Mitigation of soil compaction for boosting crops productivity at varying yield environments in Southern Brazil

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Summary

Soil compaction is one of the most relevant crop yield-limiting factors in no-till (NT) farming systems in Southern Brazil. This study aimed to identify strategies to mitigate soil compaction and increase crops productivity at low, medium and high yield environments within a field. Treatments evaluated were: control (without intervention), PG - phosphogypsum, MC - mechanical chiseling, PCC - polyculture of cover crops, MC+PG, PCC+PG, MC+PCC and MC+PCC+PG. Soil macroporosity, bulk density, penetration resistance, soybean yield (*Glycine max* L.) and black oat (*Avena strigosa* Schreb) biomass production. In the low and medium yield environments, MC+PCC+PG promoted the highest soybean yields: 5,455 kg ha^{-1} and 5,534 kg ha^{-1}, respectively. In the high yield environment, PCC+PG promoted the highest soybean yield (5,579 kg ha^{-1}), while MC decreased yields relative to the control. Black oat biomass production responded to the treatments similarly to soybean yields. Overall, integrating two or three decompaction strategies improved soil physical attributes in a greater proportion relative to single strategies and to the control, enhancing both soybean and oat performances. Selection of the right decompaction strategies for each yield environment might help increase productivity under NT and optimize the use of time, labor, fuel and other resources.

Keywords: Chiseling, phosphogypsum, polyculture of cover crops, soil quality.

Highlights

- Soil compaction limits crop yields under no-tillage farming in Southern Brazil.
- Low, medium and high yield environments were delineated with precision agriculture tools.
- Single or integrated mechanical, chemical and biological soil decompaction strategies were tested.
- Soil decompaction strategies to increase soybean yields are specific to yield environments.

Introduction

Agricultural intensification is key to overcoming global, growing demands for food production, but especial attention must be given to the dramatic increase in machinery weight and traffic for rapid crop establishment (Tullberg *et al*., 2007; Trein *et al*., 2009; Reichert *et al*., 2016) and to the depletion of soil organic matter (SOM) due to insufficient biomass input to the soil, aggravating soil compaction in croplands. In soils without or with minimal, mechanical soil disturbance this problem can persist for the long-term (Wingeyer *et al*., 2015; Sivarajan, *et al*., 2018).

In agricultural soils, natural processes of soil particles cementation or external pressures from machineries or animals may promote soil compaction (Hamza & Anderson, 2005; Reichert *et al*., 2016). Soil compaction negatively impacts soil water flow (Batey & Mckenzie, 2006; Birkás, 2008; McHugh *et al*., 2009) and root growth and distribution along the soil profile (Beutler & Centurion, 2004). These effects limit crop water and nutrients foraging capacity and resilience, leading to yield shortfalls (Wells *et al*., 2005; Queiroz *et al*., 2011; Abdollahi & Munkholm, 2014; Calonego *et al*., 2017; Sivarajan *et al*., 2018) especially under abiotic stress circumstances (e.g. drought), as commonly observed for soybean and corn in Southern Brazil (Dalla Nora & Amado, 2013; Hansel *et al*., 2017).

Soil bulk density and porosity evaluations can indicate soil compaction levels (Secco *et al*., 2004; Beutler & Centurion, 2004; Hamza & Anderson, 2005; Batey, 2009). Soil penetration resistance (PR) has been also utilized to assess soil compaction (Silva *et al*., 2003; Bayat *et al*., 2017; Colombi *et al*., 2018). Restrictive PR values for soybean growth in Oxisols have been reported by many authors. Secco *et al*. (2004) observed critical PR values ranging from 2,650 to 3,260 kPa, with a soybean yield penalty of 24%. These data agree with the findings of Beutler & Centurion (2004) and Hamza & Anderson (2005). The authors reported that PR values of 2,240 kPa or higher decreased soybean yields by 32%. The depth of compaction in no-till (NT) areas is generally observed between 0.08 and 0.15 m (Reichert *et al*., 2007; Sivarajan *et al*., 2018), varying with the specifications of the machine, soil conditions, number of times the soil is trafficked and history of pressures (Reichert *et al*., 2007). In this way, soil compaction conditions can vary broadly within small environments, frequently resulting in heterogenic plant vigor and grain yields in the same cropland (Alaoui & Diserens, 2018).

The heterogeneity of variable yields within field areas has been considered within the concept of ‘yield environments’. Yield environments are defined as subfield regions representing more homogenous attributions in landscape and soil conditions (Yan *et al*., 2007). The definition of yield environment, utilizing the spatial management tools of precision agriculture, has been proposed as a cost-effective approach to improve crop management (Franzen *et al*., 2002; Yan *et al*., 2007). Within a yield environment, the variation of yield potential, input use efficiency and environmental impact should be lower than between yield environments (Schepers *et al*., 2004).

There are multiple information sources that could be used to define yield environments. However, previous yield maps and apparent soil electrical conductivity (EC) data are the most used (Sudduth *et al*., 1995; Peralta & Costa, 2013). The EC reflects the cumulative variability in multiple soil properties, which is one criterion for defining yield environments (Sudduth *et al*., 1995). In low yield environments, poor crop performance over the years results in lower biomass input to the soil and low SOM contents and biological activity, resulting in a poor functionality of the system (Conceição *et al*., 2005; Amado & Santi, 2011). On the other hand, in high yield environments the excellence of crop performance drives a higher level of organization and functionality of the system (Doran & Parkin, 1994; Angers & Caron, 1998; Vezzani & Mielniczuk, 2009; Nicolodi & Gianello, 2015). Thus, field sites with different yield environments may require specific soil management strategies aiming to mitigate soil compaction, optimize overall resources use and increase and equalize crop yields.

Mechanical (Calonego & Rosolem, 2010; Nunes *et al*., 2014; Nunes *et al*., 2015), chemical (Dalla Nora & Amado, 2013; Dalla Nora *et al*., 2017; Hansel *et al*., 2017) and biological (Cubilla *et al*., 2002; Calonego *et al*., 2017; Colombi *et al*., 2017) interventions can alleviate soil compaction. Generally, mechanical interventions are more efficient to alleviate soil compaction in the short-term (Nicoloso *et al*., 2008; Calonego *et al*., 2017), but at the medium- and long-term the effectiveness of mechanical interventions has been controversial (Nunes *et al*., 2014; Calonego *et al.*, 2017; Daigh *et al*., 2018). The root system of cover crops, single or intercropped, can alleviate soil compacted layers (Williams & Weil, 2004; Foloni *et al*., 2006; Reichert *et al*., 2007). Cultivation of cover crops can improve soil surface protection against erosion and increase carbon allocation at surface and subsurface soil depths (Ferreira *et al*., 2018; Nicoloso *et al*., 2018). Combination of phosphogypsum and lime has also been proposed as a strategy to alleviate subsoil acidity without the need for soil mechanical disturbance (Shainberg *et al*., 1989; Summer, 1995; Rosolem & Marcello, 1998; Uusitalo *et al*., 2012; Walia & Dick, 2019) in North America and in Brazil (Caires *et al*., 2005; Caires *et al*., 2006; Caires *et al*., 2008; Dalla Nora *et al*., 2014; Dalla Nora *et al*., 2017).

Studies dedicated to investigating integrated soil decompaction methods in agriculture under NT management systems regarding different yield environments are scarce, but greatly needed to boost agriculture intensification within a sustainable Conservation Agriculture concept (Ferreira *et al*., 2013; Kassam *et al*., 2018). Therefore, the objective of this study was to identify the response of soil physical attributes and crop productivity (soybean (*Glycine max* L.) yield and black oat (*Avena strigosa* Schreb) biomass) to single or integrated strategies to mitigate soil compaction, such as mechanical chiseling, phosphogypsum and polyculture of cover crops, at varying yield environments under long-term NT system in Southern Brazil.

Material and methods

Site description, environmental conditions, and experimental design

The study site was 124 ha cropland, located at Não-Me-Toque city, Rio Grande do Sul state, Southern Brazil, with geographic coordinates 28° 28' S, 52° 47' W, 500 m a.s.l. The climate is classified as Cfa (humid subtropical) (Alvares *et al*., 2013). The average annual temperature and precipitation are 18.7°C and 1680 mm, respectively. The soil is clayey, kaolinitic and classified as a Rhodic Hapludox (Soil Survey Staff, 2014). The cropland has been managed under NT system since 2002 and monitored over the last decade in order to define yield environments (www.ufsm.br/projetoaquarius) and yield limiting factors (Amado & Santi, 2011). The yield environments were defined by aggregating past soybean and corn yield maps and apparent EC data evaluated with Veris CE® (Stara, Não-Me-Toque, Brazil). The Veris uses rolling coulter electrodes to directly sense soil electrical conductivity (Sudduth *et al*., 2005). The measure was collected at 3rd of June, 2015, when the soil moisture content was close to point of friability. These geospatial information (Figure 1A) were used to create classes and to delineate three yield environments: low (LYE), medium (MYE), and high (HYE) (Figure 1B) using the fuzzy k-means method. Fuzzy k-means uses an iterative procedure that starts with an initial random allocation of the objects to be classified to k clusters. Firstly, k initial centroids are selected, where k is specified by the user and indicates the desired number of clusters. Every point in the field data is then assigned to the closest centroid, and each collection of points assigned to a centroid form a cluster. This process is repeated until no point changes clusters (Bezdek, 1981).

Before the application of the experimental treatments, soil physical and chemical attributes were evaluated to characterize the yield environments. Soil bulk density, macroporosity and soil PR were evaluated down to 0.35 m by sampling 30 points in each yield environment. Steel cylinders were used to collect undisturbed soil samples, and soil macroporosity and bulk density were determined in four replicates. The samples were saturated through capillarity and balanced on a tension table at -6 kPa for 48h to calculate macroporosity. Thereafter, the samples were dried in oven at 105ºC for 24 h and the soil bulk density was calculated. Also, the soil PR was measured (15 replicates) using a SoloStar® penetrometer (Falker, Porto Alegre, Brazil) with readings of 0.01m. Cone type 2 with size of 12.83 mm was used with a nominal insertion velocity of the rod of 35mm s^{-1}. The evaluations were performed when the soil moisture was near 18%. Soil samples were collected at 0-to-0.20 m soil depth to evaluate the soil chemical attributes of the yield environments, as soil pH (in H_2O), clay content, soil organic matter (SOM), exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), sulphate (SO_4^{-2}) and aluminum (Al^{3+}), available phosphorus (P) and potassium (K^+) contents, and soil base saturation (BS, %), which was calculated as: (100[(Ca^{2+} + Mg^{2+} + K^+)/CEC at pH 7.0]), where CEC is the soil exchange capacity. The soil chemical attributes were determined according to the standard methods described in Tedesco *et al*. (1995). Soil physical and chemical attributes of the yield environments are shown in Figure 2 and Table 1, respectively.

The study was conducted in a randomized block design, with a 3 x 8 factorial arrangement, with three replications. The factors were: yield environment (LYE, MYE and HYE) and eight treatments for soil decompaction treatments. The treatments consisted of: control (no intervention); chemical intervention (phosphogypsum ($CaSO_4$)) (PG); mechanical physical intervention (chiseling up to 0.30 m soil depth) (MC); biological intervention (polyculture of cover crops) (PCC); integrated mechanical physical and chemical interventions (mechanical chiseling + phosphogypsum) (MC+PG,); integrated biological and chemical interventions (polyculture of cover crops + phosphogypsum) (PCC+PG); integrated mechanical physical and biological interventions (mechanical chiseling + polyculture of cover crops) (MC+PCC); and fully integrated mechanical, chemical and biological interventions (mechanical chiseling + polyculture of cover crops + phosphogypsum) (MC+PCC+PG).

Each experimental unit was 30 x 60 m, totaling 4.32 ha of the experimental area (Figure 1B). Mechanical chiseling was performed using a chisel with seven rippers FOX KS® (Stara, Não-Me-Toque, Brazil) working up to 0.30 m depth, when the soil moisture content was close to point of friability. The polyculture of cover crops consisted of 30 kg ha^{-1} of equal proportion of: garden pea (*Pisum sativum* (L.)), radish oil (*Raphanus sativus* (L.)), black oat (*Avena strigosa* (Schreb.)) and rye ((*Secale cereale* (L.)). Broadcast phosphogypsum application was carried out with the spreader HERCULES 15000® (Stara, Não-Me-Toque, Brazil) previously to the cover crop sowing operation. Cover crops seeding was performed simultaneously to the chiseling tillage (at one operation) using a seed container coupled to the chisel. The cover crops were killed using a knockdown herbicide followed by knife-roller operation, inputting around 3,100 kg ha^{-1} of dry matter to the soil (collecting the plants residues within a 1 by 1 m square and dried in a forced air oven at 60 ºC for 48h). The soybean was sown at 1st of November, 2017. The cultivar used was Ativa® (GDM Seeds, Cambé, Brazil), maturity group = 5.6. Mean plant density per hectare was 330 thousand plants. Basal row fertilization was performed applying 125 kg ha^{-1} of 10-45-00 (N-P-K) formula. Potassium (K) was applied by broadcasting potassium chloride (KCl) (140 kg ha^{-1}) as the fertilizer source.

Physical and chemical soil analyses

Undisturbed soil samples were collected after chemical desiccation of the cover crops (before soybean planting) using a 2.5 cm high and 5 cm internal diameter cylinder, to determine soil bulk density and macroporosity. Samples were taken at the following depths: 0.00 – 0.05, 0.05 – 0.10, 0.10 – 0.20, 0.20 – 0.30 and 0.30 – 0.40 m using a steel support to force the volumetric ring into the soil.

The soil PR was evaluated (15 replicates per treatment) before soybean sowing time. Measurements were taken up to 0.35 m depth using the SoloStar® penetrometer. At the time of soil PR evaluations, soil samples were collected to determine soil moisture content. In addition, disturbed soil samples were collected at the 0-to-0.20 m soil depth to analyze soil pH (in H_2O), clay, SOM (sulphromic solution with external heat and spectrophotometric determination of Cr^{+3}), exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} (extracted by 1 mol L^{-1} KCl solution) and SO_4^{-2} (extracted by calcium phosphate, barium chloride gelatine and determined by turbidimetry); available P and K^+ (extracted by Mehlich-1) contents and soil BS (%).

Crop productivity

Soybean yield was estimated using an infrared harvesting sensor (Stara APS®), installed in a mechanical harvester Case 8120 (Case, Assis, Brazil). Yields were adjusted to 13% seed moisture content. Black oat was sown on April 10th, 2018. Mean plant density was 330 seeds m^{-2}. Basal row fertilization was performed applying 70 kg ha^{-1} of 10-20-20 (N-P-K) formula. Black oat biomass production was evaluated (four replicates) at flowering stage by collecting the plants within a 1 by 1 m square. The plant samples were dried in a forced air oven at 60 ºC for 48 h and the dry matter was determined.

Statistics

The data was subjected to analysis of variance (ANOVA, F test, $p< 0.05$) and the means of the treatments were compared by Tukey test ($p<0.05$). The treatments were considered as fixed effect and replication or blocks as random effect for all the variables. Each yield environment was analyzed independently. All statistical analyses were carried out using the R program (R Core Team, 2019).

Results

Soil physical attributes affected by decompaction strategies

Soil macroporosity and bulk density were responsive to the treatments at in the different yield environments, mainly due to MC as single intervention or in combination with other soil decompaction strategies (MC+PG, MC+PCC, MC+PCC+PG). In general, MC increased soil macroporosity and decreased soil bulk density up to 0.15 m depth relative to the control, regardless of the yield environment (Figure 3). The effect of PG and PCC as single interventions in both LYE and MYE were not significantly different from the control regarding soil macroporosity and bulk density (Figures 3A and 3B). In the HYE, PCC increased soil macroporosity and decreased soil bulk density relative to the control within 0 - 0.15 m soil depth (Figure 3C). This result is associated to the fact that initial soil macroporosity and bulk density in the HYE were not limiting to plant growth, thus the plants subjected to PCC treatments were able to grow roots improving soil attributes. In general, the integration of MC+PG or MC+PCC and MC+PCC+PG tended to increase soil macroporosity and decrease soil bulk density compared to the control and to the single decompaction strategies. The PCC+PG treatment promoted intermediate soil macroporosity and soil bulk density values (up to 0.15 m soil depth), between the control and treatments with MC combined with other decompaction strategies.

The PR decreased up to 0.30 m soil depth when the MC intervention was used in single operation or combined with other strategies in relation to the control, regardless of the yield environment (Figure 4). The PG in single operation, regardless of the yield environment, did not decrease PR in relation to the control. The combination of PG+PCC promoted intermediate values of PR, between the control and MC treatments, in both MYE and HYE. Similar response was observed for soil macroporosity and bulk density data. For the LYE, the soil PR data in PG+PCC treatment did not differ from the control (Figure 4A). In this case, the initial level of soil degradation and lack of response to non-mechanical interventions in the LYE suggest the need of drastic physical decompaction methods, as MC, in this yield environment.

Soil chemical attributes affected by decompaction strategies

The treatments differed for SOM, SO_4^{-2} and Ca^{+2} contents (Table 2). Similar responses of soil chemical attributes to treatments were observed in the different yield environments. In general, the treatments: MC, MC+PG, MC+PCC, MC+PCC+PG tended to decrease SOM content compared to treatments without MC. Treatments with PG, MC+PG, PCC+PG and MC+PCC+PG) tended to increase soil Ca^{+2} and SO_4^{-2} contents, and BS values.

Soybean yield

Treatment effects on soybean yield were significant and varied according to yield environment. The soybean yield averages in LYE, MYE and HYE were 5,151 kg ha^{-1}, 5,356 kg ha^{-1}, and 5,495 kg ha^{-1} respectively (Figure 5).

All treatments increased soybean yield compared to the control in the LYE, except PG (Figure S1). Treatments can be divided into for four groups in terms of soybean yield average gain (%) compared to the control: first group (MC, PCC and PCC+PG) - 2.4-3.0%; second group (MC+PG) - 4.1%; third group (MC+PCC) - 7.5%; fourth group (MC+PCC+PG) - 9.9%. These results highlight that soybean yield in LYE was very sensitive to the decompaction strategies. The highest soybean yield (5,455 kg ha^{-1}) was obtained in the MC+PCC+PG, which increased yield by about 10% compared to the control (4,960 kg ha^{-1}) (Figure S1). Soybean yields in PCC and PCC+PG, both treatments without MC, were only 3% greater than the control, whereas treatments with MC, single or mainly associate with other methods, promoted the highest soybean yields in LYE.

Similarly to the LYE, in the MYE most of the treatments increased soybean yield compared to the control (5,150 kg ha^{-1}), except MC and PCC (Figure S1). The treatments: PG, MC+PG, PCC+PG, MC+PCC, and MC+PCC+PG promoted soybean yield increases by 4.7 up to 7.4 % relative to the control. The highest yield increments compared to the control occurred in treatments with PG (PG = 5.2%, MC+PG = 4.7%, PCC+PG = 6.3%, and MC+PCC+PG = 7.4%) (Figure S1). Soybean yield increment in MC+PCC relative to the control did not differ from that of PG.

Different from the LYE and MYE, in the HYE most of the treatments increased soybean yields, but yield decrease relative to the control was also observed. Therefore, treatments were separated in three groups: first group (MC) decreased soybean yield by 2.8% (Figure S1); second group (PG, PCC, MC+PCC, MC+PCC+PG) increased soybean yield by 2.9-3.5%; third group (PCC+PG) increased soybean yield by 5.1 %. Overall, these results indicate that soybean yield response to treatments in HYE is less sensitive compared to the other yield environments, and, moreover, that utilization of PCC and PG should be prioritized in place of inappropriate (MC) or less profitable (second group) decompaction interventions. The PCC+PG treatment promoted the highest soybean yield in the HYE, 5.1% greater compared to the control (5,390 kg ha^{-1}) (Figure S1).

Soybean yields in the control were 4,960, 5,160 and 5,390 kg ha^{-1} in LYE, MYE and HYE, respectively (Figure 6). This result evidences the influence of soil attributes status (Table 1, Figure 2) and soybean yields (Figure 1) prior to treatments implementation on soybean yield responses to treatments. Treatments leading to the highest soybean yield increments relative to the control were: LYE - MC+PCC+PG (9.9%); MYE - MC+PCC+PG (7.4%); HYE - MC+PCC (5.1%) (Figure 6). The soybean yield gap between LYE and HYE was reduced from 8.6% to 3% in the first crop season after treatments implementation if treatments cited above for each yield environment are used (Figure 6). Further equalization of soybean yields in yield environments is sought in future crop seasons and might depend on treatments effect consolidation.

Black oat biomass production

In the LYE, same treatments increasing soybean yield (relative to the control), as MC, MC+PG, MC+PCC and MC+PCC+PG, except PCC and PCC+PG, also increased black oat biomass production (Figure S2). Single MC or its combination with other decompaction strategies (MC+PG, MC+PCC, and MC+PCC+PG) promoted the highest black oat biomass production, about 8.8-11.6% greater than the control (Figure S2). The highest black oat biomass production, 11.6% greater than the control, was obtained using the fully integrated treatment (MC+PCC+PG), as observed for soybean yield, which did not differ from MC+PCC, MC+PG and MC. These data suggest that benefits of decompaction interventions persisted up to black oat season even after elapsed fifteen months after the implementation of the treatments. In the MYE, the treatments MC+PCC+PG, MC+PCC and MC promoted the highest increases in black oat biomass production (Figure S2), similar to soybean yield responses (Figure S1). Black oat biomass production increments relative to the control ranged from 6.3 to 9.8%. Treatments with PG promoted the highest values of black oat biomass production, except for MC+PG, which did not differ from the control (Figure S2). In the HYE, the treatments MC and MC+PG reduced black oat biomass production in relation to control by 22% (Figure S2). As previously reported, MC also decreased soybean yield (Figure S1). The other treatments, including the control, did not differ regarding effects on black oat biomass production (Figure S2).

Discussion

The first outcome of this research study highlights that soil decompaction strategies need to be tailored for each different yield environment. At field-level, soil management practices are applied to reduce the yield gap between current and attainable yields (van Ittersum *et al*., 2013; Bunselmeyer & Lauer, 2015). External factors to the soil such as type, intensity and frequency of applied load, as well as soil attributes such as moisture, texture, structure, carbon content, and bulk density may influence soil compaction levels (Collares *et al*., 2008; Oliveira *et al*., 2012; Nawaz *et al*., 2013; Gao *et al*., 2016; Moraes *et al*., 2016).

In our study, every yield environment presented different yield-limiting factors, demanding different soil management strategies for decompaction and for improving overall crops productivity. The characterization of the yield environments prior to treatments implementation showed that the level of organization and functionality of the system in the LYE and MYE was lower compared to that in the HYE. In this way, both the LYE and MYE were more responsive than the HYE to soil decompaction interventions aiming soybean yield gains in this case. The integration of soil decompaction strategies: MC+PCC+PG for LYE and MYE, and PCC+PG for HYE were efficient in restoring the soil physical quality in the short-term (first crop season), and boosted significantly crop productivity, especially in LYE. As soil compaction compromises the soil system functionality and self-organization, the integration of the methods: mechanical chiseling, phosphogypsum and polyculture of cover crops creates a synergistic effect of soil-plant feedback that results in mutual benefits for soil and crop production (Angers & Caron, 1998; Nicolodi & Gianello, 2015).

The second outcome is that implementing specific soil decompaction strategies in each yield environment as the fully integrated treatment (MC+PCC+PG) in LYE and MYE, may promote crop productivity in these yield environments near to the maximum yield observed in the HYE. Even in the HYE, soybean yield increments in relation to the control could be obtained using PCC+PG. Plant development and crop productivity are determined by the interactions between the plant subsystem and the specific plant growing environment, as soil fertility, physical and biological conditions, and climate arrangement (Doran & Parkin, 1994; Vezzani & Mielniczuk, 2009; Nicolodi & Gianello, 2015). Therefore, amelioration of the plant growing environment, mainly the rooting zone, may result in different crop yield increments magnitude, depending on the starting organizational level of the system (Doran & Parkin, 1994; Vezzani & Mielniczuk, 2009).

Mechanical chiseling has been used to mitigate compacted layers of soils under NT system (Nunes *et al*., 2015). This practice usually benefits root development, increases soil porosity, mainly macroporosity, and decreases soil bulk density (Calonego & Rosolem, 2010; Nunes *et al*., 2014). However, soil mechanical disturbances under NT promotes depletion of SOM levels and has negative effects on enzymatic activities, reducing soil biochemical quality in short-term (Melero *et al*., 2011). In addition, mechanical chiseling might break soil aggregates (Fabrizzi *et al*., 2009) and reduce macroaggregates percentage (Calonego & Rosolem, 2008). In this study, mechanical chiseling as single intervention was able to increase soybean yield compared to the control only in the LYE, and other treatments delivered greater crop yields in this yield environment. However, even though MC combined with other decompaction strategies was efficient to increase soybean yields in the LYE compared to the control, this soil alleviation effect may not last up to the second crop season, and mechanical chiseling will probably be frequently needed in this yield environment if other decompaction strategies are not used concomitantly. Additionally, in this case, NT would be often interrupted by mechanical disturbances and neither greater soybean yields nor long-term benefits of this system would be reached (Calonego *et al*., 2017).

In the LYE, depleted soil physical conditions prior to the implementation of the treatments, with a PR around 2,800 kPa, soil bulk density near to 1.65 Kg m^{-3} and macroporosity lower than 0.08 m^3 m^{-3} (0.1 - 0.2 m depth), might explain the soybean yield responsiveness to soil amelioration due to mechanical chiseling intervention, especially when it was integrated with other decompaction methods. These findings are in line with Secco *et al*. (2004) and Beutler & Centurion (2004), who reported soybean yield reductions under soil PR values greater than 2,650 kPa; and 2,240 kPa, respectively. The state of soil compaction for different soil textural classes and organic matter content may be assessed by the degree of compactness, which refers to the relationship between the current soil bulk density and a reference bulk density or maximum compaction (Håkansson, 1990; Reichert *et al*., 2009). Yet, it has been challenging to find the optimal degree of compactness (Beutler *et al*., 2005; Suzuki *et al*., 2007; Oliveira *et al*., 2016) or the critical degree of compactness (Reichert *et al*., 2009) for the development of each crop and the relationship between degree of compactness and plant growth (Lipiec *et al*., 1991; Silva *et al*., 2006) still needs elucidation.

Soil macroporosity in the LYE prior to treatments implementation was inferior to the critical limit of 0.10 m^3 m^{-3} established by Grable & Siemer (1968) for optimal plant growth. Increases in soil macroporosity and decreases in PR and bulk density favor root growth tend to improve water infiltration and oxygen diffusion in the soil profile, enhancing the overall system quality (Calonego *et al*., 2017; Colombi *et al*., 2017; Colombi *et al*., 2018) and, consequently, crop yields. Since mechanical chiseling may allow instantaneous amelioration of degraded soil physical attributes as PR, it explains positive soybean yield responses to mechanical chiseling in LYE.

Another important strategy to improve soybean yields was the utilization of phosphogypsum. According to Dalla Nora *et al*. (2017), phosphogypsum increases soil Ca^{+2} content in subsurface depths due to the downward movement of SO_4^{-2}, improving chemical attributes in the rooting zone, stimulating roots to grow deeper and disrupt compacted layers, and finally promoting soil structure amelioration. Consequently, the soil environment permits greater tolerance of plants to water stress during dry spells, allowing the achievement of high and stable yields over the years (Caires *et al*., 2001; Dalla Nora *et al*., 2014; Dalla Nora *et al*., 2017; Hansel *et al*., 2017; Tiecher *et al*., 2018).

The method PCC as single intervention in HYE improved soil PR, bulk density and macroporosity. The PCC+PG resulted in the highest soybean yield in HYE (Figure S1). These findings reinforce that in more organized systems, cover plants can provide more suitable soil physical conditions to soybean growth than mechanical chiseling. In fact, soybean yields obtained with MC alone or combined with PG were, on average, 6% lower than that of PCC+PG treatment for HYE (Figure S1). In general, grass species are more efficient than legumes to grow along soil profiles with compaction restrictions (Rosolem *et al*., 2002; Garcia *et al*., 2012; Calonego *et al*., 2017). Thus, the use of grass species with vigorous roots, as that of the polyculture of cover crops in this study, can improve the physical quality of compacted soils and benefit subsequent crops (Calonego & Rosolem, 2010). Furthermore, roots are source of exudates and SOM, which stimulate aggregate formation and stabilization along the soil profile (Wendling *et al*., 2005; Martins *et al*., 2009), especially in soils without mechanical disturbance (Ferreira *et al*., 2018; Nicoloso *et al*., 2018).

Conclusion

Yield environments presented different yield-limiting factors, characterized as differences in soil properties, and demanded different soil decompaction strategies to increase soybean yields.

The key highlights of this study were: i) integrated decompaction strategy increased both soybean yield and black oat biomass production in the LYE; ii) utilization of phosphogypsum alone or integrated with mechanical chiseling and polyculture of cover crop was the best soil decompaction strategy for increasing productivity of both crops in MYE; and iii) the integrated methods: polyculture of cover crops and phosphogypsum should be the preferred method to promote the greatest soybean yield gain in HYE, and mechanical chiseling should be avoided at the expenses of reductions in soybean yield and black oat biomass production. In summary, black oat biomass production and soybean yields were improved with the selection of the right interventions for the right yield environment. In this way, soybean yield gaps between both LYE and MYE relative to HYE, were narrowed allowing to attain superior yield homogeneity within field already in the first crop season after treatments implementation.

Overall, the synergic effect of decompaction strategies integration boosted up soybean yield and black oat biomass production relative to the control, regardless of the yield environment, suggesting that the restoration of crop productivity under NT systems is a complex task, demanding parallel improvement of soil chemical, physical and biological attributes and system organization. Further research should investigate soil-plant interrelationships with the objective of developing strategies to mitigate soil compaction for boosting crop yields and soil quality in medium- and long-term taking into account the heterogeneity of yield environments within a field. Synergism between soil decompaction methods, preferably avoiding mechanical disturbances should be prioritized.

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Data Availability Statement

Authors elect to not share data.

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TABLES

Table 1 Soil pH, clay, soil organic matter (SOM), available phosphorous (P) and potassium (K^+); exchangeable sulfate (SO_4^{-2}), calcium (Ca^{2+}), magnesium (Mg^{2+}) and aluminum (Al^{3+}); and base saturation (BS) at the 0 - 0.20 m soil depth in the yield environments: low yield environment (LYE), medium yield environment (MYE) and high yield environment (HYE).

Yield environ.	pH /H_2O	Clay /%	SOM /g kg^{-1}	P	K^+	SO_4^{-2}	Ca^{+2}	Mg^{+2}	Al^{+3}	BS /%
				/mg dm^{-3}			/$cmol_c$ dm^{-3}			
LYE	5.23b	31.7c	18c	20.3*	121*	7.5a	4.5b	2.1c	0.21b	56.2*
MYE	5.46ab	42.3b	24b	20.6	130	3.7b	2.7c	3.0b	0.18ab	48.9
HYE	5.75a	52.6a	36a	53.9	153	9.3a	6.5a	3.2a	0.05a	66.7

Means followed by different letters in the column differ statistically according to the Tukey test (p<0.05). *not significant.

Table 2 Soil pH, clay, soil organic matter (SOM), available phosphorous (P) and potassium (K^{+}); exchangeable sulfate (SO_4^{-2}), calcium (Ca^{+2}), magnesium (Mg^{+2}) and aluminum (Al+3); and base saturation (BS) at the 0 - 0.20 m depth in the treatments at yield environments: low yield environment (LYE), medium yield environment (MYE) and high yield environment (HYE).

Yield environ.	Treat.	pH	Clay	SOM	SO_4^{-2}	Ca^{+2}	Mg^{+2}	Al^{+3}	BS
		/H_2O	/%	/g kg^{-1}	/mg dm^{-3}	/$cmol_c$ dm^{-3}			/%
LYE	Control	5.3*	32 *	18 a	7.2 b	4.3 b	1.9 *	0.19 *	54 b
	PG	5.3	33	18 a	7.6 a	4.6 a	2.0	0.18	57 a
	MC	5.2	33	15 b	7.0 b	4.1 b	1.7	0.18	53 b
	PCC	5.3	33	18 a	7.3 b	4.4 b	2.0	0.20	55 b
	MC+PG	5.2	32	15 b	7.4 a	4.5 a	1.8	0.19	56 a
	PCC+PG	5.3	32	19 a	7.7 a	4.7 a	2.1	0.20	58 a
	MC+PCC	5.3	33	16 b	7.1 b	4.4 b	1.9	0.19	55 b
	MC+PCC+PG	5.3	33	16 b	7.5 a	4.8 a	2.0	0.17	57 a
MYE	Control	5.5 *	42 *	24 a	3.5 b	3.6 b	2.8 *	0.18 *	52 b
	PG	5.5	43	24 a	3.9 a	3.8 a	2.7	0.18	56 a
	MC	5.4	44	21 b	3.3 b	3.5 b	2.8	0.17	53 b
	PCC	5.6	42	24 a	3.6 b	3.5 b	2.9	0.18	53 b
	MC+PG	5.4	43	21 b	3.7 a	3.8 a	2.6	0.17	54 a

	PCC+PG	5.5	42	24 a	4.0 a	3.9 a	3.0	0.18	56 a
	MC+PCC	5.4	42	22 b	3.3 b	3.5 b	2.9	0.16	53 b
	MC+PCC+PG	5.4	42	22 b	3.8 a	3.9 a	2.9	0.16	56 a
HYE	Control	5.7*	52 *	36 a	9.2 b	6.3 b	2.9 *	0.06 *	64 b
	PG	5.7	52	36 a	9.4 a	6.6 a	3.0	0.06	67 a
	MC	5.6	54	32 b	9.0 b	5.9 b	2.8	0.07	63 b
	PCC	5.7	53	36 a	9.2 b	6.4 b	3.0	0.07	65 b
	MC+PG	5.6	54	33 b	9.3 a	6.5 a	2.8	0.07	63 b
	PCC+PG	5.8	53	36 a	9.4 a	6.7 a	3.0	0.06	68 a
	MC+PCC	5.7	54	33 b	9.0 b	6.3 b	3.0	0.06	66 b
	MC+PCC+PG	5.8	55	33 b	9.4 a	6.6 a	3.1	0.06	66 b

Control, PG - phosphogypsum, MC - mechanical chiseling, PCC - polyculture of cover crops, MC+PG - mechanical chiseling + phosphogypsum, PCC+PG - polyculture of cover crops + phosphogypsum, MC+PCC - mechanical chiseling + polyculture of cover crops, MC+PCC+PG - mechanical chiseling + polyculture of cover crops + phosphogypsum. Means followed by different letters in the column within yield environments differ statistically according to the Tukey test ($p<0.05$). *not significant.

FIGURE CAPTIONS

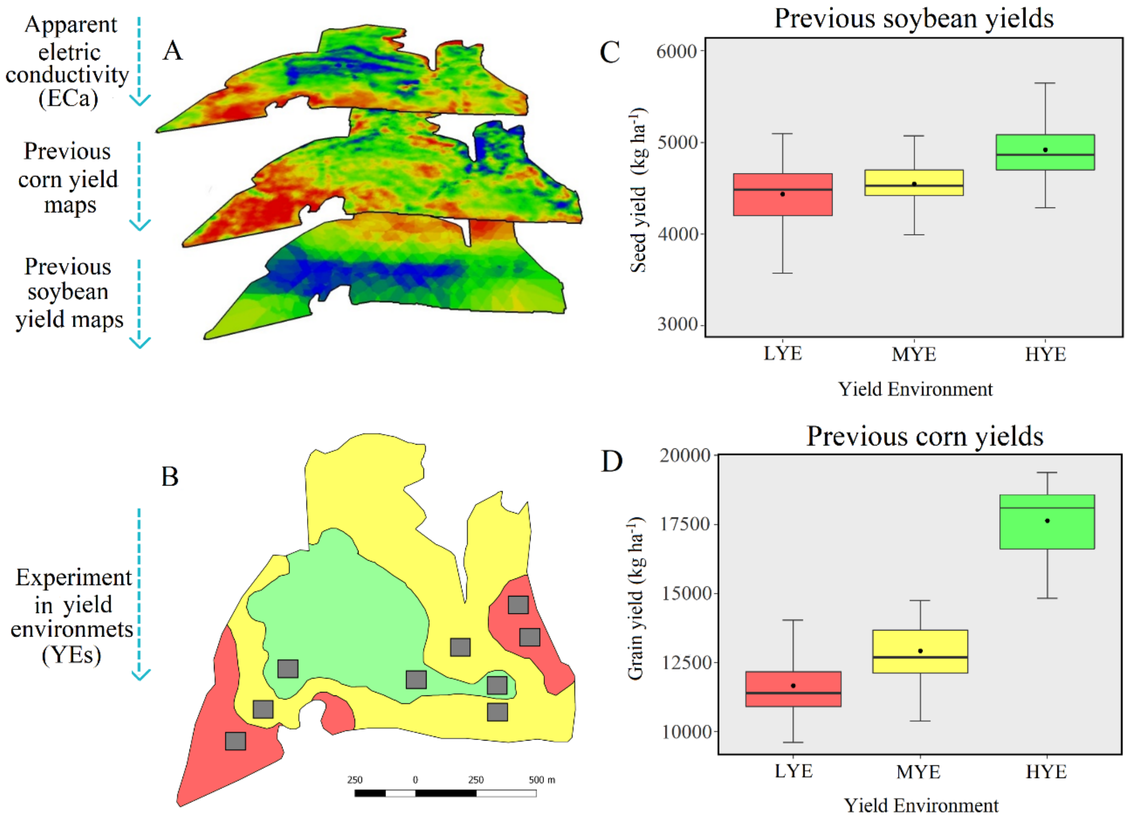

Figure 1 Framework of yield environments classification based on apparent electrical conductivity (ECa) and past-seasons soybean and corn yield maps (A). Experimental blocks (gray squares) distributed in yield environments (red = low yield; yellow = medium yield; green = high yield) (B). Boxplot of previous soybean and corn yields in the low yield environment (LYE), medium yield environment (MYE) and high yield environment (HYE) (C and D). Lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 * inter-quartile range (IQR) from the hinge. The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge.

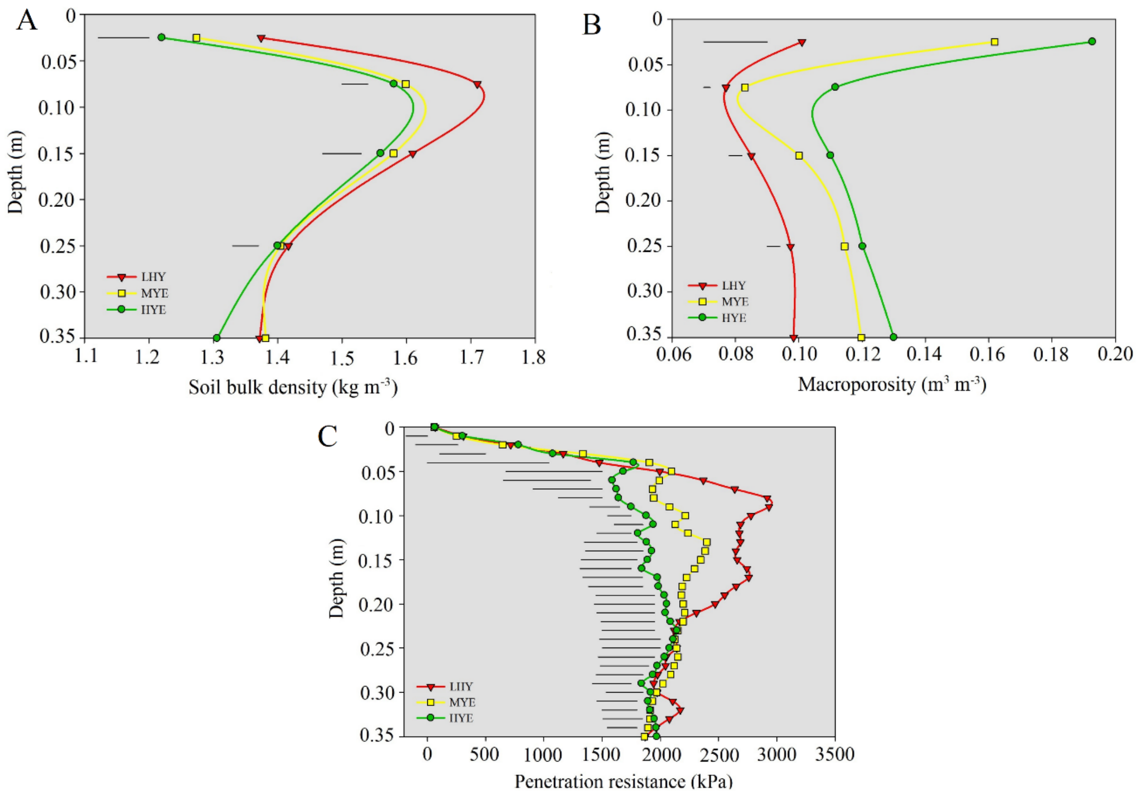

Figure 2 Soil bulk density (A), macroporosity (B) and penetrometer resistance (C) in the low yield environment (LYE, red symbols and line), medium yield environment (MYE, yellow symbols and line) and high yield environment (HYE, green symbols and line). Horizontal bars indicate the least significant difference of the Tukey test ($p<0.05$) for each depth.

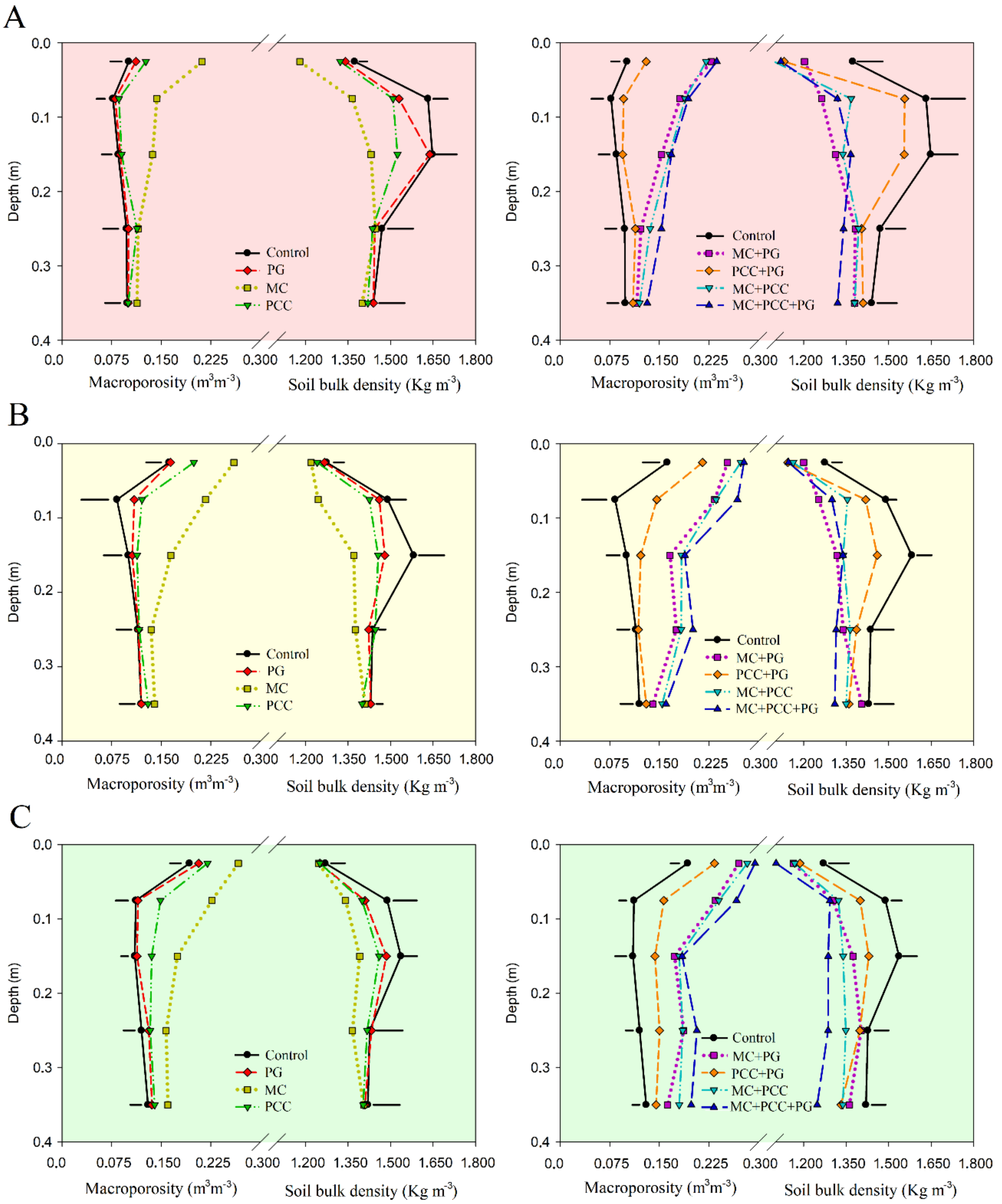

Figure 3 Macroporosity and soil bulk density of: low yield environment (LYE) (A) (red boxes); medium yield environment (MYE) (B) (yellow boxes); high yield environment (HYE) (C) (green boxes) in response to treatments: Control, PG - phosphogypsum, MC

- mechanical chiseling, PCC - polyculture of cover crops, MC+PG - mechanical chiseling + phosphogypsum, PCC+PG - polyculture of cover crops + phosphogypsum, MC+PCC - mechanical chiseling + polyculture of cover crops, MC+PCC+PG - mechanical chiseling + polyculture of cover crops + phosphogypsum. Horizontal bars indicate the least significant difference of the Tukey test ($p<0.05$) for each depth.

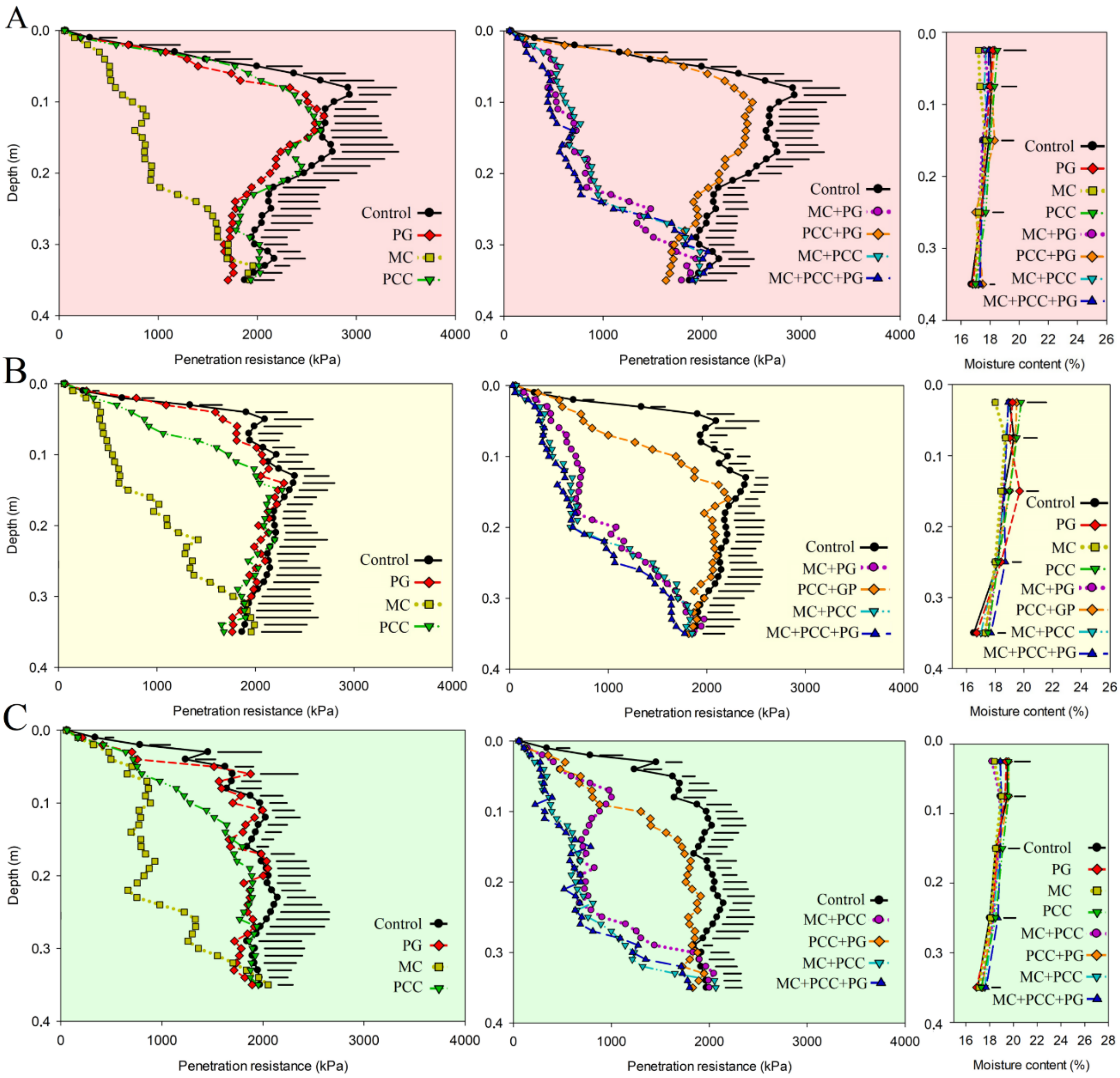

Figure 4 Soil penetrometer resistance (left and middle boxes) and the soil moisture content (right boxes) in the low yield environment (LYE) (A) (red boxes), medium yield environment (MYE) (B) (yellow boxes), and high yield environment (HYE) (C) (green boxes) in response to treatments: Control, PG - phosphogypsum, MC - mechanical chiseling, PCC - polyculture of cover crops, MC+PG - mechanical chiseling + phosphogypsum, PCC+PG - polyculture of cover crops + phosphogypsum, MC+PCC

- mechanical chiseling + polyculture of cover crops, MC+PCC+PG - mechanical chiseling + polyculture of cover crops + phosphogypsum. Horizontal bars indicate the least significant difference of the Tukey test ($p<0.05$) for each depth.

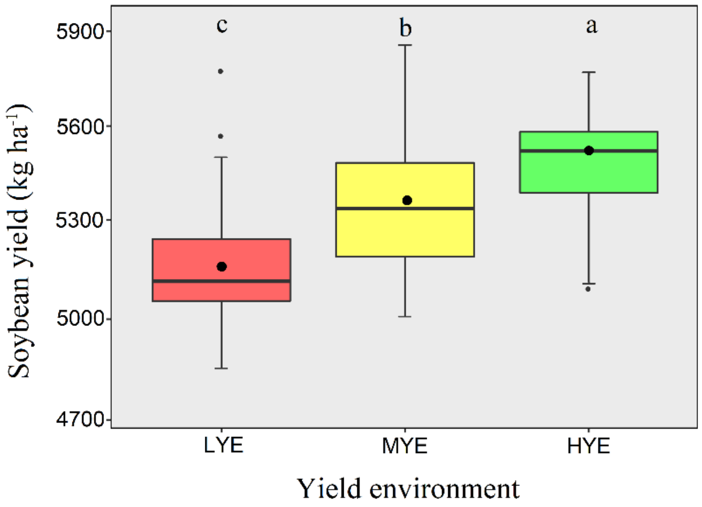

Figure 5 Soybean grain yields presented as average across all treatments within low yield environment (LYE), medium yield environment (MYE) and high yield environment (HYE). The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 x IQR (inter-quartile range) from the hinge. Letters refers to the statistical separation between yield environments using Tukey test ($p<0.05$).

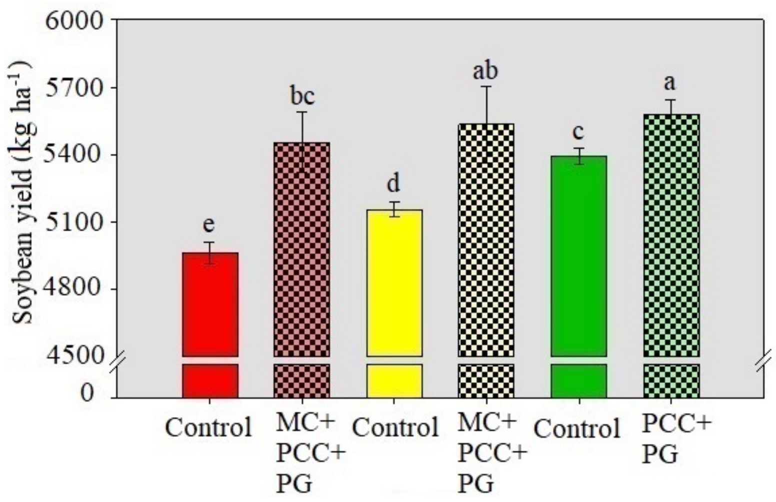

Figure 6 Comparison of soybean yields across yield environments considering the control treatment and the treatment with the highest soybean yield in the low yield environment (solid and checkered red bars), medium yield environment (solid and checkered yellow bars) and high yield environment (solid and checkered green bars). MC+PCC+PG - mechanical chiseling + polyculture of cover crops + phosphogypsum; PCC+PG - polyculture of cover crops + phosphogypsum. Means followed by different letters differ statistically according to the Tukey test ($p<0.05$).