Physical Properties and Organic Matter in Soils with High Soybean Yields under No-till in the Brazilian Cerrado

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Abstract

The present study was conducted in areas of large-scale soybean cultivation under long-term no-till (NT). Soil samples from depths of 0.0-0.10 (L1), 0.10-0.20 (L2) and 0.20-0.40 m (L3) were obtained from 65 commercial farms characterized by a high soybean yield in the state of Mato Grosso, Brazil. Oxisols were the predominant soils in these farms, which were located within the Cerrado Biome, and the main textural classes were loamy sand, sandy loam, sandy clay loam, sandy clay and clay. The following physical properties of soil were measured: penetration resistance, bulk density, particle density, total porosity, field moisture capacity, saturation and residual moisture contents, soil water retention curve (SWRC), inflection point, plant available water, n and α parameters of the Van Genuchten equation, S index, and clay and sand contents. In addition, the soil organic matter (SOM) and its densimetric fractions were also determined. The average soybean yield of the studied areas in the last three years was 4.13 Mg ha-1; however, 26 farms had yielded above 4.20 Mg ha-1. Only some of the physical properties at L1 layer, including the penetration resistance, bulk density and the porosity-related parameters, were significantly related with the soybean yield. The SOM and its fractions were directly influenced by the clay or sand contents. In conclusion, the areas with higher productivity under long-term NT showed an adequate S index at three studied layers with values of 0.11, 0.67 and 0.84 at L1, L2 and L3 layers, respectively.

1. Introduction

During the last five decades (1968-2018), the management of soils for soybean (*Glycine max*) cultivation in Brazil has changed from a conventional system to the no-till (NT) system. The rate of conversion to NT was low in the 1970s and 1980s, but increased exponentially starting from the 1990s (Wingeyer et al., 2015). The area of soybean production under NT was ˜35 million hectares (Mha) during 2017 and 2018 (Conab, 2018). During the transformation process, farmers and researchers focused on reducing disturbances to the soils and increasing the carbon (C) inputs because both of these changes exert strong direct and indirect effects on soil attributes (Cerri et al., 2012). The effects of NT on soil attributes could be both negative and positive, and the negative effects are primarily related to soil compaction. Nonetheless, much of the research indicates greater sustainability, more productivity and higher stability among crops in soil managed by NT than by conventional systems (Sa et al., 2014).

Soil compaction is a serious and persistent problem in NT areas, particularly in the Brazilian Cerrado region (Cecagno et al., 2016; Ryschawy et al., 2012). The most adverse impacts of compaction are an increase in soil resistance to penetration, reductions in the total porosity and water infiltration rate, increases in water runoff and erosion, and decreases in the plant available water (Reichert et al., 2016), and all of these impacts negatively affect crops (Krebstein et al., 2014). These problems can be reduced through the adoption of a system approach involving a high input of crop residues and a consequent increase in the soil organic carbon (SOC) content (Sa et al., 2014).

The input of biomass-C through a cover crop and/or crop residue in NT areas could be a viable option for increasing the total SOC stock (Daigh et al., 2014). The accompanying increase in SOC has positive effects on the chemical, physical (Andruschkewitsch et al., 2013, Steele et al., 2012) and biological properties of soils (Derpsch et al., 2014). Numerous studies on SOC stocks have confirmed their positive role in the vital functions of soil and have revealed that proper management is also pertinent to addressing current issues such as climate change and the increasing demand for food (Lal, 2015). In addition to obtaining data on total SOC stocks, it is also important to understand the different fractions of SOC and their effects on soil properties and crops' response (Anghinoni et al., 2013; Cambardella and Elliott, 1992).

Soil water storage is an essential factor in agricultural production, and the available water capacity (AWC) is related to the physical attributes of the soil. Indeed, to achieve and sustain high productivity, the AWC of soil is an important edaphological property (Williams et al., 2016). Site-specific soil management systems can alter physical-hydraulic attributes (Basche et al., 2016). In particular, NT systems can strongly affect the water retention and structure of soils (Carducci et al., 2016; Rabot et al., 2018) as well as the quantity, forms and distribution of SOC (Tan et al., 2007). Thus, cropping systems can impact the AWC of the soil (Qi et al., 2011).

The strong need to harmonize productive, environmental, social and economic issues in agriculture has led to increased research based on a holistic approach to the agricultural system. In this context, the objectives of the present study were; i) to establish the relationships between physical properties and soybean yields, and ii) to determine the effects of the SOC contents on the soil physical properties in high-productivity environments under long-term NT management.

2 Material and methods

2.1 Site description

This study was performed in areas of soybean cultivation in the southern area of the state of Mato Grosso in the Cerrado region, Brazil. By Koppen classification, the climate of study region is classified as type Aw with dry winters. The average rainfall remains 1300-1600 mm per year, the annual average temperature is 24-26 °C, and the average regional altitude is 400-500 m a.s.l. (Alvares et al., 2013). The studied areas are covered by Oxisols (Latosols) (Santos Et al., 2018).

In this study, the 65 farms, dominant by soybean cultivation under a long-term NT system, were sampled. The cultivation system is characterized as soybean in the summer and maize (*Zea mays*) during the second season. However, cover crops, including Crotalaria (*Crotalaria juncea*), millet (*Panicum miliaceum*) or Brachiaria (*Brachiaria mutica*) are also being rotated with the second season's crop. Furthermore, intercropping of Brachiaria in maize was practiced over an approximately 20% of the study area during last five years.

2.2 Collection and analyses of soil samples

Soil samples were collected in February 2017, when soybean was ready to be harvested. The total twenty-six fields with soybean yields > 4.20 Mg ha^{-1} were selected to represent the high-productivity environments. These selected plots were those whose average productivity of the last three crops was higher relative to the national average yield (3.08 Mg ha^{-1}; Conab, 2018

Soil samples from depths of 0-0.10, 0.10-0.20, and 0.20-0.40 m were collected for the measurement of soil physical properties. These soil depths were designated Layer (L) 1, L2 and L3, respectively. These soil samples were obtained from locations in the plot that could be considered representative of the plot. The plot harvest map was used to locate the pit for sample collection according to the described productivity. Undisturbed soil samples were obtained using a volumetric core of approximately 0.1 dm^{-3} (50-mm height and 50-mm diameter).The indices of soil physical properties such as penetration resistance (PR, MPa), soil bulk density (BD, Mg m^{-3}), total porosity (TP, m^3 m^{-3}) and soil water retention curve (SWRC) were estimated for all collected samples. Additionally, bulk samples were also obtained to determine the clay (g kg^{-1}) and sand (g kg^{-1}) contents and the particle density (PD, Mg m^{-3}).

2.2.1 Determination of soil physical characteristics

The SWRC was measured for matric potentials of -1, -2, -4, -6, -8 and -10 kPa using Buchner funnels (Haines, 1930) and for matrix potentials of -33, -66, -300 and -1,500 kPa using a Richards pressure plate extractor (Klute, 1986). The samples were allowed to reach the equilibrium moisture content at each potential, weighed and subjected to the next potential as per drainage procedure. After exposure to a tension of 1500 kPa, the samples were re-saturated and equilibrated at a tension of 6 kPa for determination of the PR. The samples were then dried in an oven at 105 ± 2 ºC for 24 hours to determine the water content (ϑ) and BD.

The soil penetration resistance (PR) was determined using an electronic bench penetrometer equipped with a straight circular cone tip of 45° and a diameter of 4 mm at a constant velocity of 2 mm $s^{-1}$for the entire length of the sample (50 mm) (Tormena et al., 1998). After disregarding the first and the last 25 readings, an average PR value for each sample was calculated (Serafim et al., 2013). The clay-sand contents and PD were measured according to Teixeira et al. (2017). For the granulometric analysis, the soil was physically dispersed in a Wagner-type rotary agitator with slow agitation.

2.3 Analyses of SOM and densimetric fractions

Soil samples, to determine SOM in 0-0.1-m layer, were collected at random locations within a radius of 50 to 60 m from the profile. Twenty bulk samples were collected and pooled. Additional samples from depths of 0.1-0.2 and 0.2 and 0.4 m were also obtained from the walls of the profile.

2.4 Procedures for SOM and density fractionation

The soil samples obtained for the determination of the SOM and its densimetric fractions were air-dried and passed through a 2-mm sieve. The total carbon content was determined by oxidation with potassium dichromate and colorimetric determination (Cantarella et al., 2001).

The SOM was fractionated into the free light fraction (FLF), occluded light fraction (OLF) and heavy fraction (HF) by following the methodology proposed by Elliott and Cambardella (1991). Briefly, 35 mL of sodium polytungstate solution (PTS) with a density of 1.85 g cm^{-3} was added to 10 g of soil contained in a 50-mL centrifuge tube. The tube was closed and inverted manually and slowly five times to release the FLF without breaking the aggregates. The suspension was centrifuged at 4100 g for 60 min, and the supernatant containing the FLF was vacuum-filtered on a pre-weighed AP40 glass fiber filter. To remove the excessive PTS, the filters and FLF contained in the sample were washed twice with distilled water and dried at 60 °C for 24 hours. The mass of the filter plus the FLF was quantified. To separate the OLF, the PTS solution was returned to the tube containing the pellet, and two glass balls with a diameter of 7 mm were added. The tubes were slowly dispersed in a shaker at a rate of 75 oscillations per min for 18 hours. After dispersion, the suspension was centrifuged again (4100 g for 60 min), and the OLF was obtained by filtration using the same protocol as that used for the FLF. The mass of the HF was obtained as the difference between the SOM and the mass of FLF + OLF.

2.5 Modeling and statistics of the data

The soil water content at saturation (ϑs), residual moisture (ϑr), soil S index (slope at the inflection point), potential at the inflection point, water content at field capacity (FC) and permanent wilting point (PWP) were derived from SWRC.

The SWRC was adjusted considering the following parameterization of the van Genuchten model (Van Genuchten, 1980); according to Equation 1:

$\theta(h) = \theta r + \frac{\theta s - \theta r}{(1+exp\{n(\alpha+h)\}^{1-1/n}}$(1)

where θ is the volumetric soil moisture content (m^3 m^{-3}), h is the log base 10 of the applied matric potential (kPa), θr is the residual moisture (lower asymptote), θs is the saturation moisture (upper asymptote), and α and n are empirical parameters of the shape of the water retention curve. The model was fitted to the data using the least squares method with the Newton-Raphson algorithm to obtain estimates for the parameters.

The SWRC parameters were used towas also applied to calculate the S index (Dexter, 2004) and the matric potential at the SWRC inflection point (Mello et al., 2002). according to Equations 2 and 3. The field capacity (FC) value was obtained considering the moisture corresponding to the matric potential of the SWRC at the inflection point (Silva et al., 2014) according to Equation 4. The plant available water capacity (AWC) was computed as the difference between the FC and the PWP at 1500 kPa of the SWRC.

$S = -n. \frac{\theta s - \theta r}{(1+1/m)^{m+1}}$ (2)

$I = -\alpha - log(m)/n$ (3)

$\theta i = \theta(h = I)$ (4)

In the equations, S is the slope at the inflection point, which is an index that uses the pore distribution volume function for assessment of the physical quality of soil, and I correspond to the log of the matric potential at the inflection point of the soil water retention curve. The moisture corresponding to the potential at the inflection point is represented by ϑI.

For each response variable, a sequence of three models, ranging from the most complex to the simplest model, was tested. Firstly, the polynomial models of the second degree were tested for the three layers, and the models, which did not show a significance for the second-order term were then reduced to a simple model with only first-order terms. The significant models ($p<0.05$) are presented in the figures, and for the nonsignificant soil properties related to productivity, the model of the layer that showed the best fit above the null model is presented. The figures contain the adjusted models with confidence bands ($p> 0.95$), and the horizontal dashed lines in the figures represent the average of the productivity observations. If the confidence bands do not contain the dashed line, a significant relationship between the variable and the soybean yield in the specific layer was obtained. The clay, AWC, PR and S index properties were also tested based on the FLF, OLF, HF and SOM in L1.

3 Results

In the studied region, the average soybean yield in the 2015-2017 three-year period was 4.13 Mg ha^{-1} at 65 plots. The minimal and maximal values of soybean yield were 3.23 Mg ha^{-1} and 4.97 Mg ha^{-1}, respectively. The box plots of the SOM, FLF, OLF and HF properties contain only the data for the 0.0-0.10-m (L1) layer. The presented data in figure 1 for the other variables are at L1 (0.0-0.10-m), L2 (0.10-0.20-m) and L3 (0.20-0.40-m). The classification of the 65 studied plots revealed that 50, eight, five and two plots formed the textural classes, including clay, sandy clay loam, sandy clay and sandy loam, respectively. Although, the clay exhibited an incremental function with increasing depth, this increment was not sufficient to constitute a textural gradient, and the soils in all the tested areas were Oxisols (Latosols;Fig. 1).

The relationships between the soil physical properties at each layer (L1, L2 and L3) and the soybean yield indicated that seven significant response variables explained the soybean yield. Specifically, the PR, BD, n parameter, I, TP, S-index and macro-porosity presented significant relationships (Table 1). Of these properties, positive and negative relationships were obtained with the S index, macro-porosity, TP and n parameter and with PR, I and BD, respectively (Table 1).

The analysis of the relationships of the SOM,FLF, OLF and HF with the clay, sand, PAW, S and PR properties showed significant values between the clay and sand contents and all forms of SOM studied. Among the properties affected by the soil management (i.e., PAW, S and PR), the significant relationships were only detected between OLF and PR, and between FLF and S index (Table 2).

The RP and BD values obtained at L1 showed a significant negative relationship with the soybean yield. In contrast, PD did not show significant relationship with productivity at L1 the most relevant among the three studied layers, with p=0.32 (Fig. 2).

The α parameter of the Van Genuchten equation also showed non-significant relationship with the soybean yield. However, the n parameter and the inflection point (I) of the SWRC showed positive and negative significant associations with the soybean yield, respectively (Fig. 3).

The total porosity, macro-porosity and S-index properties at L1 exhibited a significant positive relationship with the soybean yield (Fig. 4). The AWC, water content at saturation (ϑs) and residual water content (ϑr) showed no significant relationship with the soybean yield in any of the studied layers (Fig. 5). The AWC and ϑs obtained at L3 had a stronger relationship with productivity, with p=0.53 and p=0.56, respectively, than those obtained for the other layers, whereas the relationship with the ϑr value obtained for L2 was stronger, with p = 0.60, compared with those found for the other layers.

The clay and sand contents did not show a significant relationship with the soybean yield. However, L1 was found to be the most relevant for clay content, with p=0.16, and L2 was the most important for the sand content, with p=0.22 (Fig. 6). The field capacity that describes the soil water content for the potential matrices obtained at the SWRC inflection point was also not significant at all layers, although a stronger relationship was found at L3, with p=0.52, than in the other layers.

The clay content of the soil exhibited significant positive relationships with the SOM,FLF, OLF, and HF, whereas significant negative relationships of SOM and its fraction (FLF, OLF and HF) were also found with sand contents. The SOM did not present a significant association with the PAW (p=0.46), PR (p=0.19) and S (p=0.20). The FLF was also not significantly related to the PAW (p=0.66), PR (p=0.76) and S index (p=0.14). Whereas, the OLF presented a significant positive relation with PR, but was not significantly related to the PAW (p=0.62) and S (p=0.57). The HF did not show a significant relationship with the PAW (p=57%), PR (p=89%) or S index (p = 71%;Fig. 7).

4 Discussion

The physical properties studied did not present great variation in the profile, as demonstrated through a comparison of the three layers. L2 layer showed slightly lower values for porosity but higher values for BD and PR than the other layers; however, this layer presented the normal values for S index (Fig. 1). The PR values increased with increasing soil depth, as demonstrated by a comparison of L2 with the surface layer of Oxisols in the Brazilian Cerrado. Similar trends have also been reported by Silva et al. (2012) and Cherubin et al. (2015). Further, de Moraes et al. (2016) also reported the reduction in hydric properties and porosity at soil depth of 0.10-0.20-m.

The subdivision of the layered profile (L1, L2 and L3) was important in this study due to direct influence of the variables on soybean productivity.. Nevertheless, variables only at L1 were significantly related with the soybean yield (Table 1). However, the soil properties at L2 indicated a lower quality compared with those of L1 and L3, nonsignificant and negative influence of this lower quality was observed on the soybean yield. These trends might be attributed to the strong stratification of the chemical properties in the surface layer under long-term NT (Caires et al., 2015; Martínez et al., 2016) because L1 contains most of the roots of the cultivated plants (Calonego et al., 2017). Therefore, any fluctuation in variables atL1, which contains most of the roots of soybean, would have greater effects on productivity than changes in L2 and L3.

The development of the root system of plants depends on various factors, including the physical conditions of the soil, such as BD, PR and particle size (Rogers et al., 2000). The ability of the soybean's root system to provide a sufficient amount of water to the entire plant depends on its abundance, diameter and root length. These characteristics of the root system increase its area of absorption, its transport capacity and the volume of soil exploited (He et al., 2016). However, the benefits of favorable soil physical conditions, such that the genetic potential is expressed and the root growth in the profile is adequate, might not result in productivity gains in relation to those found in lower-quality areas if the rains are well distributed or if the chemical properties are stratified in the surface layer (Conte et al., 2009). Although the architecture of the root system depends on several factors, the distribution of nutrients in the profile is also important;

for example, phosphorus stimulates lateral growth of the root system, and nitrogen stimulates an improved depth distribution. Thus, the surface application of nutrients might restrict the depth distribution of roots (He et al., 2016).

The direct positive relation of SOM and its fractions to the clay content might be attributed to favorable conditions for the formation of aggregates that arise from the combination of clay and SOM, which is intensified in high-fertility soils due to the presence of divalent cations (Denef and Six, 2005). The formation of aggregates increases the chemical stabilization of SOM by cations (Kogel-Knabner et al., 2008), increases the sorption of SOM on clay surfaces (Vogel et al., 2014) and decreases the action of microorganisms due to physical insulation (Baldock and Skjemstad, 2000). However, in this study, the opposite trends were also observed in sandy soils (Fig.7), a negative relationship shown.

The non-significant relationship of PAW and S index with SOM and its fractions was expected because NT increases the AWC to plants with greater efficiency (in cases with the same water content (PAW) and the same pore distribution (S index)) compared with that obtained under conventional plow-based systems (Le Quere et al., 2015). The significant relationship of PR with OLF is important which should further be investigated to potentially alleviate the soil compaction under NT systems.

The PR and BD are strongly correlated (Mota et al., 2014), and both exerted a negative direct effect on soybean yield. The values of PR and BD for which the line of adjustment of the model crossed the line of the productivity. The average values of PR and BD in studied plots were approximately 1.6 MPa and 1.25 Mg m^{-3}, respectively. The value of PR below than 2.0 MPa was proposed by Taylor et al. (1966) and the values of 2.5 MPa and 1.64 Mg m^{-3} proposed by Tormena et al. (2017) for PR and BD, respectively. Furthermore, the PR was measured at the soil moisture content corresponding to a potential of 6 kPa. Both PR and BD might have adversely affected the root growth at 0-0.07 m soil layer (Tormena et al., 2017), but an increment in soil moisture can alleviate these negative effects.

The value of the α parameter of the Van Genuchten model was strongly affected by water loss at high potentials close to zero. The increase in the value of α has a positive and direct relationship with the presence of macropores with diameters close to the lower limit of the class, and drainage starts at high potentials. The parameter n depends on the rate of water loss from the point of inflection of the curve, and increases the rate of water loss with increase in the value of n. Therefore, to obtain an increase in the modulus of n, an equilibrium of the proportion of pores with each diameter class is required. In this context, the interventions that promote soil mobilization or the use of a seed drill can lead to a strong disturbance in the seeding row, increases the volume of macropores, and reduces the value of n, leading to advesre effects on productivity.

The matric potential at the inflection point of the curve, as indicated by I, reveales the continuity of the pore quality which is given by n, and its value depends on the pore size distribution in the micropore class. A lower loss of water in this category is associated with a lower potential. The distribution of pores that increases the values of n and I depends on the structural arrangement of the soil, which can only occur in the absence of plowing, and the combined effects of the SOM, plant root system, biological activity and other mineralogical and chemical components that moderate soil aggregation.

The significant positive effect of total porosity and S index at L1 on the soybean yield indicates the need to balance the capacity between water and air (gas exchanges) to harvest high yields. Aeration, when reduced by water in the pores, linearly affects the root growth (Benjamin and Karlen, 2014). The soybean yield under Brazilian edaphic conditions is strongly dependent on biological nitrogen fixation by symbiotic bacteria. However, the fixation efficiency depends on satisfactory aeration and gaseous exchange (Tewari and Arora, 2016). A pore size distribution with balanced proportions in different diameter classes ensures the desired combination of aeration and water availability, as indicated by the S index (Dexter, 2004).

The non-significance of the relationship between the soybean yield and PAW/AWC might be attributed to a favorable rainfall distribution in quantities greater than the minimum soybean demand during the three harvest cycles of soybean. In the case of frequent rains, the role of soil capacity to supply water is minimal

(Calonego et al., 2017). In this study, the soils under NT management had moderate to high PAW values.

For soils of sandy and clayey texture, NT management can affect the PAW and the productivity. The factors influenced by NT to reduce the difference in productive potential between sandy and clayey soils are increase in the SOC concentration, soil fertility (Sá et al., 2015) and water use efficiency by plants (Le Quére et al., 2015). The presence of crop residue mulch on the soil surface reduces the water loss through evaporation. The straw mulch also creates micro dams that delay water runoff and increase infiltration into the soil (Zhao et al., 2013). These effects add to the productive potential of sandy soils, which can then approach that of clayey soils.

Minasny and McBratney (2018) reported a modest SOM effect from increases in the PAW; specifically, only 1.4 and 1.9% increase in the PAW were obtained for every 10 g.kg^{-1} (1%) increase in the SOC in clayey and sandy soils, respectively. However, other benefits of conservation agriculture are obtained through the indirect effects of mulching, which can reduce evaporation and runoff and improve soil aggregation and biogeochemical functioning. Nonetheless, the review was primarily based on data from soils in temperate regions of the north-central USA and Europe or in dry regions of Australia. Under these conditions, predominant soils contain high-activity clays with strong affinity for physiochemical interaction with water. In contrast, the soils of the tropical Brazilian Cerrado region contain predominantly low-activity clays and under these conditions, SOM could be most critical for soil aggregation, structure (Vezzani and Mielniczuk, 2012), and CEC (Ciotta et al., 2002) and replaces the effect of clays on physiochemical interactions with water. In contrast, to the conclusions drawn by Minasny and McBratney (2018) reported a strong and positive effect of SOM on the PAW.

The data reported in this study regarding the relationship of SOM and its fractions to the PAW, PR and S depended on the predominance of clayey soils in the study area: 85% of the plots contained more than 40% clay, and the high levels of SOM masked the effects. Tavares Filho et al. (2012) reported a negative relationship between the PR and SOM in a red Oxisol, with a SOM content ranging from 12 to 40 g.kg^{-1}. The S index, affected by the pore size distribution, was positively related with the FLF, and this relationship constitutes the basis for microbial activity, leading whose action is critical to the formation and stabilization of aggregates (Six and Paustian, 2014) and to increases in the S index.

5 Conclusions

The data presented support the following conclusions:

> * The physical quality of the soil measured by the S index was not limiting in areas with a high soybean yield under NT * The penetration resistance and bulk density at L1 showed a significant negative relationship with soybean yield. * The total porosity and pore size distribution significantly affected the soybean yield. * The clay or sand content strongly influenced the SOM content,FLF, OLF and HF. *

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Table 1 . Regression terms for the soybean yield as a function of the physical properties of each layer in soil cultivated with soybean under long-term NT in the state of Mato Grosso, Brazil.

Soil properties[1]	Depth (m)	Depth (m)	Depth (m)	Depth (m)	Depth (m)	Depth (m)
	0.0-0.10 B_0	0.0-0.10 B_1[1]	0.10-0.20 B_0	0.10-0.20 B_1[2]	0.20-0.40 B_0	0.20-0.40 B_1
PR (MPa)	4.399	-0.178**	4.128	-	4.128	-
Bulk density (Mg m^{-3})	4.834	-0.565'	4.128	-	4.128	-
Particle density (Mg m^{-3})	6.245	-0.794	4.128	-	4.128	-
Alpha	4.128	-	4.128	-	4.165	0.076

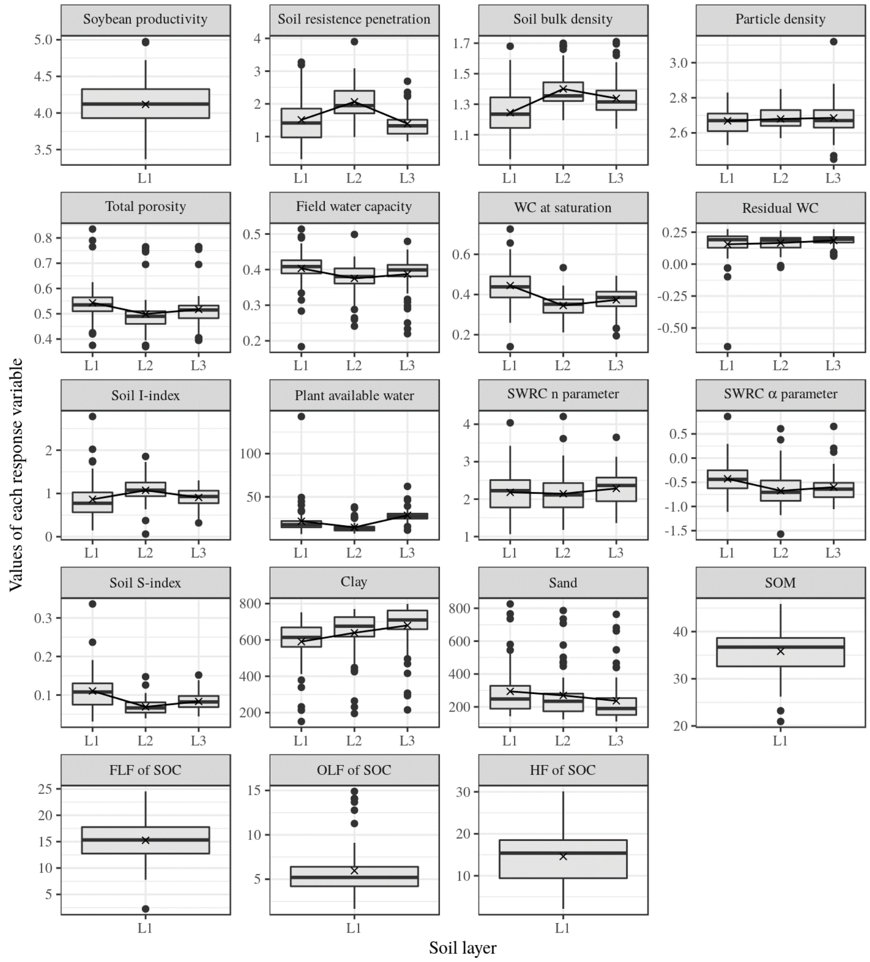
Soil properties[1]	Depth (m)	Depth (m)	Depth (m)	Depth (m)	Depth (m)	Depth (m)
n parameter	3.780	0.156’	4.128	-	4.128	-
I (kPa)	4.354	-0.263*	4.128	-	4.128	-
Total porosity (m^3 m^{-3})	3.455	1.266’	4.128	-	4.128	-
S index	3.816	2.923*	4.128	-	4.128	-
FC (m^3 m^{-3})	4.128	-	4.128	-	4.449	-0.855
AWC (mm)	4.128	-	4.128	-	4.282	-0.005
Saturation	4.128	-	4.128	-	4.313	-0.525
Residual	4.128	-	4.200	-0.414	4.128	-
Sand (g kg^{-1})	4.128	-	4.128	0.001	4.128	-
Clay (g kg^{-1})	4.444	-0.001	4.128	-	4.128	-
Macroporosity (m^3 m^{-3})	3.832	2.215’	4.128	-	4.128	-

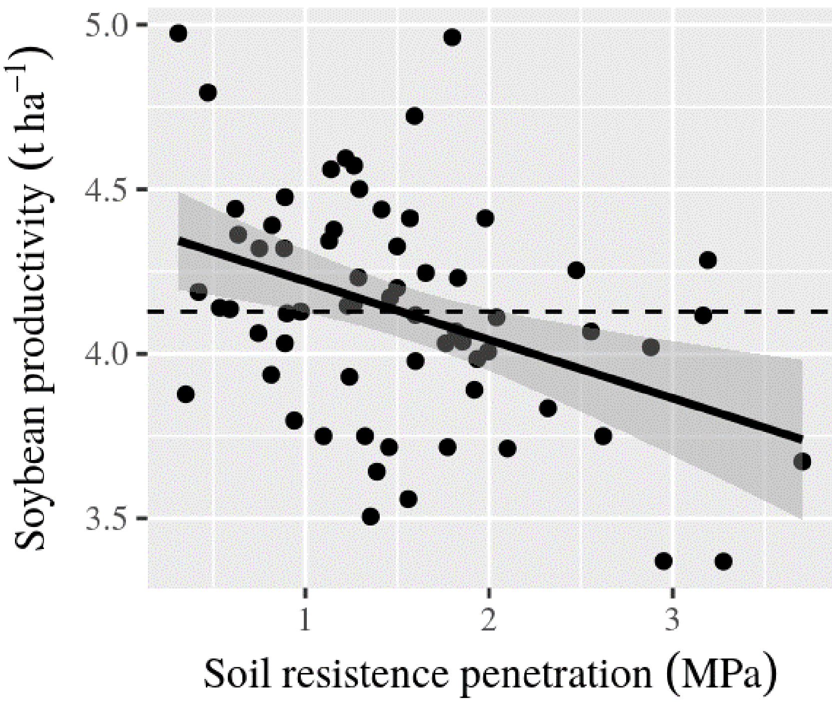
**, *, and ‘ indicate a significant difference at 1, 5 and 10%, respectively, as demonstrated by t-test.[1]B_0 and B_1 are model-setting parameters.[2]A “-” indicates that no significant adjustment was obtained for the model, and the value presented in B_0 corresponds to the average productivity.

Table 2 . Regression terms for the physical properties as a function of SOM and its densimetric fractions in the 0.0-0.10-m layer in soil under soybean cultivation with long-term no-till management in the state of Mato Grosso, Brazil.

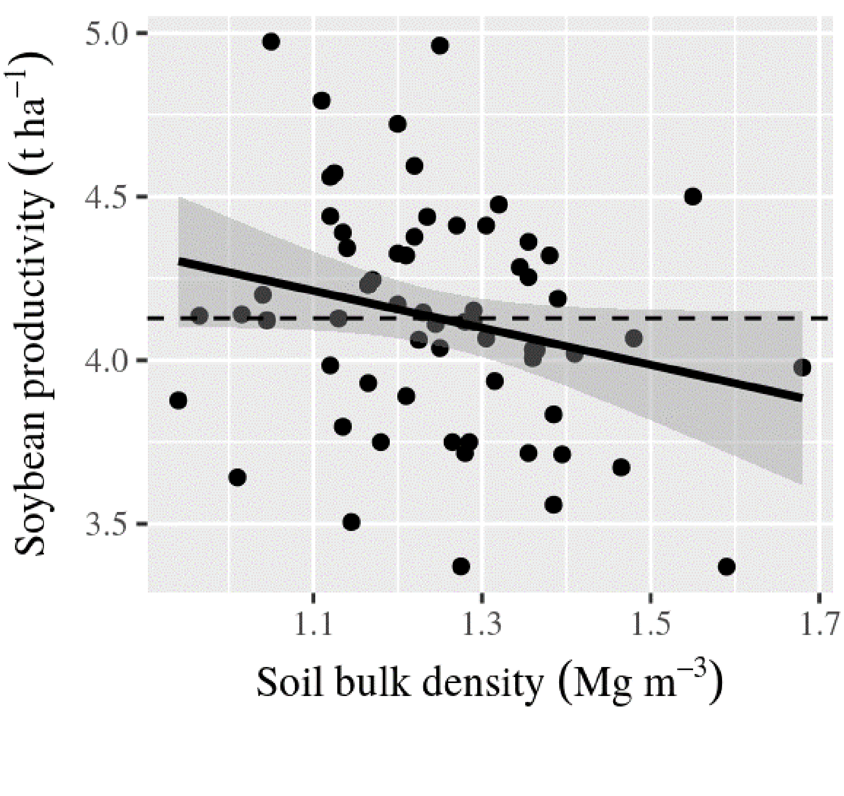
Soil properties[1]	Parameter	Parameter
	B_0	B_1[1]
HF x clay	7.218	0.013*
HF x sand	17.930	-0.011*
HF x PAW	13.560	0.058
HF x S	14.978	-4.752
HF x PR	14.326	0.164
FLF x clay	10.908	0.007’
FLF x sand	17.091	-0.007’
FLF x PAW	14.428	0.031
FLF x S	12.300	26.980’
FLF x PR	14.682	0.242
OLF x clay	2.532	0.006’
OLF x sand	7.576	-0.006*
OLF x PAW	6.142	-0.020
OLF x S	5.460	4.196
OLF x PR	4.341	0.986’
SOM x clay	20.609	0.025**
SOM x sand	42.597	-0.023**
SOM x PAW	34.170	0.069
SOM x S	32.743	26.419
SOM x PR	33.349	1.392

**, *, and ‘ indicate significance at 1, 5 and 10%, respectively, as demonstrated by t-test.[1]B_0 and B_1 are model-setting parameters.

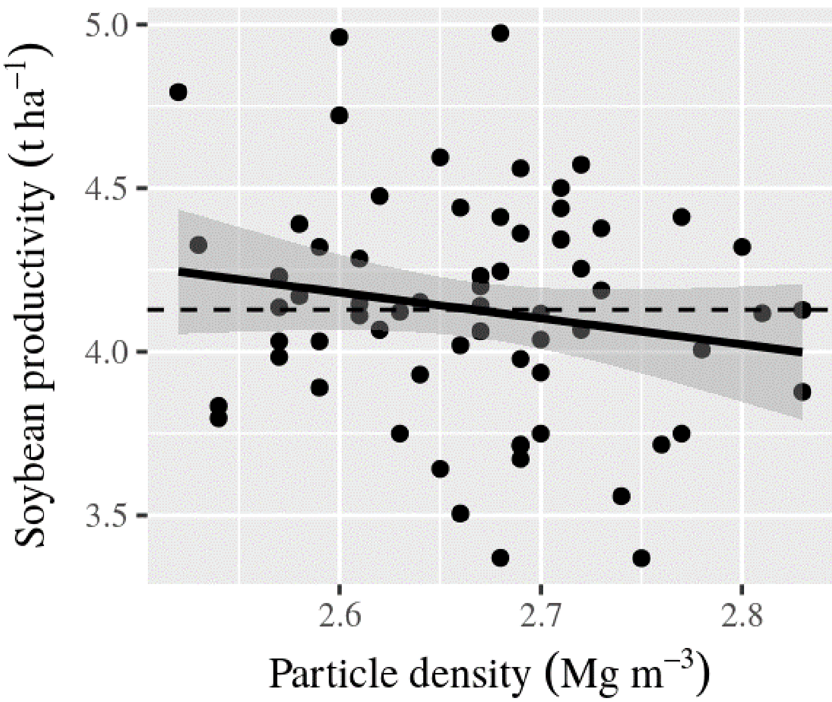

Soybean productivity
Soil resistence penetration
Soil bulk density
Particle density
Total porosity
Field water capacity
WC at saturation
Residual WC
Soil I-index
Plant available water
SWRC n parameter
SWRC α parameter
Soil S-index
Clay
Sand
SOM
FLF of SOC
OLF of SOC
HF of SOC
Values of each response variable
Soil layer
L1
L2
L3



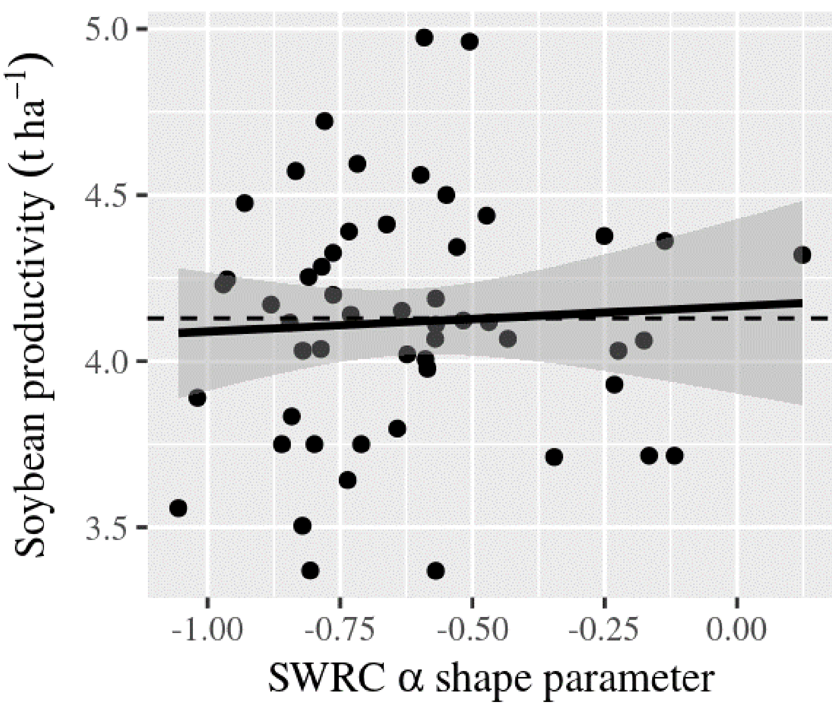
Soybean productivity (t ha^{-1})
5.0
4.5
4.0
3.5
1
2
3
Soil resistence penetration (MPa)



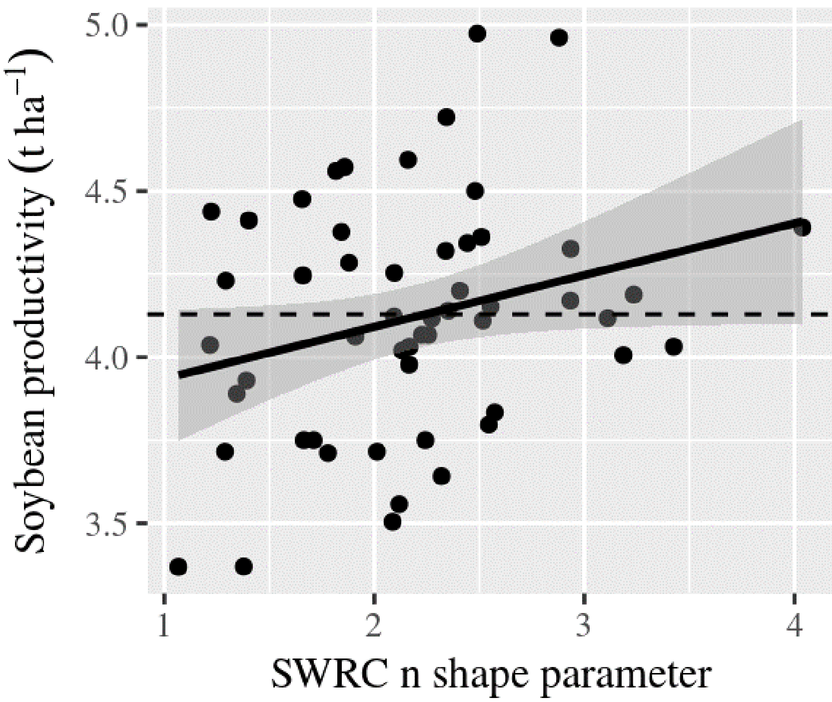
Soybean productivity (t ha^{-1})
5.0
4.5
4.0
3.5
1.1
1.3
1.5
1.7
Soil bulk density (Mg m^{-3})



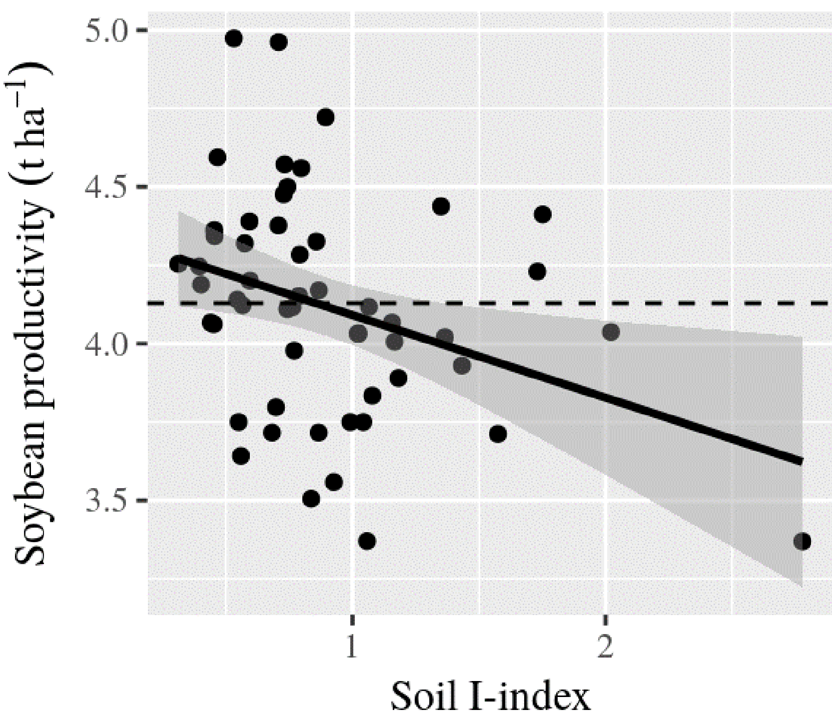
Soybean productivity (t ha^{-1})
5.0
4.5
4.0
3.5
2.6
2.7
2.8
Particle density (Mg m^{-3})



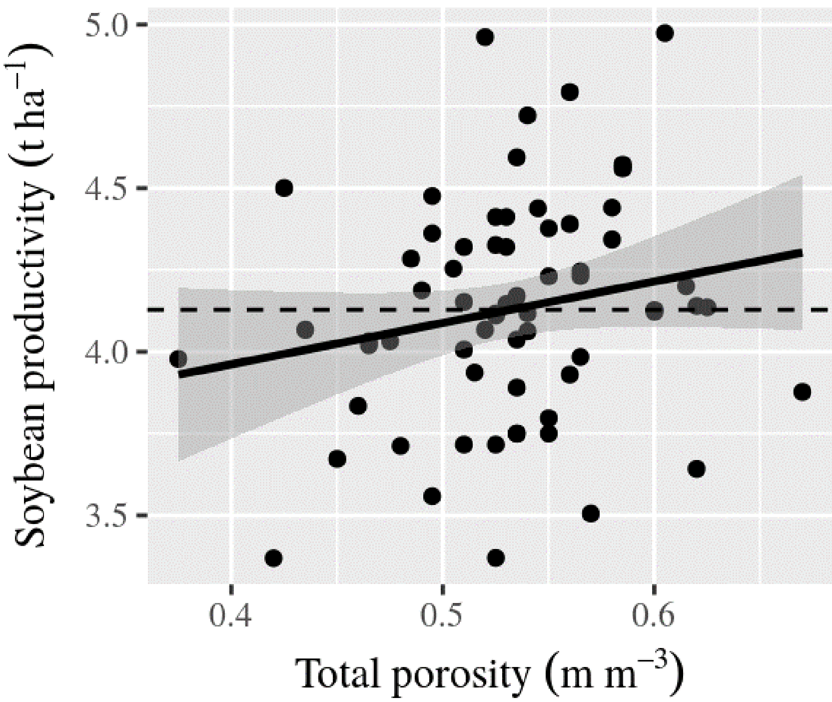
Soybean productivity (t ha^{-1})
5.0
4.5
4.0
3.5
-1.00
-0.75
-0.50
-0.25
0.00
SWRC α shape parameter

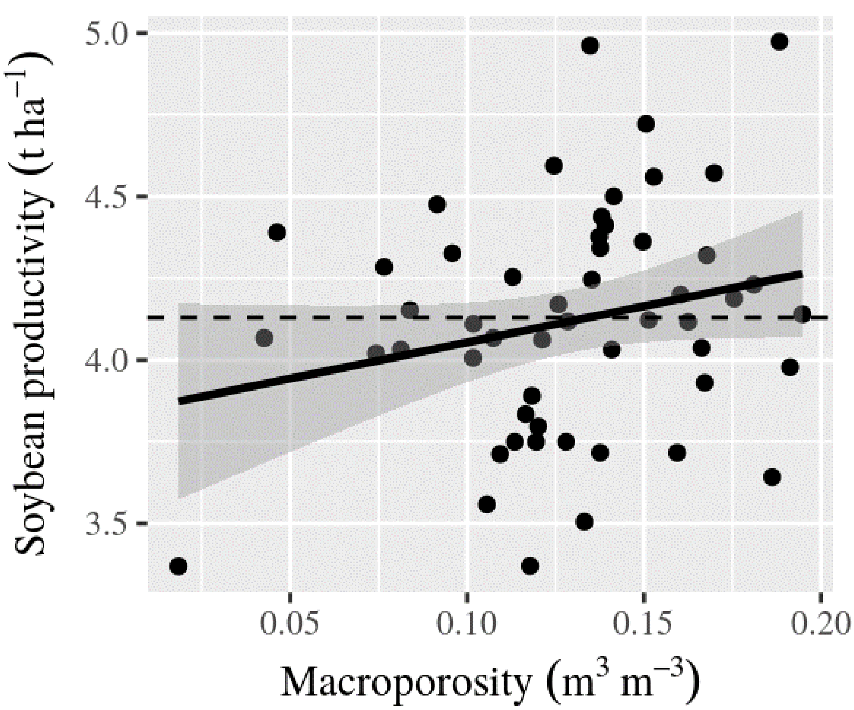


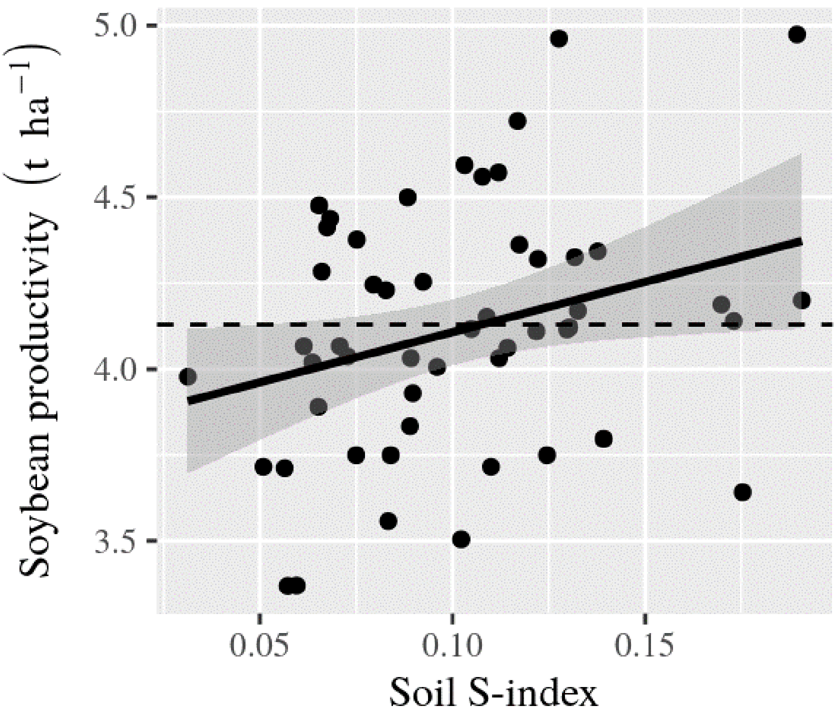
5.0
4.5
4.0
3.5
1
2
3
4
Soybean productivity (t ha^{-1})
SWRC n shape parameter



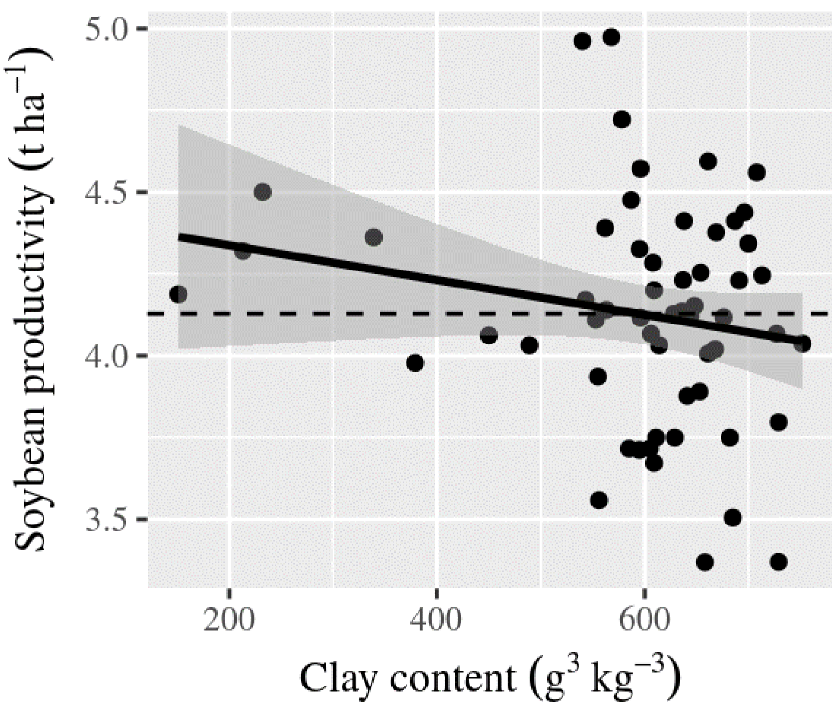
5.0
4.5
4.0
3.5
1
2
Soybean productivity (t ha^{-1})
Soil I-index


Soybean productivity (t ha^{-1})
5.0
4.5
4.0
3.5
0.4
0.5
0.6
Total porosity (m m^{-3})

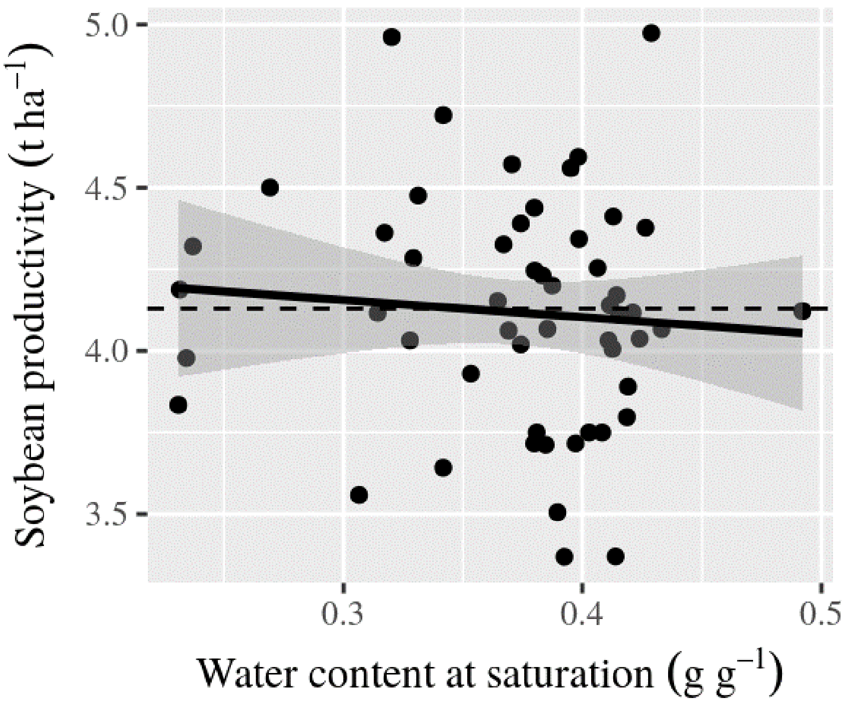

Soybean productivity (t ha^{-1})
5.0
4.5
4.0
3.5
0.05
0.10
0.15
0.20
Macroporosity (m^3 m^{-3})

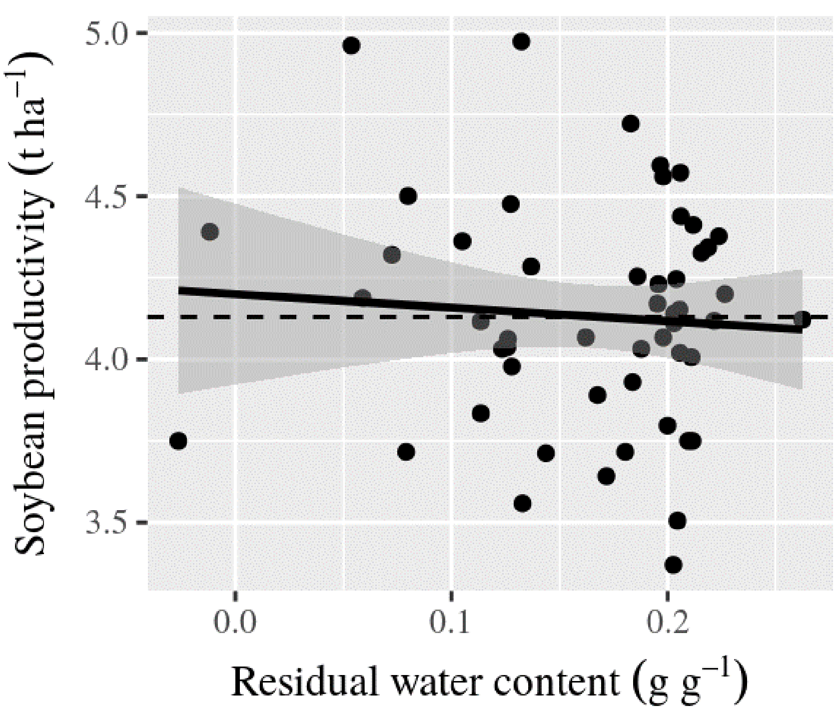


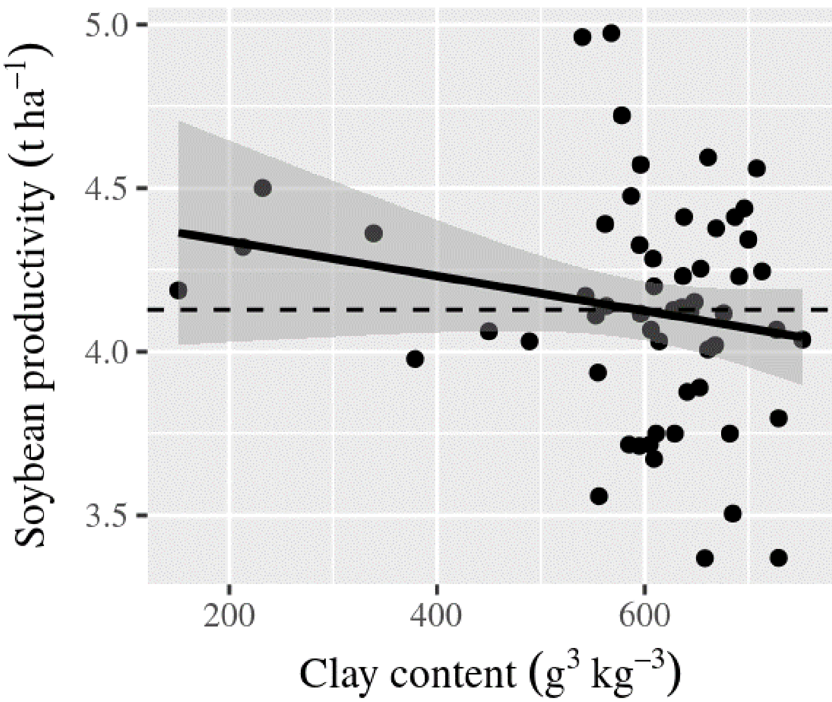
Soybean productivity (t ha^{-1})
5.0
4.5
4.0
3.5
0.05
0.10
0.15
Soil S-index

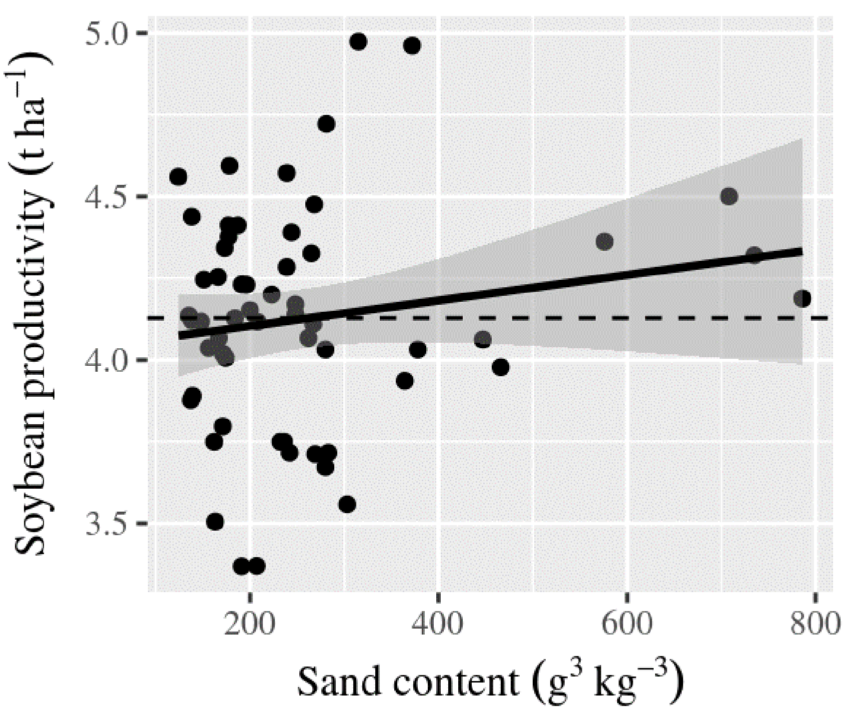


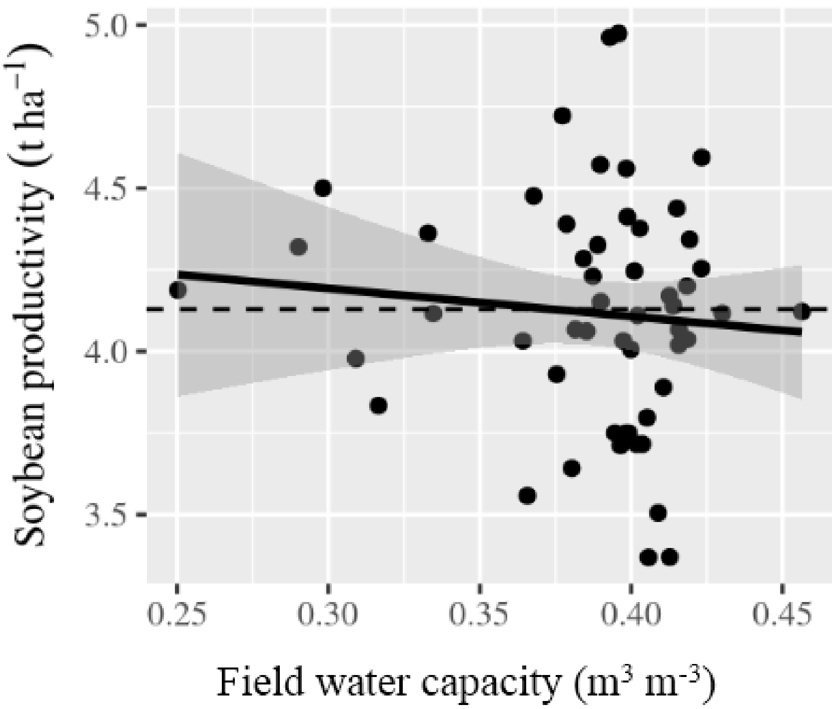
Soybean productivity (t ha^{-1})
5.0
4.5
4.0
3.5
200
400
600
Clay content (g^{3} kg^{-3})


5.0
4.5
4.0
3.5
Soybean productivity (t ha⁻¹)
0.3
0.4
0.5
Water content at saturation (g g⁻¹)

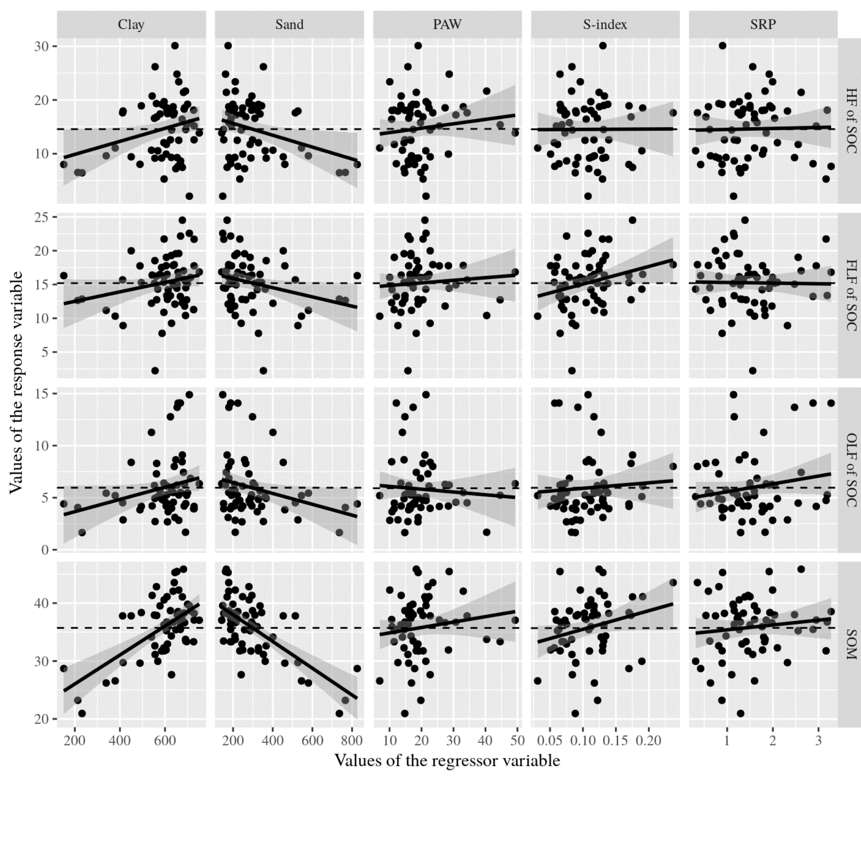

5.0
4.5
4.0
3.5
Soybean productivity (t ha⁻¹)
0.0
0.1
0.2
Residual water content (g g⁻¹)


5.0
4.5
4.0
3.5
Soybean productivity (t ha−1)
200
400
600
Clay content (g3 kg−3)


5.0
4.5
4.0
3.5
Soybean productivity (t ha−1)
200
400
600
800
Sand content (g3 kg−3)



Soybean productivity (t ha^{-1})
5.0
4.5
4.0
3.5
0.25
0.30
0.35
0.40
0.45
Field water capacity (m^3 m^{-3})



Clay
Sand
PAW
S-index
SRP
HF of SOC
FLF of SOC
OLF of SOC
SOM
Values of the response variable
Values of the regressor variable

Figure captions

Fig. 1 Descriptive analysis of the physical properties and SOM content of each layer of soil studied. L1 = 0.0-0.10-m layer; L2 = 0.10-0.20-m layer; and L3 = 0.20-0.40-m layer. The x contained in the box plot is the average value of the specific property in each layer.

*Units: soybean yield, Mg ha^{-1}; PR, MPa; BD and PD, Mg m^{-3}; TP, FC, θs and θr, m^3 m^{-3}; I, kPa; AWC, mm per layer; n and α parameters; S index, unit-less; clay, sand, SOM, FLF, OLF and HF, g kg^{-1}.

Fig. 2 (a, b, c) Relationship of the soybean yield with penetration resistance (PR), bulk density (BD) and particle density (PD). The gray band around the fitted line represents the 95% confidence interval for the fitted values.

Fig. 3 (a, b, c) Relationship of the alpha parameter (α), n parameter and inflection point (I) of the Van Genuchten model with the soybean yield. The gray band around the fitted line represents the 95% confidence interval for the fitted values.

Fig. 4 (a, b, c) Relationship of the total porosity (TP), macroporosity and soil index-S with the soybean yield. The gray band around the fitted line represents the 95% confidence interval for the fitted values.

Fig. 5 (a, b, c) Relationship of the plant available water (AWC), water content at saturation (θs) and residual water content (θr) with the soybean yield. The gray band around the fitted line represents the 95% confidence interval for the fitted values.

Fig. 6 (a, b, c) Relationship of the clay content, sand content and field water capacity (FC) with the soybean yield. The gray band around the fitted line represents the 95% confidence interval for the fitted values.

Fig. 7 Relationships of the clay content (PAW), penetration resistance (PR), S-index (S) and sand content with the SOM and its FLF, OLF and HF. The gray band around the fitted line represents the 95% confidence interval for the fitted values.