis rate (A) (G, H, I) of soybean subjected to different soil densities (ρ_s) and daily water depths in a greenhouse.



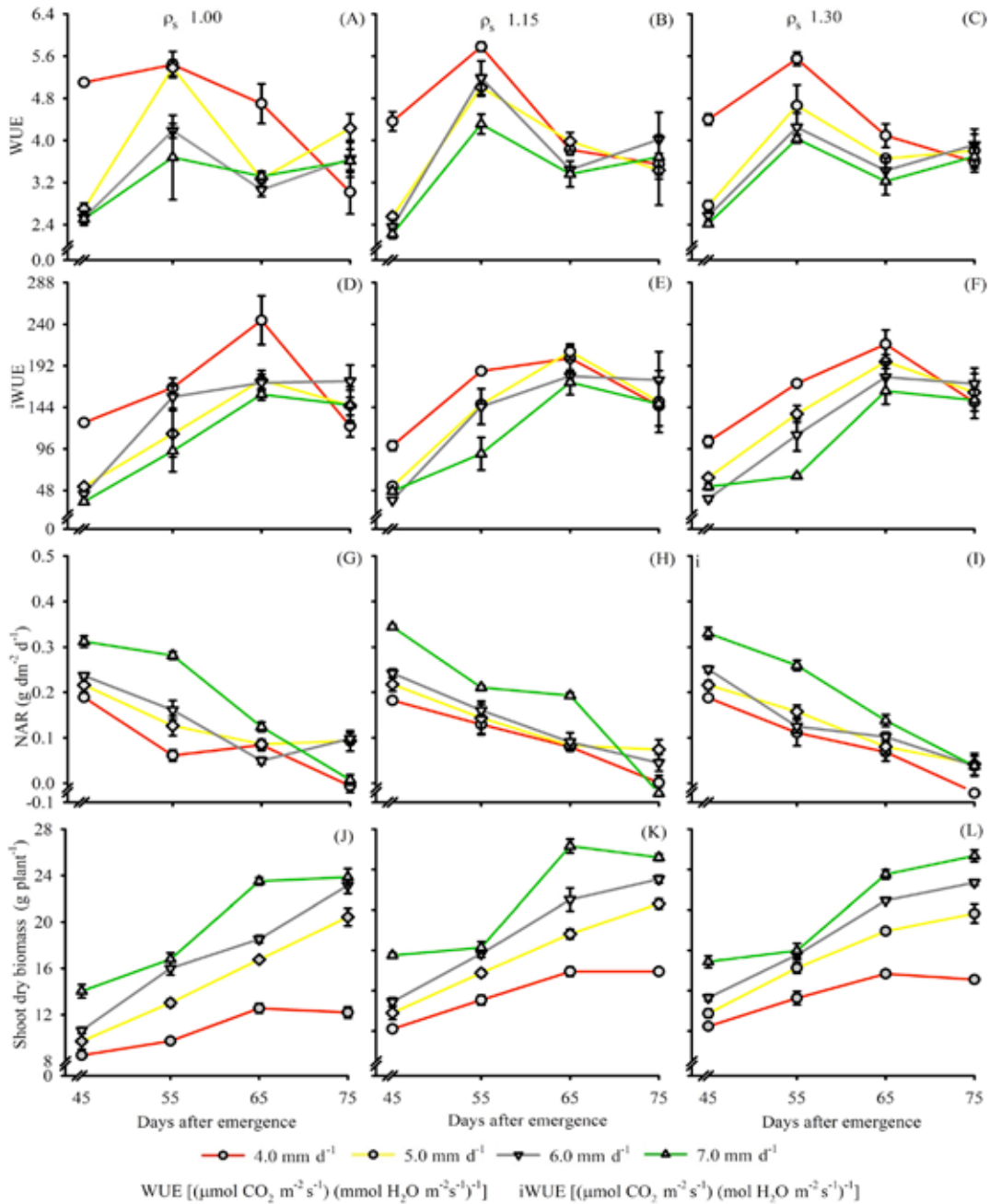
Bars represent the standard error of the means ($n = 3$).

Dry biomass of shoot was twice smaller at 4.0 mm d⁻¹ in uncompacted soil, compared to 7 mm d⁻¹ depth (Figures 3J-3L). These results corroborate those of Machado Júnior et al. (2017), despite the values being very different, which obtained from 30 to 45 g in a soybean cultivar with indeterminate growth from 44 to 57 DAE under severe water stress (25% moisture in field capacity). Dynamics in the accumulation of the biomass of the soybean's shoot followed a characteristic pattern of annual crops, where accumulation was rapid from 45 DAE onwards, except for the 4.0 mm d⁻¹ water depth, where the plant was under water stress, which resulted in smaller leaf area and biomass, associated with smaller g_s , E and NAR over time, causing less CO₂ assimilation, which resulted in less biomass accumulation in the shoot of these plants.

These results clearly show that the WUE (amount of CO₂ assimilated per unit of water transpired), as well as the iWUE (amount of CO₂ assimilated per unit of water by stomatal conductance) in each evaluated period, increase as a result of the water deficit. However, it did not result in leaf surface weight gain over time (NAR) under water deficit, as it represents the reduction in A and, consequently, the increase in shoot biomass. Under these conditions, due to the different distribution of water applied, A was not proportional to leaf area and LAI, which had higher values at 55 and 65 DAE.

Biomass production of the soybean's shoot was increased in intermediate water depths in soil with density up to 1.30 Mg m⁻³. This is due to the increase in E and A, as they are highly correlated, even with a deficient water depth for soybean.

Figure 3. Water use efficiency (WUE) (A, B, C), instantaneous water use efficiency (iWUE) (D, E, F), net assimilation rate (NAR) (G, H, I) and shoot dry biomass (J, K, L) of soybean subjected to different soil densities (ρ_s) and daily water depths in a greenhouse.

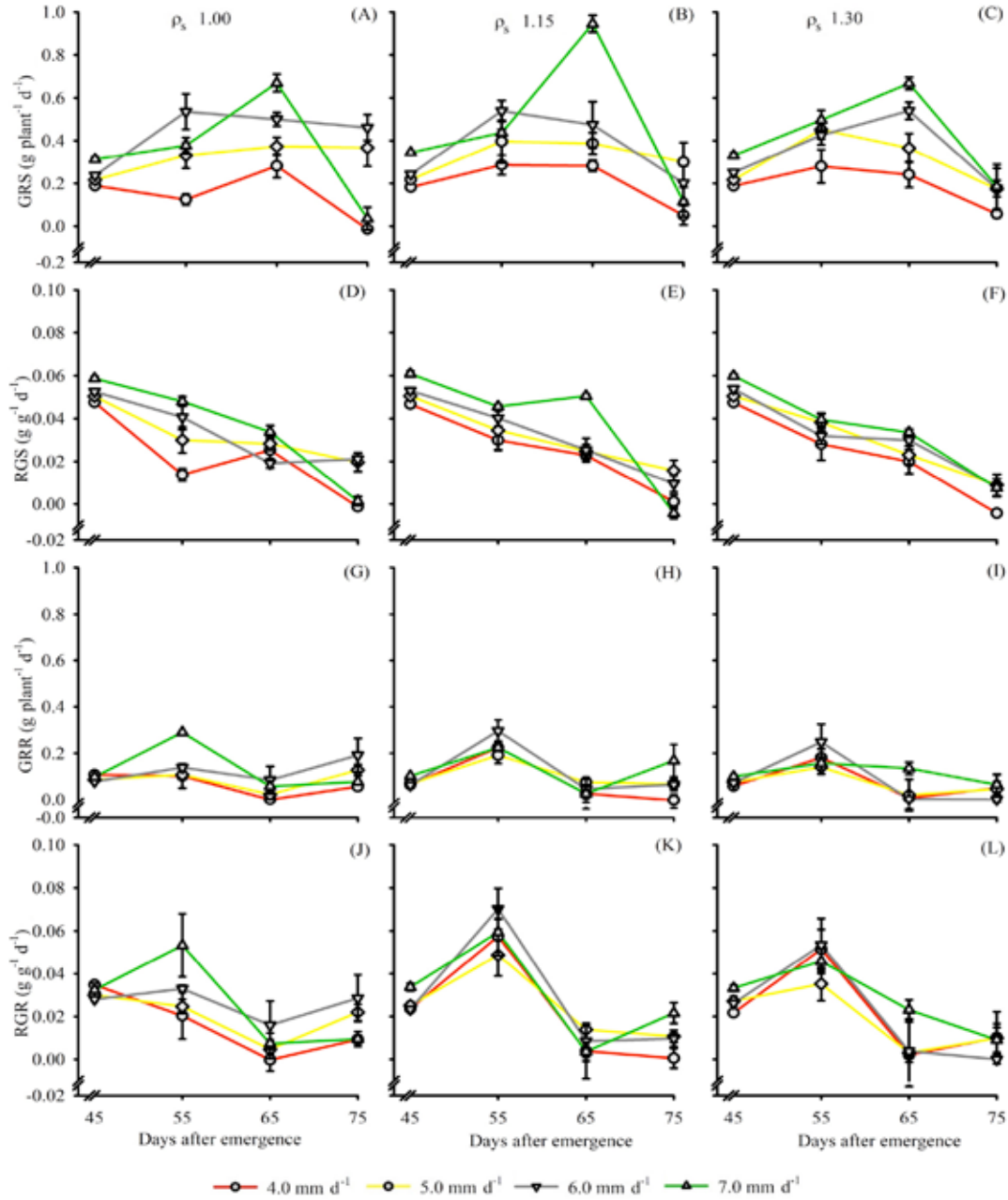


Bars represent the standard error of the means (n = 3).

Growth rate and relative growth rate of the shoot

The growth rate of shoot (GRS) and relative growth rate of shoot (RGS) were significantly influenced by the water depths (Figures 4A-4F), showing different behaviors, with the lowest values verified in the water depths of 4.0 and 5.0 mm d⁻¹, being the maximum time, at 65 and 45 DAE, respectively, mainly at 7.0 mm d⁻¹, regardless of whether there was soil compaction or not.

Figure 4. Growth rate of the shoot (GRS) (A, B, C), relative growth rate of the shoot (RGS) (D, E and F), growth rate of the root (GRR) (G, H, I) and relative growth rate of the root (RGR) (J, K, L) of soybean subjected to different soil densities and daily water depths (ρ_s) in a greenhouse.



Bars represent the standard error of the means (n = 3).

Highest RGS of the soybean crop at 45 DAE with subsequent decline due to its growth was verified by Petter et al. (2016) in soybean cultivars under different planting densities, where the authors claim that this is related to the formation of new plant tissues in the initial growth and development phase of the soybean, in which the RGS rises as a result of the increased emergence of new leaves and leaf expansion. And these are directly related to the photosynthetic capacity of the assimilatory tissues, which is lower in smaller water depths, as the water deficit is more intense, as well as g_s and E.

Unlike growth rate, RGS allows us to verify the soybean growth pattern over time and, consequently, the effect of water stress on the increase in biomass. Thus, it is evident that soybeans, from 45 DAE at 4.0 to 5.0 mm d⁻¹, reduce the RGS and form less dry biomass from pre-existing matter to prioritize the growth of roots (growth rate [GRR] and relative growth rate [RGR]) (Figures 4G-4L) with a maximum peak of increments in biomass at 55 DAE. This response was a soybean strategy, attributed to the gradual allocation of photoassimilates for the growth of non-assimilatory tissues (roots), which limited shoot growth. The significant reduction of GRR and RGR after 55 DAE was due to the soybean directing the allocation of photoassimilates for shoot growth, after the establishment of the root system.

For the RGS, which had the same behavior as the NAR, this reduction, at 65 DAE, can be attributed to the reduction in leaf expansion along with the abortion of flowers observed in the experiment, followed by the senescence phase, mainly in the smallest water depths applied. However, with the increase in the availability of water in the soil, there was an increase in relative growth rate, mainly due to the greater assimilation of CO₂.

Dry biomass of roots and pods

Regardless of the daily water depth applied, the increase in soil density provided an increase in root biomass in the layer above the compacted layer throughout the soybean's cycle, with higher values in the highest water depths (Figures 5A-5C). However, the opposite behavior, with a reduction in root biomass, occurred starting at the compacted layer (B) (Figures 5D-5I). These results corroborate with Sato et al. (2015) who obtained a reduced dry mass of soybean roots in clayey and very clayey soil with increased soil density. This response is related to the increase in resistance to root penetration in compacted soil associated with lower water content to reduce the deepening of the root system and increase the proliferation and distribution of secondary roots in the upper layer above the layer compacted soil (Bengough et al., 2011; He et al., 2017; Biberdzic et al., 2020).

However, the effect of soil compaction was reduced in the soil density of 1.3 Mg m⁻³ with an increase in the water depth applied, which led to an increase in root biomass in the layer below the compacted layer. This fact may have been benefited by the formation of cracks in the soil produced by mobilization at the time of compaction and/or by the variation of the standard error in 0.035 Mg m⁻³ of the density of 1.30 Mg m⁻³ which may have attenuated the soil's resistance effect to penetration and root growth.

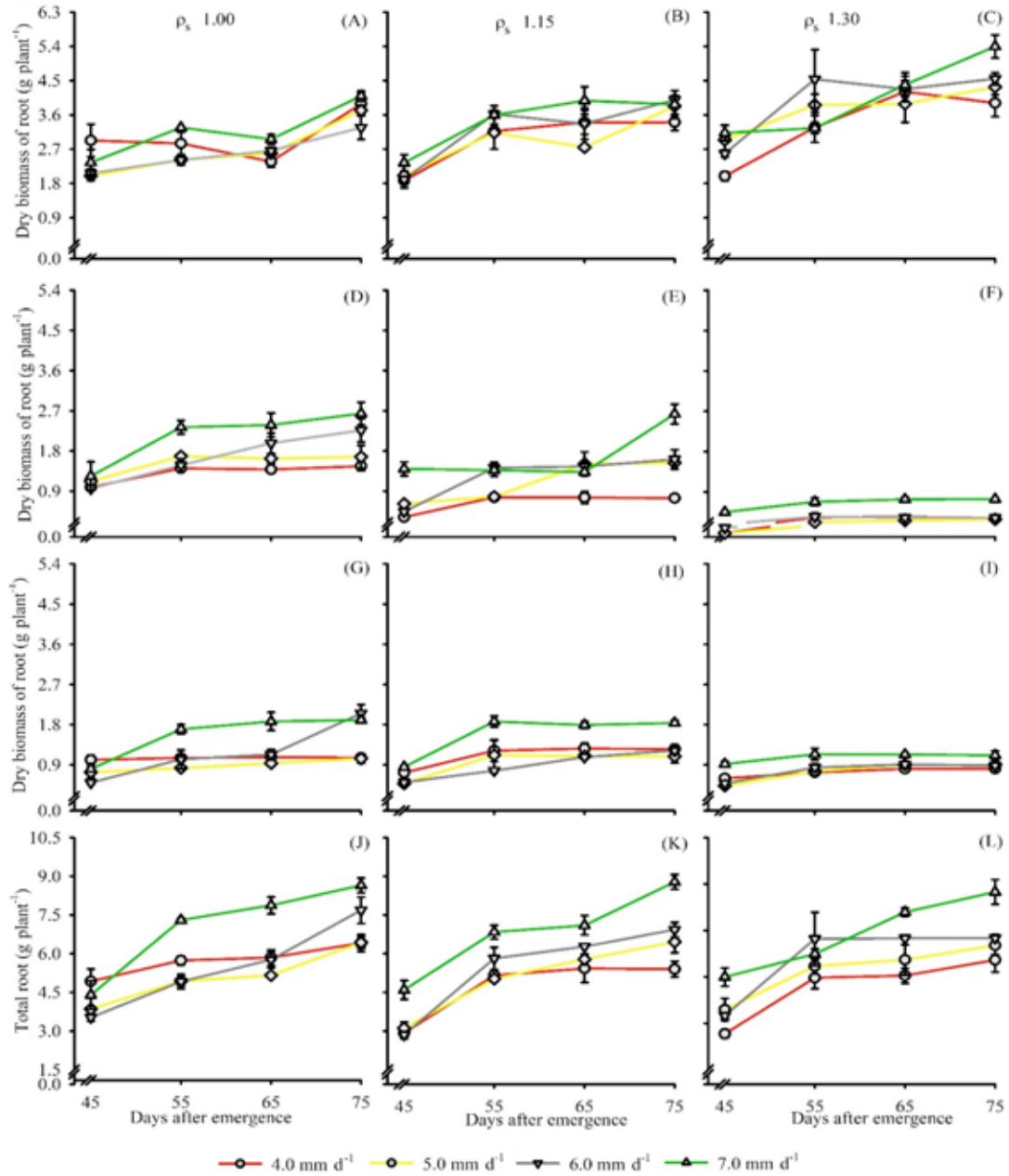
As in the WUE and iWUE, caution must also be exercised when evaluating the total root biomass (Figures 5J-5L) as a growth and development parameter in compacted soil, as the results show that in the layer before the compacted one, in the soil density of 1.3 Mg m⁻³, the root biomass is over 65% compared to the others. With this, the smaller accumulation of dry biomass in the smallest water depths applied in compacted soil masks the real effect of soil compaction, which can lead to misinterpretations about the management in these cultivation conditions.

Severe water deficit induced with the use in soybeans in a water depth of 4 mm d⁻¹ associated with low water availability in leaf tissues, with higher WUE and iWUE, did not reflect a greater accumulation of dry biomass of the pods in all of the evaluated soil densities (Figure 6).

Smallest accumulation of dry biomass of the pods was observed in the water depth of 4.0 mm d⁻¹. Comparing 4.0 mm d⁻¹ with the 5.0 mm d⁻¹ depth, at each soil density at 75 DAE, the greatest variation was in the non-compacted soil, at the density of 1.00 Mg m⁻³, with approximately 102%, while at densities 1.15 and 1.30 Mg m⁻³, they were 58% and 53%, respectively. These results partially corroborate those of Catuchi et al. (2012) who detected a reduction in pod formation in the soybean crop, for 25 d, at severe levels of soil moisture deficit. Gava et al. (2016) observed a reduction in plant height and reduction in grain filling when soybeans are subjected to a water deficit of 50% to 70% between the vegetative periods until the beginning of pod formation.

Although the possibility and the possible negative effects of soil compaction in soybean cultivation have been addressed mainly in theory, in practice the results can be very divergent for some physiological parameters. These results of the dry pod biomass, supported by the agronomic and physiological performance, reflected in a greater increase in pod biomass, even with low water availability in leaf tissues at a depth of 5.0 mm d⁻¹. However, from 5.0 mm d⁻¹ depth onwards, there was no difference in the biomass production of pods with soil compaction, due to the high phenotypic plasticity of the soybean root and shoot, as the increase in soil density increased the rate of transpiration and photosynthesis without compromising the pod biomass production.

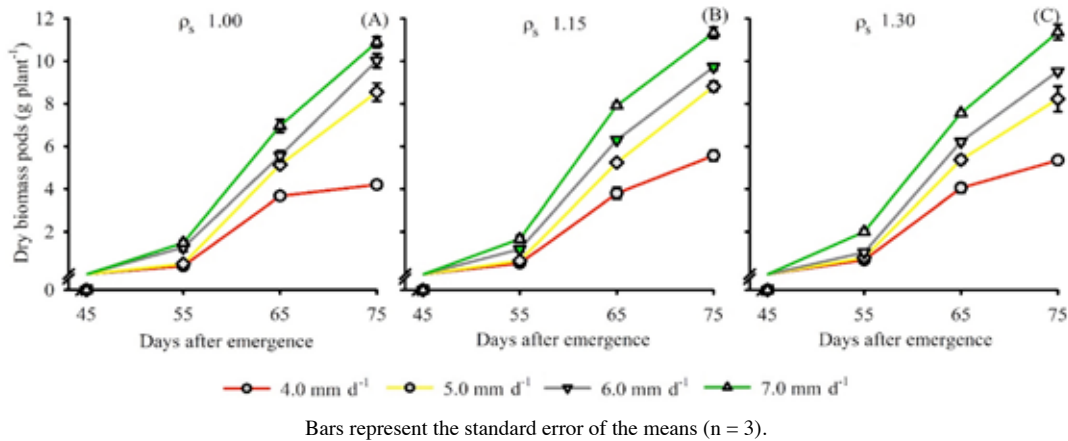
Figure 5. Dry biomass of roots in upper layer (root biomass) (A, B, C), dry biomass of roots in compacted layer (root biomass) (D, E, F), dry biomass of roots of lower layer (root biomass) (G, H, I) and total root dry biomass (total root) (J, K, L) of soybean subjected to different soil densities (ρ_s) and daily water depths in greenhouse.



Bars represent the standard error of the means (n = 3).

Therefore, proportional reductions in the shoot and root biomass of soybeans cannot be asserted by just the increase in soil density, as both the adopted management and the physiological performance interfere in the gas exchange of the soybean crop, which reflect on yield of the grain.

Figure 6. Dry biomass of the soybean pod (A, B, C) subjected to different soil densities (ρ_s) and daily water depths in a greenhouse.



CONCLUSIONS

The daily water depths of 4.0 and 5.0 mm d⁻¹ provided the best results in terms of water use efficiency, however, it did not reflect an accumulation in the biomass of the soybean. In these depths, soil compaction at a soil density of 1.15 Mg m⁻³ provided an increase in stomatal conductance, transpiration rate and net photosynthesis and, consequently, in the accumulation of the dry biomass of the soybean shoot during the cycle.

Growth rate of the shoot presented a different behavior as compared to the relative growth rate of the shoot and net assimilation rate from 45 to 65 d after emergence (DAE), with a maximum peak at 7.0 mm d⁻¹ water depth in compacted soil, while the growth rate and the relative growth rate of roots showed smaller biomass increments at 65 DAE.

Gas exchange supports information which allows us to infer not only negative effects of soil density on the agronomic performance of soybean crops.

ACKNOWLEDGEMENTS

The authors express their gratitude to Coordination of Superior Level Staff Improvement (CAPES) and National Council for Scientific and Technological Development (CNPq) for providing the research grant to the first and second authors, respectively. We thank Foundation for Research Support of the State of Mato Grosso (FAPEMAT), Federal University of Lavras (UFLA) and Federal Institute of Education, Science and Technology of Mato Grosso (IFMT) for the financial support of this research.

REFERENCES

- Banzatto, D.A., e Kronka, S.N. 2013. Experimentação agrícola. Universidade Estadual Paulista (UNESP), Jaboticabal, São Paulo, Brasil.
- Bengough, A.G., McKenzie, B.M., Hallett, P.D., and Valentine, T.A. 2011. Root elongation, water stress, and mechanical impedance: A review of limiting stresses and beneficial root tip traits. *Journal of Experimental Botany* 62(1):59-68. doi:10.1093/jxb/erq350.
- Biberdzic, M., Barac, S., Lalevic, D., Djikic, A., Prodanovic, D., and Rajcic, V. 2020. Influence of soil tillage system on soil compaction and winter wheat yield. *Chilean Journal of Agricultural Research* 80:80-89. doi:10.4067/S0718-58392020000100080.
- Calonego, J.C., and Rosolem, C.A. 2010. Soybean root growth and yield in rotation with cover crops under chiseling and no-till. *European Journal of Agronomy* 33(3):242-249. doi:10.1016/j.eja.2010.06.002.
- Catuchi, T.A., Guidorizzi, F.V.C., Guidorizzi, K.A., Barbosa, A.M., e Souza, G.M. 2012. Respostas fisiológicas de cultivares de soja à adubação potássica sob diferentes regimes hídricos. *Pesquisa Agropecuária Brasileira* 47(4):519-527. doi:10.1590/S0100-204X2012000400007.

- Conab. 2020. Acompanhamento da safra 2020, Brasil. Companhia Nacional de Abastecimento (Conab), Brasília, Brasil. Available at <http://www.conab.gov.br/safras.asp> (accessed February 2020).
- Correa, J., Postma, J.A., Watt, M., and Wojciechowski, T. 2019. Soil compaction and the architectural plasticity of root systems. *Journal of Experimental Botany* 70(21):6019-6034.
- Gava, R., Frizzzone, J.A., Snyder, R.L., Almeida, B.M., Freitas, P.S.L., e Rezende, R. 2016. Estratégias de manejo de deficit hídrico na irrigação da cultura da soja. *Brazilian Journal of Biosystems Engineering* 10(3):305-315.
- He, J., Jin, Y., Du, Y.L., Wang, T., Turner, N.C., Yang, R.P., et al. 2017. Genotypic variation in yield, yield components, root morphology and architecture, in soybean in relation to water and phosphorus supply. *Frontiers in Plant Science* 8:1499. doi:10.3389/fpls.2017.01499.
- Hossain, M.M., Hossain, M.M., Liu, X., Qi, X., Lam, H.M., and Zhang, J. 2014. Differences between soybean genotypes in physiological response to sequential soil drying and rewetting. *The Crop Journal* 2(6):366-380. doi:10.1016/j.cj.2014.08.001.
- Machado Júnior, C.S., Silva, C.R., Sanches, M.C., Hamawaki, O.T., and Sousa, L.B. 2017. Physiologic parameters of soybean of determinate and indeterminate growth habit subjected to levels of soil moisture. *Pesquisa Agropecuária Brasileira* 52(6):419-425. doi:10.1590/S0100-204X2017000600005.
- Malavolta, E. 1980. Elementos de nutrição mineral de plantas. Agronômica Ceres, São Paulo, Brasil.
- Moraes, M.T., Debiasi, H., Carlesso, R., Franchini, J.C., Silva, V.R., and Luz, F.B. 2016. Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil. *Soil and Tillage Research* 155(1):351-362. doi:10.1016/j.still.2015.07.015.
- Moraes, M.T., Debiasi, H., Franchini, J.C., Mastroberti, A.A., Levien, R., Leitner, D., et al. 2020. Soil compaction impacts soybean root growth in an Oxisol from subtropical Brazil. *Soil and Tillage Research* 200:104611.
- Moraes, M.T., Moraes, M.T.D., Debiasi, H., Carlesso, R., Franchini, J.C., and Silva, V.R.D. 2014. Critical limits of soil penetration resistance in a Rhodic Eutrudox. *Revista Brasileira de Ciência do Solo* 38(1):288-298. doi:10.1590/S0100-06832014000100029.
- Nosalewicz, A., and Lipiec, J. 2014. The effect of compacted soil layers on vertical root distribution and water uptake by wheat. *Plant and Soil* 375(1-2):229-240. doi:10.1007/s11104-013-1961-0.
- Ohashi, Y., Nakayama, N., Saneoka, H., and Fujita, K. 2006. Effects of drought stress on photosynthetic gas exchange, chlorophyll fluorescence and stem diameter of soybean plants. *Biologia Plantarum* 50(1):138-141. doi:10.1007/s10535-005-00893.
- Oliveira, K.R., Sampaio, F.R., Siqueira, G.S., Galvão, Í.M., Bennett, S.J., Gratão, P.L., et al. 2021. Physiological quality of soybean seeds grown under different low altitude field environments and storage time. *Plant, Soil and Environment* 67:92-98.
- Petter, F.A., Silva, J.A., Zuffo, A.M., Andrade, F.R., Pacheco, L.P., e Almeida, F.A. 2016. Elevada densidade de semeadura aumenta a produtividade da soja? Respostas da radiação fotossinteticamente ativa. *Bragantia* 75(2):173-183. doi:10.1590/1678-4499.447.
- Rahnama, A., Munns, R., Poustini, K., and Watt, M.A. 2011. Screening method to identify genetic variation in root growth responses to a salinity gradient. *Journal of Experimental Botany* 62(1):69-77. doi:10.1093/jxb/erq359.
- Santos, G.A., Dias Júnior, M.D.S., Guimarães, P.T.G., e Furtini Neto, A.E. 2005. Diferentes graus de compactação e fornecimento de fósforo influenciando no crescimento de plantas de milho (*Zea mays* L.) cultivadas em solos distintos. *Ciência e Agrotecnologia* 29(4):740-752. doi:10.1590/S1413-70542005000400005.
- Sato, M.K., Lima, H.V., Oliveira, P.D., and Rodrigues, S. 2015. Critical soil bulk density for soybean growth in Oxisols. *International Agrophysics* 29:441-447. doi:10.1515/intag-2015-0050.
- Selim, A.F.H., and El-Nady, M.F. 2011. Physio-anatomical responses of drought stressed tomato plants to magnetic field. *Acta Astronautica* 69(7-8):387-396. doi:10.1016/j.actaastro.2011.05.025.
- Silva, J.A., Santos, P.A.B., Carvalho, L.G., Moura, E.G., and Andrade, F.R. 2020. Gas exchange and growth of soybean cultivars submitted to water deficiency. *Pesquisa Agropecuária Tropical* 50:e58854. doi:10.1590/1983-40632020v5058854.
- Tanaka, Y., and Shiraiwa, T. 2009. Steam growth habit affects leaf morphology and gas exchange traits in soybean. *Annals of Botany* 104(7):1293-1299. doi:10.1093/aob/mcp240.
- Tian, Z., Wang, X., Lee, R., Li, Y., Specht, J.E., Nelson, R.L., et al. 2010. Artificial selection for determinate growth habit in soybean. *Proceedings of the National Academy of Sciences of the United States of America* 107(19):8563-8568. doi:10.1073/pnas.1000088107.
- Torres, E., e Saraiva, O.F. 1999. Camadas de impedimento mecânico do solo em sistemas agrícolas com a soja. Circular Técnica 23. 58 p. Embrapa Soja (CNPSo), Londrina, Parana, Brasil.
- Troldborg, M., Aalders, I., Towers, W., Hallett, P.D., McKenzie, B.M., Bengough, A.G., et al. 2013. Application of Bayesian Belief Networks to quantify and map areas at risk to soil threats: Using soil compaction as an example. *Soil and Tillage Research* 132:56-68. doi:10.1016/j.still.2013.05.005.
- Valentine, T.A., Hallett, P.D., Binnie, K., Young, M.W., Squire, G.R., Hawes, C., et al. 2012. Soil strength and macropore volume limit root elongation rates in many UK agricultural soils. *Annals of Botany* 110(2):259-270. doi:10.1093/aob/mcs118.