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CROP PRODUCTION

# Soil compaction and cover with black oat on soybean grain yield in lowland under no-tillage system

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**ABSTRACT**: *Brazil is the largest exporter and second largest producer of soybean grains. Most of this production is from plants grown under no-tillage system (NT). This research evaluated the effect of soil compaction, and different amounts of black oat residues on the soil surface on soybean growth and grain yield in lowland under NT. The experiment was conducted in a completely randomized design with seven treatments and four replications, in the 2016/2017 and 2017/2018 crop seasons. The treatments consisted of: 1) winter fallow without soil compaction (WF); 2) winter fallow with soil compaction (WF-C); 3) black oats and complete removal of surface residues, with soil compaction (0R-C); 4) black oats and removal half of surface residues, with soil compaction (0.5R-C); 5) black oats without surface residue removal, with soil compaction (1R-C); 6) black oats without surface residue removal, plus the residues from treatment 3, with soil compaction (2R-C); 7) black oats without surface residue removal, without soil compaction (1R). When the soybean plants were at the phenological stage R2, they were evaluated nodule, root and shoot dry matter, nitrogen contents, plant height, and grain yield. The soil physical properties were evaluated in the 0.0-0.05, 0.10-0.15 and 0.20-0.25 m layers. The soybean aerial dry matter is > 38% in non-compacted soil in year with soil water excess, regardless of the amount of surface oat straw. In year with small water deficit, soil with more surface oat straw produced > 5% shoot dry matter and > 4% of soybean grain, regardless of compaction. The plant growth and grain yield soybean in lowland varied according to the water conditions, and were affected by soil compaction and amounts of black oats residues on soil surface.*
**Key words**: *Glycine max, Avena strigosa, direct seeding.*

## Compactação do solo e cobertura com aveia preta na produtividade de grãos de soja em várzea sob sistema de plantio direto

**RESUMO**: *O Brasil se destaca na produção de soja, sendo o maior exportador e o segundo maior produtor do grão e a maior parte é cultivado em sistema plantio direto (SPD). Objetivou-se avaliar o efeito da compactação, cultivo e quantidades de palha de aveia preta na superfície do solo sobre o crescimento e o rendimento de grãos de soja em SPD em terras baixas. O delineamento experimental foi inteiramente casualizado com sete tratamentos e quatro repetições. Os tratamentos, nas safras 2016/17 e 2017/18, foram: 1) Pousio no inverno sem compactação (WF); 2) Pousio no inverno + compactação (WF-C); 3) Aveia preta e retirada da palha superficial + compactação (0R-C); 4) Aveia e retirada da metade da palha + compactação (0,5R-C); 5) Aveia + permanência da palhada + compactação (1R-C); 6) Aveia + a palha retirada do tratamento 3 (2 doses palha) + compactação (2R-C); 7) Aveia + permanência da palha, sem compactação (1R). No estádio fenológico R2 a soja foram avaliadas a massa seca de nódulos e de raízes, massa seca e nitrogênio da parte aérea, altura de plantas e produtividade de grãos. No solo foram avaliadas propriedades físicas nas camadas de 0,0-0,05; 0,10-0,15 e 0,20-0,25 m. A produção de massa seca da parte aérea de soja é > 38% em solo não compactado em ano com excesso hídrico independente da quantidade de palha de aveia na superfície. Em ano com pequeno déficit hídrico os tratamentos com mais palha produziram > 5% de massa seca da parte aérea e > 4% de grãos de soja, independente da compactação. O crescimento e o rendimento de grãos de soja em terras baixas oscilam de acordo com as condições hídricas, sendo influenciada pela compactação e quantidade de palha superficial.*
**Palavras-chave**: *Glycine max, Avena strigosa, semeadura direta.*

## INTRODUCTION

Soybean (*Glycine max* (L.) Merrill) is the main oilseed produced and consumed in the world, having great food and economic importance. Brazil is the largest exporter and the second largest world producer of soybean grains (FAO, 2018). Soybean crops are usually conducted under no-tillage system (NT) because of its benefits, such as lower implementation costs, soil and water conservation, which are essential for the sustainability of agricultural systems (EMBRAPA, 2013). However, NT can result

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in excessive soil compaction due to machinery traffic on the soil, in special excessive traffic with machines with high weight per axle and under conditions of high water content in soil, decreasing crop growth and grain yield as verified by BOTTA et al. (2010) and GUBIANI et al. (2014)).

Excessive soil compaction results in soil physical degradation, increases soil resistance to penetration and bulk density, and reduces porosity, aeration, water infiltration into the soil and internal water flow reducing nutrients transport in soil. Soil compaction also deforms the root system, and alters carbon cycle and soil biological activity reducing amount of nutrient mineralized from organic matter (NAWAZ et al., 2013), which also decreases crop grain yield (MOALEMI ORE & KARPARVARFARD, 2008; BOTTA et al., 2010; GUBIANI et al., 2018). SICZEK & LIPIEC (2011) reported decreases in nodulation and in nitrogen fixation in soybean plants due to compaction, but the use of mulching with crop residues attenuated the detrimental effects of soil compaction.

Soybean crops have been grown in the state of Rio Grande do Sul, Brazil, in rotation with irrigated rice in lowlands. These soils have different dynamics and characteristics when compared to well-drained highlands. Most lowland soils have unfavorable physical characteristics to soybean crops, such as excessive soil compaction, flat relief with drainage deficiency and poor aeration. Additionally, lowland are most susceptible to compaction because remain more wet because deficiency drainage, and the clay type with greater activity and cohesion, sticky when wet and very hard when dry, compared to soil well-drained highlands traditionally used for soybean cultivation. BEUTLER et al. (2014) reported that flooded soil for 16 days at soybean reproductive stage resulted in a decrease of up to 29% in grain yield. In this context, the use of cover crops, like black oats, improves the soil structure and superficial straw reduce water evaporation when water deficit occurs, mainly in soybean reproductive stage when water demand is greater and water deficit is common.

The objective was to evaluate the effect of soil compaction and amounts of black oat residues on the soil surface in soybean growth and grain yield in lowland under no-tillage system.

## MATERIALS AND METHODS

The experiment was conducted in the 2016/2017 and 2017/2018 crop seasons at the geographic coordinates 29°09’09’’ S and 56°33’03’’ W, at 64 m altitude. The soil was classified as Typic Ultisol, medium texture, presenting granulometric composition (g $kg^{-1}$) of 197 clay, 269 silt and 534 sand. The area had a 0.5% slope. The climate of the region is Cfa, humid subtropical with no defined dry season, and hot summers (PEEL et al., 2007).

The experimental design was completely randomized with seven treatments and four replications, consisting of plots of 2.7 × 4.0 m. The treatments consisted of: 1) winter fallow with weed control without soil compaction (WF); 2) winter fallow with weed control and soil compaction (WF-C); 3) black oats and complete removal of surface residues, with soil compaction (0R-C); 4) black oats and removal of half of surface residues, with soil compaction (0.5R-C); 5) black oats without surface residue removal, with soil compaction (1R-C); 6) black oats without surface residue removal, plus the residues from treatment 3, with soil compaction (2R-C); 7) black oats without surface residue removal, without soil compaction (1R).

The area consisted of a native field, which was limed, chiseling at 0-0.20 m depth, and leveled in September 2015 and remained in fallow. The soil chemical analysis in the 0-0.20 m layer in March 2016 presented: pH $H_2O$ of 5.9, 6.0 mg $dm^{-3}$ of P; 0.072 of K, 3.9 of Ca, 1.6 of Mg; 0.0 of Al ($cmol_c$ $dm^{-3}$); base saturation of 73.4%; 1.3% of organic matter. The organic matter content was determined by the Walkley-Black method; the extractable P by Mehlich-1; pH $H_2O$ in a soil:water solution (1:1); and K, Ca, Mg, and Al as described in TEDESCO et al. (1995).

In May 2016 and 2017, herbicide was applied for weed control and the black oat seeds were sowed in rows spaced 0.17 m apart, using 80 kg $ha^{-1}$ of seeds in all treatments . Soil fertilization consisted of 300 kg $ha^{-1}$ of N-P-K fertilizer (5-20-20); and 100 kg $ha^{-1}$ of urea was applied as coverage in all treatments. It was sown throughout all area to equalize the amount of fertilizer in all treatments. In the winter fallow treatments, herbicide was applied at 20 days to kill weed and black oat plants, and at 90 days to control weed plants.

In October, the black oats were cut at 0.03 m from the soil surface to adjust the amounts of residues in the treatments. The shoot dry matter was 8 Mg $ha^{-1}$ in 2016 and 7 Mg $ha^{-1}$ in 2017, with 1.0% N in dry biomass. Soil compaction in treatments 2 to 6 was carried out after the amounts of residues were established, on 11/07/2016, using a tractor with weight of 11 Mg and four same width and pressure tires for one side-by-side passing over the entire soil surface, twice; the soil water content was at field capacity. The compaction was performed only at the 2016 year.

In the first half of November, soybean seeds of the cultivars Bmx Magna RR (2016) and NS 6601 IPRO (2017) were treated, inoculated, and sown in all plots, using a fertilizer sowing-machine with shank furrower; the sowing rows were spaced 0.45 m apart, with 16 seeds per meter, and were arranged transversally to the soil compaction. The soil was fertilized according to recommendations of the CQFS (2016). Drains were made on the sides of the experimental plots to remove excess water since the area had a flat relief, groundwater near the soil surface, and slow drainage.

In February 2017 and 2018, when the soybean plants were at the R2 stage, 28 samples were taken with a 0.3 × 0.3 × 0.15 m deep metal box, placing the soybean row in the center of the square, with 4 to 5 plants. These samples were used to evaluate the nodule, root dry matter, and nitrogen contents in the shoot dry matter. Nitrogen was determined using two sub-determinations in laboratory by the Kjeldahl method. The plant heights on 0.5 linear meters and shoot dry matter on 0.25 $m^2$ were also evaluated. The 100-grain weight and grain yield of the plants were evaluated after harvesting in areas of 6 $m^2$ per plot in 2018; in 2017 grain yield was not evaluated due to intense and sudden attack of soy bugs from adjacent areas that decimated the experiment in few days in grain filled phase. The grain moisture was adjusted to 13%. It was not possible to evaluate the soybean grain yield in the first crop season.

The soil physical analysis was carried out using a completely randomized design, in a 7 × 3 factorial arrangement consisting of seven treatments and three depths, with six replications.

In December 2016 and 2017, soil cylinders with height of 0.03 m and diameter of 0.05 m were collected in the 0.0-0.05, 0.10-0.15, and 0.20-0.25 m soil layers, between the soybean rows. The soil cylinders were placed in a tray containing 0.02 m water depth for 24 h for saturation by capillarity, weighed, and subjected to 0.006 MPa stress in Richard pressure chambers for microporosity determination (FLINT & FLINT, 2002). Soil dry weight and bulk density (BD) were determined after 24 h in an oven at 105 °C. Total porosity was determined according to FLINT & FLINT (2002), and macroporosity by the difference between total porosity and microporosity.

The maximum BD was determined by the Proctor test, with reuse of material from deformed samples collected in the 0.0-0.20 m soil layer and passed through a 0.04 m mesh sieve; the Proctor test was performed by three soil layers added to a cylinder, each receiving 25 socket stroke of 2.5 kg failing from 0.3 m height, corresponding to compaction energy of 60.2 kJ $m^{-3}$; the maximum bulk density was 1.90 g $cm^{-3}$, and the optimum moisture of compaction was 12.4%. The bulk relative density (BDr) was evaluated, which consisted of dividing the BD found by the maximum BD.

The results were subjected to analysis of variance and, when the results were significant, the Scott-Knott test at 5% probability of error was applied to compare the means.

## RESULTS AND DISCUSSION

In the 2016/2017 crop season, rainfall was more regular, and there was excess water in the first half of January and February (Figure 1A). This left the soil with high water content, and close to saturation for several days, since the soil presents flat relief, groundwater near the soil surface, and slow drainage. In the 2017/2018 crop season, there were periods with little rainfall (Figure 1B) causing a water deficit in the soil, especially in February and early March (25 days), which is a critical period for soybean grain filling.

The interaction between treatments and soil layers was not significant for the soil physical properties. BD was higher in treatments with additional soil compaction, regardless of the amount of black oat residues on soil surface, in the 2016/2017 crop season (Table 1).

However, in the 2017/2018 crop season, the 2R-C treatment presented equal BD to the non-compacted treatments, denoting the positive effects of large amounts of black oat residues (16 and 14 Mg $ha^{-1}$ straw in 2016/17 and 2017/18, respectively) on soil restructuration and BD reduction, since in the second year was not additional compaction. Considering the differences between treatments 1R-C and 1R, the two years of black oat and soybean crops in no-tillage system (NT) were not enough to restructure the soil and reduce BD in 1R-C, nor increase BD in 1R. According to GUBIANI et al. (2018), tillage reduces BD and increases porosity in the soil surface layer; according to SILVA et al. (2012), this effect decreases over time and remains less than a year because of the restructuring and natural densification of the soil.

This explains why BD of the treatment 1R did not increase: the soil was subsoiled and harrowed in 2015, which was one year before starting the experiment in NT with and without additional machinery traffic. In the treatment 1R-C, the soil compaction and higher BD due to additional machinery traffic were not attenuated throughout

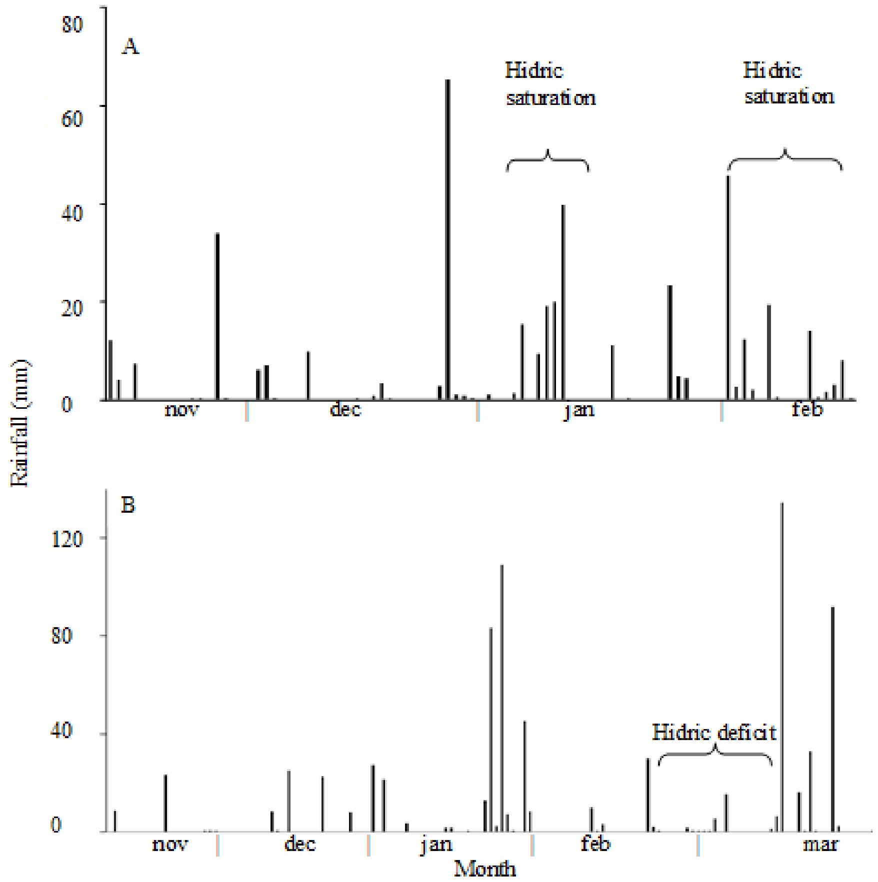


Figure 1 - Rainfall in 2016/17 (A) and 2017/18 (B) (Geas/Unipampa/Campus Itaqui/Brazil).

the two years of crops with inclusion of only black oats in winter.

BD was lower in the 0-0.05 m layer than in the 0.10-0.15 and 0.20-0.25 m soil layers in all treatments, possibly because of the decompaction effect of the furrower of the fertilizer seeder in the two annual seeding operations in this layer, increasing total porosity and macro or microporosity. Moreover, high BD values were reported in the 0.10-0.15 and 0.20-0.25 m layers, considering that the soil had 20% clay, resulting in relative bulk density (BDr) above 0.90. The BDr above 0.90, combined with excess water in the 2016/2017 crop season, resulted in lower plant heights and shoot dry matter (Table 2). In the 2017/2018 crop season, which presented water deficit, BDr up to 0.92 resulted in higher soybean grain yield, which was more related to amount of black oat residues on the soil surface than to soil compaction. SANTOS et al. (2019) found in clayey Oxisol under NT for 15 years that chiseling and descompaction did not increase soybean grain yield in years with good rain distribution.

In the 2016/2017 crop season, the plant height and soybean shoot dry matter were more than 22% higher in the treatments WF and 1R, which had no additional compaction by machinery traffic (Table 2). Shoot dry matter is directly related to grain filling. The treatments WF and 1R would probably have higher grain yield, considering the relation between shoot dry weight and grain yield, when comparing treatments with the same cultivar. This was reported in the 2017/2018 crop season, with correlation of 0.88 between shoot dry matter and grain yield. GUBIANI et al. (2018) reported a correlation of 0.97 between shoot dry matter and grain yield of soybean plants grown in lowlands soils with drainage problems.

The soybean shoot dry matter is dependent on plant height, which is a genetic trait and may

Table 1 - Bulk density (BD), relative bulk density (BDr), total porosity, macro and microporosity in treatments and layers in December of 2016 and 2017.

| Treatments | Bulk density | BDr | Total porosity | Macroporosity | Microporosity |
|---|---|---|---|---|---|
| | (g cm$^{-3}$) | | ------------------------------(cm$^3$ cm$^{-3}$)------------------------------ | | |
| ------------------------------2016/17------------------------------ | | | | | |
| WF | 1.71 b | 0.90 | 0.39 a | 0.11 a | 0.27 b |
| WF-C | 1.77 a | 0.93 | 0.37 b | 0.09 b | 0.27 b |
| 0R-C | 1.77 a | 0.93 | 0.36 b | 0.09 b | 0.27 b |
| 0.5R-C | 1.80 a | 0.95 | 0.35 b | 0.07 c | 0.28 a |
| 1R-C | 1.77 a | 0.93 | 0.35 b | 0.07 c | 0.28 a |
| 2R-C | 1.75 a | 0.92 | 0.36 b | 0.07 c | 0.29 a |
| 1R | 1.69 b | 0.89 | 0.37 b | 0.08 b | 0.29 a |
| ------------------------------Layers (m)------------------------------ | | | | | |
| 0-0.05 | 1.70 b | 0.89 | 0.38 a | 0.09 a | 0.29 a |
| 0.10-0.15 | 1.78 a | 0.94 | 0.36 b | 0.08 a | 0.28 b |
| 0.20-0.25 | 1.78 a | 0.94 | 0.36 b | 0.09 a | 0.27 b |
| ------------------------------2017/18------------------------------ | | | | | |
| WF | 1.72 b | 0.91 | 0.37 b | 0.10 a | 0.28 d |
| WF-C | 1.73 a | 0.91 | 0.37 b | 0.10 a | 0.27 d |
| 0R-C | 1.77 a | 0.93 | 0.35 b | 0.07 b | 0.29 c |
| 0.5R-C | 1.76 a | 0.93 | 0.36 b | 0.08 b | 0.28 d |
| 1R-C | 1.75 a | 0.92 | 0.37 b | 0.08 b | 0.29 c |
| 2R-C | 1.72 b | 0.91 | 0.38 b | 0.07 b | 0.30 b |
| 1R | 1.68 b | 0.88 | 0.41 a | 0.08 b | 0.32 a |
| ------------------------------Layers (m)------------------------------ | | | | | |
| 0-0.05 | 1.68 b | 0.88 | 0.39 a | 0.10 a | 0.29 a |
| 0.10-0.15 | 1.75 a | 0.92 | 0.37 b | 0.07 b | 0.30 a |
| 0.20-0.25 | 1.76 a | 0.93 | 0.36 b | 0.07 b | 0.28 b |

Averages followed by lowercase letters in the column not differ from one another (Scott-Knott test, P≤0.05). There was no interaction treatment x layer. Winter fallow without soil compaction (WF); winter fallow with soil compaction (WF-C); black oats and complete removal of surface residues, with soil compaction (0R-C); black oats and removal of half of surface residues, with soil compaction (0.5R-C); black oats without surface residue removal, with soil compaction (1R-C); black oats without surface residue removal, plus the residues from treatment 3, with soil compaction (2R-C); black oats without surface residue removal, without soil compaction (1R).

vary according to edaphoclimatic conditions and cultural practices (TORRES et al., 2015). The excess rainfall in the first half of January and February 2017 hindered the soybean plant growth in treatments with additional soil compaction, which presented higher BD; this considering that the plants were grown in a soil with flat relief, groundwater near the soil surface, and low total porosity and macroporosity, which are responsible for drainage and aeration. Similar results were found by GUBIANI et al. (2018), who reported that the soybean plants grown in compacted soil under NT had lower shoot dry weight and grain yield than those grown in less compacted soils under conventional tillage system, in a year with frequent rainfall, in lowlands. The authors attributed this result to oxygen deficit in the NT due to the slow drainage of this soil. Soil compaction results in low plant growth by reducing soil aeration and water and nutrient absorption from the soil (CALONEGO et al., 2011). According to SCHÖFFEL et al. (2001), lowlands are characterized by poor drainage and, in times of frequent rainfall, their soil saturation is rapidly reached, which may cause negative effects on plant growth because of the stress caused by water saturation. Thus, soil compaction, combined with soil water saturation, reduces oxygen availability to the roots, impairing their growth and activity.

The 2016/2017 crop season presented a higher root dry matter in the WF-C treatment, in the 0-0.15 m soil layer; this was probably a response to soil compaction to supply the plant needs for water, air, and nutrients. This root dry matter in WF-C in

0-0.15 m layer possibly occurred due the absence of plants in winter because they were controlled with herbicides compared to others compacted treatments where oat was cultivated; this because oats roots create biopores and galleries in soil, which remain after roots decomposition allowing greater soybean roots growth in depth by galleries and improving soil structure, although it was not enough to reduce soil density; there is also additional effect of oat straw on soil surface that keeps soil more wet and reduce resistance to root growth in depth.

According to MOALEMI ORE & KARPARVARFARD (2008), soil compaction prevents the passage of roots, which compensates this effect by lateral expansion of roots through points of lower soil resistance; this possibly occurred in the treatment WF-C, which had additional compaction and no plant residues on the soil surface. The nodule dry weight and nitrogen content in the shoot dry matter were not affected by soil compaction and amount of black oat residues on the soil surface.

In the 2016/2017 crop season, which presented excess rainfall, black oat residues on the soil surface had no effect on the soybean plant growth, but the additional soil compaction was harmful. In the 2017/2018 crop season, differences in plant height and shoot dry matter between treatments were smaller compared to the previous crop season; treatments with higher shoot dry matter had higher grain yields, with a correlation of 0.88 (Table 2).

In the 2017/2018 crop season, which presented a 25-day water deficit in late February and early March, the results were opposite when compared to the previous crop. The amount of black oat residues on the soil surface presented benefits, and the additional soil compaction had little effect on the variables. Thus, treatments with plant residues on the soil surface > 7 Mg $ha^{-1}$ (1R-C, 2R-C, and 1R) presented higher soybean grain yield than those without plant residues (WF, WF-C, 0R-C) or with half of the black oat residues (0.5R-C) on the soil surface. Grain yield was 9% higher in the treatment 1R compared to WF due to the growth of black oat and its residues on the soil. This occurred probably because the residues on the soil surface formed a physical barrier, reducing the soil temperature and

Table 2 - Plant height, shoot dry matter, roots and nodules, and nitrogen in shoot dry matter of soybean in full flowering (R2), in 2016/17/18, and more grain yield and mass of 100 grains in 2017/18.

| Treatments | Plant height | Shoot dry matter | Root dry matter | Root nodules | Nitrogen in dry matter | Grain yield | Mass of 100 grain |
|---|---|---|---|---|---|---|---|
| | (cm) | (Mg $ha^{-1}$) | --------(g) (0.30x0.30x0.15 m)------- | | (%) | (Mg $ha^{-1}$) | (g) |
| -----2016/17----- | | | | | | | |
| WF | 102 a | 10,315 a | 24 b | 6.7 $^{ns}$ | 2.4 $^{ns}$ | - | - |
| WF-C | 68 c | 5,201 b | 34 a | 4.4 | 2.3 | - | - |
| 0R-C | 63 d | 5,728 b | 21 b | 6.0 | 2.8 | | |
| 0.5R-C | 69 c | 5,978 b | 20 b | 5.8 | 2.5 | - | - |
| 1R-C | 80 b | 7,046 b | 19 b | 7.1 | 2.9 | - | - |
| 2R-C | 75 b | 6,499 b | 19 b | 5.4 | 3.0 | - | - |
| 1R | 110 a | 9,711 a | 22 b | 6.6 | 2.5 | - | - |
| -----2017/18----- | | | | | | | |
| WF | 101 a | 6,197 b | 18 a | 3.0 b | 3.0 a | 2,976 b | 14.4$^{ns}$ |
| WF-C | 97 a | 6,420 b | 21 a | 3.6 b | 2.9 a | 2,753 b | 14.7 |
| 0R-C | 85 c | 5,402 b | 18 a | 4.0 a | 3.0 a | 2,731 b | 15.1 |
| 0.5R-C | 89 b | 5,620 b | 19 a | 4.1 a | 3.0 a | 2,873 b | 15.0 |
| 1R-C | 97 a | 7,499 a | 20 a | 4.5 a | 2.8 a | 3,234 a | 14.4 |
| 2R-C | 98 a | 6,753 a | 16 b | 4.4 a | 2.8 a | 3,097 a | 14.7 |
| 1R | 100 a | 7,411 a | 16 b | 3.4 b | 2.4 b | 3,251 a | 14.4 |

Averages followed by lowercase letters in column not differ from one another (Scott-Knott test, $P \leq 0.05$). $^{ns}$Not significant. – Not determined. Winter fallow without soil compaction (WF); winter fallow with soil compaction (WF-C); black oats and complete removal of surface residues, with soil compaction (0R-C); black oats and removal of half of surface residues, with soil compaction (0.5R-C); black oats without surface residue removal, with soil compaction (1R-C); black oats without surface residue removal, plus the residues from treatment 3, with soil compaction (2R-C); black oats without surface residue removal, without soil compaction (1R).

water evaporation and; consequently, allowing a higher soil water content when compared to the treatments without residues. According to RIBEIRO et al. (2016), a cohesive soil managed in NT with millet mulch residues and soybean crops has higher moisture compared to that in conventional tillage. ROSIM et al. (2012) found higher soil water content in the 0-0.10, 0.10-0.20 and 0.20-0.30 m layers with the use of 5 and 10 Mg $ha^{-1}$ of millet residues on the soil surface when compared to soils without residues.

Moreover, BALBINOT JUNIOR et al. (2017) evaluated a Typic Hapludox and found that the use of residues of *Brachiaria* sp. on the soil surface did not present higher soybean grain yield compared to fallow soil; however, the treatment with root system plus surface residues or with root system without residues of the aerial part provided soybean grain yields 22% higher than the fallow area. This indicated that the root system of cover crops can increase soybean grain yield, probably due to biopores and galleries remained in soil after roots decomposition enabling better soybean roots growth in depth, nutrient recycling, by relocating nutrients back to the topsoil, or even by increasing P availability in the soil layers explored by soybean roots.

Therefore, in addition to these benefits—higher water availability and lower thermal amplitude—to soils, the use of black oat can improve nutrient cycling and availability. According to CAIRES et al. (2006), the use of black oat as cover crop increases N and P contents in the shoot dry matter of soybean plants grown in the following crop season.

Comparing NT with soil compaction to NT without soil compaction (1R-C × 1R), soybean grain yield presented no differences, indicating that the additional soil compaction was not the limiting factor in the 2017/2018 crop season. This possibly occurred because the additional compaction occurred more than a year ago and resulting in small variations in the soil physical properties (BD, total porosity and macroporosity) between the two treatments in 2017/18 soybean cultivation; yet, all oat straw remained on soil surface reducing surface temperature and water evaporation, mitigating the effect of the water deficit occurred in February 2018, soybean grain filling period. In addition, it appears that soybean yield was close to 3 Mg $ha^{-1}$ indicating that the water deficit was small.

## CONCLUSION

In lowland, the soybean crop presented 22% higher plant height and shoot dry matter in the treatments without additional soil compaction in the 2016/2017 crop season, when excessive rain occurred, regardless of the amount of black oat residues on the soil surface. In the 2017/2018 crop season, when water deficit occurred, the highest shoot dry matter and soybean grain yield were reported in treatments with use of black oat residues on the soil surface, regardless of soil compaction.

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## DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

## AUTHORS' CONTRIBUTIONS

All authors contributed equally to the design and writing of the manuscript. All authors critically reviewed the manuscript and approved the final version.

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