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GUILHERME ANGHINONI

Qualidade do Solo em Sistemas de Produção de Soja no Cerrado Mato-grossense

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Tese apresentada ao Programa de Pós-Graduação em Agronomia do Departamento de Agronomia, Centro de Ciências Agrárias da Universidade Estadual de Maringá, como requisito parcial para obtenção do título de Doutor em Agronomia.
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Aprovado em 27 de janeiro de 2020.
Local de defesa: Bloco J57, sala 01, campus sede da Universidade Estadual de Maringá, às 14:00 h.

A Deus, que me deu a vida e os motivos para vivê-la,

Dedico.

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SUMÁRIO

RESUMO

Qualidade do solo em sistemas de produção de soja no Brasil central e seus efeitos na sustentabilidade agrícola

A sustentabilidade agrícola é rotineiramente apontada como um objetivo chave em sistemas de produção agrícola, de forma que não apenas a quantidade de alimentos produzidos é importante, mas também a sua qualidade. Os grãos de soja (*Glycine max* (L.) Merril) são importantes na alimentação humana e animal pois contém, em média, 20% e 40% de óleo e proteína em sua massa seca, respectivamente. A sojicultura, inserida em um cenário sujeito às interferências climáticas variáveis, demanda medidas que minimizem os riscos e os impactos ambientais inerentes a produção, e maximizem os lucros e as produtividades, aumentando sua eficiência. Dessa forma, a hipótese desse estudo, que foi dividido em dois capítulos, é de que diferentes práticas de manejo em sistema de plantio direto envolvendo sucessões e rotações de culturas influenciam a qualidade física, química e biológica do solo após cultivo de longo prazo. No primeiro capítulo, estudou-se o efeito de esquemas de sucessão (soja-milheto ; soja-brachiaria e soja-milho) e rotação de culturas em diferentes conformações sob plantio direto na qualidade física do solo, medindo-se os indicadores densidade do solo (B_d), porosidade total (TP), água disponível (AWC), saturação relativa na capacidade de campo(FC/TP), permeabilidade ao ar (Ka) e índice de continuidade de poros (K1), assim como o intervalo hídrico ótimo (LLWR), nas camadas de 0-10, 10-20 e 20-40 cm de profundidade. De maneira geral, identificou-se que as sucessões de culturas apresentaram qualidade física do solo mais depreciada em relação às rotações de culturas, especialmente a sucessão soja-milho, que apresentou uma camada compactada superficial (0-10 cm). A variável mais afetada pelos tratamentos foram aquelas associadas a aeração e a continuidade de poros na camada de 20-40 cm, devido o efeito das raízes das plantas nessa camada. No segundo capítulo, a qualidade física, química e biológica do solo foi acessada por meio do LLWR, do teor de fósforo trocável e pela atividade da enzima β-glicosidase no solo, respectivamente, em quatro tratamentos: monocultivo de soja, sucessão soja-brachiaria, sucessão soja-milho e rotação de culturas com soja, milho, brachiaria e crotalária. Além disso, foram obtidas as variáveis, teor de proteína e flavonoides e produtividade de grãos de soja, lucratividade anual, carbono orgânico do solo e biomassa vegetal na superfície do solo. Nesse caso, foi possível concluir que o aumento da diversidade de culturas e do acúmulo de biomassa na superfície do solo proporcionou maior qualidade do solo – principalmente qualidade física e biológica – na rotação de culturas, seguido de maiores produtividades, teores de proteína e flavonoides nos grãos e lucratividade ao produtor, enquanto o monocultivo de soja apresentou resultado oposto. Pode-se concluir que a hipótese desta tese foi aceita, uma vez que houveram expressivas diferenças na qualidade do solo, principalmente nos componente físicos e biológicos, entre os diferentes sistemas de produção de soja estudados.

Palavras chave: qualidade física do solo; intervalo hídrico ótimo; qualidade biológica do solo; flavonoides; proteína.

ABSTRACT

Soil quality under soybean production systems in central Brazil and its effects on agricultural sustainability

Agricultural sustainability is a key to agricultural production systems, so that not only the quantity of food produced is important but also its quality. Soybean (*Glycine max* (L.) Merril) grains are important in human and animal feed because they contain, on average, 20% and 40% of oil and protein in their dry mass, respectively. The soybean, inserted in a scenario subject to variable climate interference, demands measures that minimize the risks and environmental impacts inherent to crops production, and maximize profits and productivity, increasing its efficiency. Thus, the hypothesis of this study, which was divided into two chapters, is that different management practices in no-tillage system involving crop successions and rotations influence the physical, chemical and biological quality of the soil after long-term cultivation. In the first chapter, we studied the effect of succession schemes (soybean millet; soybean brachiaria and soybean corn) and crop rotation in different no-tillage conformations on soil physical quality by measuring soil density indicators. (Bd), total porosity (TP), available water capacity (AWC), relative saturation at field capacity (FC / TP), air permeability (Ka) and pore continuity index (K1) as well as the least limiting water range (LLWR) in the 0-10, 10-20 and 20-40 cm soil layers. In general, it was found that crop successions presented more depreciated soil physical quality in relation to crop rotations, especially the soybean-corn succession, which presented a superficial compacted layer (0-10 cm). The variables most affected by treatments were those associated with aeration and pore continuity in the 20-40 cm layer, because of plant roots in this layer. In the second chapter, the physical, chemical and biological quality of the soil was assessed by LLWR, exchangeable phosphorus content and the activity of the enzyme β-glycosidase in the soil, respectively, in four treatments: soybean monoculture, soybean-brachiaria succession, soybean-maize succession and crop rotation with soybean, maize, brachiaria and crotalaria. In addition, the variables were obtained, protein and flavonoid content and soybean grain yield, annual profitability, soil organic carbon and plant biomass on the soil surface. In this case, it was concluded that the increase of crop diversity and biomass accumulation on the soil surface provided higher soil quality - mainly physical and biological quality - in crop rotation, followed by higher yields, protein and flavonoid contents of soybean grains and profitability to the producer, while the monoculture of soybean presented opposite result. It can be concluded that the hypothesis of this thesis was accepted, since there were significant differences in soil quality, mainly in the physical and biological components, between the different long-term soybean production systems studied.

Keywords: soil physical quality; least limiting water range; soil biological quality; flavonoids, protein.

INTRODUCTION

Agricultural sustainability depends on economic, social and environmental components (Purvis *et al.*, 2019). The growing demand for food, fiber and energy is a critical aspect of modern agriculture (Schipanski *et al.*, 2016). Sustainability is therefore the key to guarantee the access to sufficient quantity and quality of agricultural products. Soybean grains (*Glycine max* (L.) Merril) are important for food and feed supply, because they contain around 20% and 40% of oils and proteins on its dry weight, respectively (Miransari, 2016), and other components, like macronutrients (P). Still, the exact oil and protein content of soybean grains is highly dependent of genotype and environment interaction (Fehr *et al.*, 2003; Wilson, 2004; Veiga *et al.*, 2010).

The protein synthesis is a complex process, that occurs in numerous steps and locals within the plant cell (Beltrão e Oliveira, 2007). Environmental stresses occuring during any process involved in this synthesis may, therefore, limit its correct formation.

Lobato (2008) evaluated the grains biochemical quality generated by soybean plants submitted to six days of water deficit during the beginning of the reproductive phase, and found a 20% reduction on the grain's protein content. Bellaloui *et al.* (2010) studied the impact of poorly-diversified cropping systems on the soybean seeds biochemical composition, and found that the protein content of soybean grains after three cropping seasons of soybean monoculture was lower than that under soybean and maize crop succession. Bellaloui and colleagues also found higher P, Fe and B contents in seeds of soybean cultivated in succession with maize when compared to those from soybean monoculture. Because of those effects on soybean protein synthesis, it is very important to understand which environmental conditions are the best suited for protein production.

Brazil features an important position on the world soybean production scenario. No tillage (NT) is a strategic soil management practice with advantages related to lower energy demands, soil loss for erosion and greenhouse gases emission for agricultural production. (da Silva et al., 2014; Pöhlitz et al., 2018). NT is currently adopted in 125 million hectares around the world (Pittelkow *et al.*, 2015; Blanco-Canqui e Ruis, 2018). It is estimated that 42% of this area is contained within South America, and that Brazil has the second largest agricultural area under NT (32 million ha), behind only the USA (35 million ha; Kassam *et al.*, 2015; Blanco-Canqui e Ruis, 2018). In this context, it is appropriated to affirm that the Brazilian economy relies on the soil quality of its agricultural lands.

Differently from temperate climate regions around the world, the most part of the agricultural areas in Brazil are affected by long rainy seasons at the beginning of the spring and summer, while the severity of cold, in whinter, is not high. Some producing regions, however, are affected by a dry winter, as an example of the agricultural region of the Mato Grosso State, in central Brazil. The main cropping season of this region is sown between the spring and the summer, after the beggining of the rainy season, while the secondary cropping season is sown between the end of summer and the autuum, still in the rainy season, while the harvest is performed on the dry season. Those conditions favour an intensive agricultural production.

Aiming the increase of agricultural profits, some farmers of other parts in Brazil cultivate three cropping seasons in a year, adding a short-cycle crop, or a cover crop, after the second cropping season. Because of this, and despite all the advantages of crop rotation, the Brazilian farmlands are predominantly cultivated under soybean, on the main cropping season, during summer, and maize (*Zea Mays*), on the secondary cropping season, at the winter. Arvor *et al.* (2012) describe that, since the early 70's, soybean production was focused on exportations, and was the main factor affecting the agricultural expansion on the mato Grosso State, reaching aproximately 27% of the brazilian agricultural area under annual production of soybeans, and indicating predominace of the soubean/maize crop succesion. Spera *et al.* (2014) and Abrahão e Costa (2018) also indicated that the soybean/maize succession is currently predominant on the Brazilian farmlands.

The hypothesis of this study is that high crop diversity positively affects soil quality after long-term cultivation, causes decreases in production costs with positive effects in soybean production. The objective of this study was to study the effects of different soybean production systems on soil quality, as well as its influence on qualitative and quantitative plant production indicators of soybean.

This study is a result of the combination of two other, which have already been submitted to specialized journals. The first chapter was submitted to the Soil & tillage Research journal, while the second chapter was submitted to the Land Use Policy journal. Both chapters are under review, formatted according to the journal norms, and therefore written in English.

CHAPTER 1

LONG TERM CONSERVATION AGRICULTURE POSITIVELY AFFECTS SOIL PHYSICAL QUALITY OF SOYBEAN FARMING SYSTEMS IN CENTRAL BRAZIL

Resumo: Neste estudo, testamos a hipótese de que a rotação de culturas pode influenciar positivamente a qualidade física do solo de sistemas de produção à base de soja (*Glycine max* (L.) Merril) a longo prazo no plantio direto. A densidade do solo (B_d), porosidade total (TP), conteúdo de água disponível (AWC), saturação relativa na capacidade de campo (FC/TP), permeabilidade do solo ao ar (Ka), continuidade dos poros do solo (K1) e o intervalo hídrico ótimo (LLWR) foram avaliados para as camadas de solo de 0-10, 10-20 e 20-40 cm. Foram testados três tratamentos de sucessão de culturas envolvendo a soja na safra de primavera/verão: CS-Ma, CS-Me e CS-Br, com milho (*Zea Mays*), milheto (*Pennisetum glaucum*) e braquiária (*Urochloa ruziziensis*) como culturas de outono/inverno, respectivamente. CR-3 e CR-3D foram tratamentos trienais de rotação de culturas, enquanto CR-2 representou um tratamento bianual de rotação de culturas. Os tratamentos com rotação de culturas envolveram o cultivo de soja, milho, milheto, braquiária e crotalária (*Crotalaria ochroleuca*). A conectividade dos poros da camada de 20-40 cm do solo foi o aspecto da qualidade física do solo mais influenciada pelos tratamentos - devido às diferenças no acesso da raiz da planta ao subsolo - afetando a permeabilidade ao ar do solo. Em geral a sucessão de culturas danificou a qualidade física do solo no perfil do solo quando comparada aos efeitos da rotação de culturas. No entanto, a sucessão de soja e milheto resultou em aumento da qualidade física do solo na camada de 0-10 cm após 9 anos de cultivo. O CS-Ma exibiu qualidade física do solo depreciada na camada superficial do solo causada pela compactação. A diversidade de culturas afetou positivamente a qualidade física do solo da camada de solo de 20 a 40 cm.

Palavras chave: Compactação do solo, interval hídrico ótimo, continuidade de poros, rotação de culturas, diversidade cultural.

Abstract: In this study, we tested the hypothesis that crops rotation may positively influence the soil physical quality of long-term no tillage soybean-based production systems. Soil bulk density (B_d), total porosity (TP), available water content (AWC), relative saturation at field capacity (FC/TP), air permeability (Ka), soil pore continuity (K1) and the least limiting water range (LLWR) were evaluated for the 0-10, 10-20 and 20-40 cm soil layers. Three crop succession treatments were tested involving soybean as a spring/summer crop, CS-Ma, CS-Me and CS-Br, with maize (*Zea Mays*), millet (*Pennisetum glaucum)* and brachiaria (*Urochloa ruziziensis*) as the fall/winter crop, respectively. CR-3 and CR-3D were tri-annual crop rotations treatments while CR-2 represented a bi-annual crop rotation treatment. Crop rotation treatments involved soybean, maize, millet, brachiaria and crotalaria (*Crotalaria ochroleuca*) cultivation. Pore connectivity of the 20-40 cm soil layer was the soil physical quality property most influenced by the treatments – because of differences in plant root access to the subsoil – affecting soil air permeability. Overall crop succession damaged soil physical quality through the soil profile when compared with crop rotation. Nevertheless, succession of soybean and millet resulted in increased soil physical quality in the 0-10 cm soil layer after 9 years of cultivation. CS-Ma exhibited poor soil physical quality in the surface soil layer caused by soil compaction. Crop diversity positively affected soil physical quality of the 20-40 cm soil layer.

Keywords: Soil compaction; least limiting water range; soil pore continuity; crop rotation; crop diversity.

INTRODUCTION

Sustainable soil use and management to meet the growing demand for food, fiber and energy of an ever-growing world population is one of the critical issues for modern agriculture (Schipanski *et al.*, 2016). No-tillage (NT) is an advanced soil management system with the advantages of decreased energy and time consumption, effective control of soil loss, soil water conservation, decreased greenhouse gas emissions, seeding optimization and crop yield (da Silva et al., 2014; Pöhlitz et al., 2018). Currently, NT is being used in around 125 million ha of agricultural land around the world (Pittelkow *et al.*, 2015; Blanco-Canqui e Ruis, 2018). Estimates indicate that 42% of the total area under NT is in South America, with Brazil comprising the second largest agricultural area under NT (32 million ha) after the USA (35 million ha) (Kassam *et al.*, 2015; Blanco-Canqui e Ruis, 2018).

No-tillage in intensive conservation agriculture is founded on crop rotation with high biomass production, little mechanical disturbance of the soil, and the retention of crop residue on the soil surface, which are essential for the maintenance and increase of soil carbon pools in the Oxisols of the Brazilian region under the *Cerrado* biome (CER) in Central Brazil. Due to particular climatic conditions, soil organic matter mineralization rates in tropical soils of Brazil may be five times greater than those found under temperate conditions (Sanchez e Logan, 1992). Therefore, high levels of plant biomass production and maintenance as well as crop rotation are critical for Brazilian agriculture and may be considered the supports for conservation agriculture (Rusinamhodzi, 2015). NT may contribute to soil physical quality improvement through reduced machinery traffic, more diverse and prolific root growth into the soil (Anghinoni *et al.*, 2019), and the reestablishment of soil microorganism diversity (Bottinelli *et al.*, 2015) due to increasing soil organic carbon (SOC). A diversified root system, with different diameters and exudation capacity may positively affect soil aggregation and functional porosity through the creation of pores of different shapes and diameter, as well as the better pore continuity and connectivity that is favored by the growth of aggressive roots (Anghinoni *et al.*, 2019; Colombi *et al.*, 2019). Even so, it is difficult to establish an “ideal” crop diversity in farmlands as there is considerable reluctance from farmers to adopt crop rotation in NT due to the additional expense, complexity and uncertainties to the already risky "agricultural business" as mentioned by Weil e Kremen (2007).

soil physical quality is a soil capacity linked to good structural mainterance, root proliferation and microbial population diversity, as well as the ability of the soil to resist erosion and compaction (Reynolds *et al.*, 2002). soil physical quality is directly related to soil penetration resistance (PR), temperature, soil aeration and water availability to the roots, because those soil physical properties directly influence the metabolic processes related to plant growth (Passioura, 2002; Foloni *et al.*, 2006; Berisso *et al.*, 2012; Chen *et al.*, 2014). The limiting of root penetration directly impacts root physiology, which promotes a decrease in the elongation of cells near the root tip and negatively affects root growth (Bengough *et al.*, 2006), leaf stomatal functioning and therefore crop growth and yield (Lipiec *et al.*, 2003). Water and air supply to the roots affects plant growth, as they are an important component of active nutrient absorption (Marschner e Rimmington, 1996) and are critical for plant transpiration and photosynthesis, the processes of which are intimately linked to soil physical quality.

Brazilian farmlands experience long rainy seasons in spring/summer and no severe cold in the winter, even though some regions such as the CER in central Brazil experience dry winters. The first cropping season (spring/summer) is sown and harvested under rainy weather, while the second cropping season (fall/winter) is mostly sown under rainy weather and harvested in the dry season. Aiming for maximum profitability, some farmers even grow three crops in a year, with the inclusion of a short-cycle crop after the second cropping season, or a cover crop, if the winter dry season is not severe. Because of this, and despite all the advantages of conservation agriculture and crop rotation, the most widely spread farming system in Brazilian agricultural fields in the CER is the succession of soybean (*Glycine max* (L.) Merril), cropped in the spring/summer, and maize (*Zea Mays*), cropped in the fall/winter. Arvor *et al.* (2012) stated that since the 1970's, the production of soybean grains for export was the main factor affecting agricultural expansion in Mato Grosso state, central Brazil, accounting for approximately 27% of the total Brazilian area under soybean, indicating a predominance of a soybean/maize double cropping system. Spera *et al.* (2014) and Abrahão e Costa (2018) even indicate that the succession of soybean and maize has been dominant in Brazilian farmlands.

The NT production system tends to reduce machine traffic in the field compared with conventional tillage, however, larger and heavier machines are being used (Sivarajan et al., 2018). Machinery traffic under unfavorable soil moisture conditions can lead to the compaction of the surface soil layers under NT (Drescher et al., 2017). In addition, soil compaction has intensified in less diversified crop rotation systems (Sivarajan et al., 2018). Keller *et al.* (2019) state that heavier machinery is a cause of soil physical quality decrease, negatively affecting crop yields. Under surface soil compaction, occasional or strategic tillage can be used with the aim of breaking up compacted layers and improving root penetration in the soil (Nunes *et al.*, 2015) and therefore crop performance. However, soil tillage effects are transient and may not last to the next cropping season, as indicated by Calonego *et al.* (2017) and Filho, Osvaldo Guedes *et al.* (2013). Anghinoni *et al.* (2017) found that the effect of the sowing row of soybean crop, tilled with a furrow opener, was transient and did not last to the end of the soybean crop cycle. As found by Moreira *et al.* (2016), soil wetting and drying cycles positively affect soil physical quality under NT and may be more effective than the beneficial effects caused by the furrow opening for seed and fertilizer placement. In tropical areas, such as in Brazil, high temperatures and high annual precipitation levels within a short term may enhance soil wetting and drying cycle effects on soil physical quality. Daigh *et al.* (2018) found that tillage had no effect on long-term yields of soybean under drought stress. Furthermore, deep compacted layers may remain untouched by soil tillage, since operations for this purpose are often restricted to a layer 20-30 cm deep in the soil, with little or no effect on soybean yield.

In addition, to positively affect soil carbon pools crop rotation can be used for buffering soil compaction effects in cash crops and even as a tool to enhance soil physical quality in the medium/long term (Filho, Osvaldo Guedes *et al.*, 2013; Calonego *et al.*, 2017; Anghinoni *et al.*, 2019). Nevertheless, the positive effects of cover crops on soil quality is diverse (Chen *et al.*, 2014; Bacq-Labreuil *et al.*, 2019), positively affecting the soil organic carbon pool, and decreasing variations in soil temperature and water content. However, Martínez *et al.* (2016) found that NT yields are expected to be higher than those under conventional tillage when proper crop rotation and crop residues are maintained on the soil surface. Recently, Anghinoni *et al.* (2019) found that increased diversification of crops in cotton (*Gossypium hyrsutum* [L.]) production systems under NT led to an improved soil physical quality and therefore caused cotton yields to be less subject to environmental risks, such as dry spells, when compared with tillage-based and poorly diversified production systems.

Crops may withstand the deleterious effects of soil compaction when proper crop rotation is used, due to the positive effect of the latter on total porosity, and pore continuity and connectivity. Improved continuity and connectivity of previously formed pores positively affect the root growth of subsequent crops by providing less resistant channels that are better suited for root growth to access water and nutrients in deeper layers. Therefore, pore connectivity is a result of root growth– especially of cover crops (Chen *et al.*, 2014) – and microbial activity (Reynolds *et al.*, 2002) acting as secondary channel builders, in which roots grow deep despite higher levels of bulk density (B_d) and soil penetration resistance (PR). Colombi *et al.* (2017) found that roots may sense the best suited environment for growth, and that soil macropores attracted roots that grew inside them, while Pfeifer *et al.* (2014) found that artificial macropores positively affected barley root and shoot growth. Even if the diameter is reduced, energy spent for radial expansion in thin but continuous pores is less than that spent for axial expansion (e.g. root penetration through the soil matrix) within large and discontinuous pores (Bengough *et al.*, 2006). Roots influence soil physical quality through different mechanisms: mucilage secretion is beneficial to roots growing within a root channel (Ghezzehei e Albalasmeh, 2015), and soil water content changes caused by root absorption may enhance soil shrinkage, and therefore pore continuity (Bottinelli *et al.*, 2016).

Information regarding the soil physical quality of the Brazilian soybean-based production systems and how crop rotation affects it are still scarce. Furthermore, this information is critical to gain sustainable crop production systems in Brazilian Agriculture. In this study, we tested the hypothesis that crop rotation may positively influence the soil physical quality of long-term NT soybean-based production systems. The objective of this study was to evaluate the long-term effect of CS and crop rotation systems on soil physical properties such as bulk density (B_d), total porosity (TP), available water content (AWC), relative saturation at field capacity (FC/TP), air permeability (Ka) and soil pore continuity (K1), as well as on the least limiting water range.

MATERIALS AND METHOD

This study was carried out at the experimental farm of the Mato Grosso Foundation (Fundação MT) in Itiquira county, Mato Grosso state, central Brazil (170°09′S, 540°45′W, 490 m above sea-level). The climate of the region is classified as tropical with a dry winter (Aw) according to the Köppen classification. The average annual rainfall and temperature are 1600 mm and 22ºC, respectively. The soil is classified as Rhodic Ferralsol according to the WRB (2006), or Latossolo Vermelho distrófico according to the Brazilian classification system (Santos *et al.*, 2013). This soil type represents the soils of central Brazil, covering about 46% of the CER (Fageria e Baligar, 2008). Soil texture analysis indicated a clayey texture (567 g kg^{-1} clay and 386 g kg^{-1} sand) for the 0.0-0.1 m layer and a very clayey texture at the 0.1-0.2 m and 0.2-0.4 m depths (613 g kg^{-1} clay, 358 g kg^{-1} sand; and 724 g kg^{-1} clay, 254 g kg^{-1} sand, respectively).

The experiment began in 2008 at a commercial farm that had been cultivated with soybean and maize for 25 years. Before the setup of the experiment, subsoiling was conducted down to 40 cm to loosen compacted soil layers. The experiment was designed to study the influence of different soybean cropping systems on the soil physical quality and crop yield. Each plot was 600 m^2 (20 m wide and 30 m long). Eight treatments were originally established involving soil tillage and crop rotation in a complete randomized blocks design with four replications. Six treatments involving no-till were selected for this study: three treatments were under crop succession (CS-Ma, CS-Me and CS-Br) and three under crop rotation (CR-2 CR-3 and CR-3D) as described in Table 1. CS-Ma, CS-Me and CS-Br were CS schemes involving soybean as a spring/summer crop and maize (*Zea Mays)*, millet (*Pennisetum glaucum)* and brachiaria (*Urochloa ruziziensis*) as the fall/winter crop, respectively. The arrangement of the crop within crop rotation include CR-3 and CR-3D as tri-annual crop rotation treatments, while CR-2 represents a bi-annual crop rotation treatment. In the treatments under crop rotation, maize was always intercropped with brachiaria, in such a way that after the maize harvest, brachiaria remained in the area until the next summer crop season (CR-3D and CR-2) or for eighteen months (CR-3). In CR-3, brachiaria was mown up to three times depending on yearly soil weather conditions.

Each experimental plot consisted of 44 rows, spaced 45 cm apart when cultivation was with soybean or maize. The sowing of soybean and maize was performed with a mechanical seeder, equipped with cutting discs for seed and fertilizers deposition. When intercropped with maize, brachiaria seeds were sown in the maize row, mixed with the fertilizer. When cropped individually, millet, crotalaria and brachiaria were sown using a seeder for small seeds (SEMEATO TDAX 3500), with a distance of 17 cm between the rows. The application of lime, fertilizers, and agrochemicals were made according to the regional recommendations for each crop (EMBRAPA, 2013).

Table 1. Crop succession and rotation schemes in soybean production systems.

Treatment	**Year 1**	**Year 2**	**Year 3**
CS-Ma	Soybean/Maize	Soybean/Maize	Soybean/Maize
CS-Me	Soybean/Millet	Soybean/Millet	Soybean/Millet
CS-Br	Soybean/Brachiaria	Soybean/Brachiaria	Soybean/Brachiaria
CR-2	Soybean/Crotalaria	Summer Maize+Brachiaria	--
CR-3	Soybean/Maize+Brachiaria	Brachiaria	Soybean/Crotalaria
CR-3D	Soybean/Crotalaria	Summer Maize+Brachiaria	Soybean/Millet

Soybean: *Glycine max* (L.) Merril; Maize: *Zea Mays*; Millet: *Pennisetum glaucum; Brachiaria: Urochloa ruziziensis* and Crotalaria: *Crotalaria Ochroleuca*. In each year, crops before and after slashes were cropped during the summer and winter, respectively. Maize+brachiaria: Maize intercropped with brachiaria.

One undisturbed soil sample (215 cm^3) was obtained from the 0-10, 10-20 and 20-40 cm layer depths for each of the plots between 5-10th February 2017, around nine years after the setting up of the experiment. The samples were randomly taken from between the crop rows to avoid any effect of the sowing furrow. The total number of samples for each layer was 24 (six treatments and four replications per treatment), totaling

72 samples. Soil core samples were prepared and subjected to gradual water saturation. After saturation, samples were weighed and subjected to a matric potential of -0.01 MPa on a tension table similar to that described by Ball e Hunter (1988). After equilibration, air-permeability (Ka) measurements (Ball e Schjønning, 2002) were taken using a constant air head permeameter as described by Figueiredo (2010). The K1, a pore continuity index was calculated according to Groenevelt *et al.* (1984) through the ratio between Ka and the air-filled porosity (ε_a). The air-filled porosity was calculated according to equation 1:

$$\varepsilon_a = TP - \theta_{0.01\,MPa} \qquad \text{eq. 1}$$

where ε_a is air-filled porosity ($m^3\ m^{-3}$) when Ψ=-0.01 MPa, TP is total porosity ($m^3\ m^{-3}$) and $\theta_{0.01\ \mathrm{MPa}}$ is soil water content ($m^3\ m^{-3}$) when Ψ=-0.01 MPa. Total porosity (TP) was obtained by measuring the soil water content at saturation.

The field capacity (FC) and wilting point (WP) were obtained for each sample through the soil water content at Ψ=-0.01 MPa (Reichardt, 1988) and Ψ =-1.5 MPa, respectively. The WP was obtained using the psychometric method using a WP4-T Dewpoint potential meter as described by Campbell *et al.* (2007) and Leong *et al.* (2003). Approximately 10 g of soil was inserted into the equipment capsule at two measurements of water potential (Ψ). To obtain the WP, we followed the methodology described in the equipment manual (Decagon, 2007). Soil relative saturation at field capacity (FC/TP) was obtained according to the method described by Reynolds *et al.* (2002), assuming a value of 0.66 being optimal for soil biological activity. The available water content (AWC, $m^3\ m^{-3}$) was calculated as the difference between FC and WP as described by Hillel (1998).

The definitions and procedures involved in the conception of the FC rely on aspects exclusively related to inherent soil properties while its relation with the physiological behavior of the plants is only taken into consideration when it is stated that the FC is the maximum water content with non-limiting aeration. Even so, this limit is already defined in the LLWR concept as the θ_{Air} - the soil water content in which the air-filled porosity is equal to 0.10 $m^3\ m^{-3}$. Usually, FC defines the upper limit of the LLWR when θ_{Air} overcomes FC, while root functionality would only be limited when θ_{Air} is reached. Therefore, the use of FC as an upper LLWR limit may result in a misrepresentation of the soil capacity by the latter, due to an overestimation of water-induced plant aeration stress at near saturation soil water contents (i.e. rainy seasons in which the soil is near saturation for long periods). Van Lier (2017) describes how the amount of water used by plants during periods in which the soil water content is higher than FC may represent 50% of the total water volume used by the plant. Yet, this consumption may vary according to the definition of FC, since different water tensions are used for measuring FC (i.e. 0,0033; 0,001 or 0,0006 MPa) according to Zangiabadi *et al.* (2017). Van Lier also concludes that FC may misrepresent the superior limit of soil water availability to plants.

Therefore, the LLWR was obtained using a modified approach of Silva *et al.* (1994), in which FC was not used as the upper limit of the LLWR; instead, the soil water content in which air-filed porosity reaches a critical value (θ_{Air}, m^3 m^{-3}) was adopted. θ_{Air} represents a soil water content limit in which, when exceeded, soil aeration may restrict air supply to plants and microbe respiration. It was obtained using equation 2:

$$\theta_{Air} = TP - 0.1 \qquad \text{eq. 2}$$

The soil water content at which the penetration resistance reaches the critical value (θ_{PR}) represents the soil water content at which soil penetration resistance may reach a critical limit for root growth. To obtain $\theta_{PR,}$ the samples were dried at room temperature and 6-8 penetration resistance (PR) measurements were performed for each sample during the drying steps. PR measurements were made using a bench penetrometer equipped with a 4 mm wide and 30° semi-angle penetration cone. Cone penetration speed was constant (0.01 m min^{-1}) resulting in one PR measurement for every 0.75 s and the average PR for each sample was calculated. After that, samples were weighed to obtain the soil water content for each PR average. With those measurements, each sample was used to make a soil penetration resistance curve as a function of soil water content. The data for PR f(θ) were fitted to an exponential model using the PROC NLIN procedure of SAS (Institute, 2002) that followed equation 3:

$$PR = a\theta^{b} \qquad \text{eq.3}$$

where PR is penetration resistance (MPa), θ is soil water content (m^3 m^{-3}), and *a* and *b* are the fitted coefficients.

With the fitted equation, we proceeded to estimate the θ at which PR reached a critical or limiting value. The limiting θ_{PR} value of 3.5 MPa as used herein was established by Moraes *et al.* (2014) for soil under long-term NT and also used by Anghinoni *et al.* (2019) for another study conducted in soil close to this experiment site. Using WP, θ_{PR} and θ_{Air}, we calculated the LLWR. The upper limit of the LLWR was defined by θ_{Air}, and the lower limit was the highest water content defined by θ_{PR} or WP. With that, a single value of LLWR was calculated for each sample.

After all the measurements were taken, samples were oven dried at 105 ºC for 48 h. B_d (Mg m^{-3}) was estimated according to Grossman e Reinsch (2002). The volumetric moisture contents (θ), such as the FC, were obtained through the gravimetric water content and B_d.

The data homogeneity was tested using the Levene test ($p>0.05$) prior to computing the ANOVA (Institute, 2002) through the method of Gomez e Gomez (1984) for a completely randomized block design. Comparisons among the treatment means were performed using the Tukey test ($p>0.1$). The data for each soil layer (0-10, 10-20 and 20-40 cm) were individually analyzed, and comparisons were not performed among layers.

RESULTS AND DISCUSSION

The average values of B_d, TP, FC, FC/TP, AW, θ_{PR}, θ_{Air} and ε_a for the 0-10, 10-20 and 20-40 cm soil layers of each treatment are shown in Table 2. For the 0-10 cm layer, B_d was higher under CS-Ma when compared with CR-3, CR-3D and CS-Me as well as under CR-2 compared with CS-Me. Similarly, FC was higher under CS-Ma in comparison with CS-Me, CS-Br and CR-3D. These results suggest the occurrence of a compacted superficial layer in CS-Ma, as indicated by the decreased volume of pores retaining water at high matric potentials such as -0.001 MPa.

Soil compaction promotes an increase in micropore or mesopore volume by reducing macropore diameter (Dorner *et al.*, 2010; Lipiec *et al.*, 2012). The decrease in large pores results in an increase in the pores responsible for water retention, and identified herein by the FC/TP ratio. In fact, B_d, FC/TP also indicated lower porosity in the surface layer (0-10 cm) of the CS-Ma treatment in comparison with CR-3 and CR-3D. Furthermore, the FC/TP under CS-Me was also lower than under CS-Ma, indicating that the soil under soybean and millet succession was less prone to compaction than that under soybean and maize succession. The compacted surface layer under CS-Ma was probably caused by machinery traffic, since CS-Ma is the only treatment under twice yearly heavy machinery traffic, such as harvesters. As discussed by Fu *et al.* (2019) and Keller *et al.* (2019), increasing heavy machinery traffic results in soil compaction, causing loss of macroporosity, negatively impacting soil physical functionality and crop yields.

Table 2. Physical quality variables of a Rhodic Ferralsol at the 0-10, 10-20 and 20-40 cm layer depth, under crop succession treatments (CS-Ma, CS-Me and CS-Br) and crop rotation treatments (CR-2, CR-3 and CR-3D).

Layers (cm)	**TREAT.**	**B_d**	**TP**	**FC**	**FC/TP**	**AWC**	**θ_{PR}**	**θ_{Air}**	**ε_a**
0-10	**CS-Ma**	1.24 A	0.52 A	0.41 A	0.80 A	0.15 AB	0.36 A	0.41 C	0.11 A
	CS-Me	1.11 C	0.56 A	0.39 B	0.73 B	0.15 AB	0.23 B	0.47 A	0.17 A
	CS-Br	1.18 ABC	0.54 A	0.39 B	0.75 AB	0.14 B	0.29 AB	0.43 BC	0.12 A
	CR-2	1.20 AB	0.52 A	0.41 AB	0.76 AB	0.16 A	0.28 AB	0.45 AB	0.10 A
	CR-3	1.14 BC	0.54 A	0.40 AB	0.74 B	0.16 A	0.32 AB	0.43 BC	0.24 A
	CR-3D	1.12 BC	0.55 A	0.39 B	0.71 B	0.15 AB	0.31 AB	0.43 BC	0.14 A
	CV (%)	3.37	5.35	2.45	3.49	6.78	16.72	3.76	65.11
10-20	**CS-Ma**	1.27 A	0.52 A	0.40 A	0.77 A	0.24 A	0.32 A	0.41 A	0.12 A
	CS-Me	1.21 C	0.51 A	0.39 B	0.76 A	0.21 B	0.31 A	0.41 A	0.12 A
	CS-Br	1.21 C	0.52 A	0.39 B	0.75 A	0.21 B	0.31 A	0.42 A	0.14 A
	CR-2	1.24 AB	0.52 A	0.39 AB	0.78 A	0.22 AB	0.31 A	0.41 A	0.12 A
	CR-3	1.21 C	0.53 A	0.39 AB	0.75 A	0.22 AB	0.33 A	0.41 A	0.13 A
	CR-3D	1.22 BC	0.51 A	0.39 B	0.75 A	0.21 B	0.29 A	0.42 A	0.13 A
	CV (%)	1.25	2.87	1.50	3.59	4.61	8.58	2.91	17.28
20-40	**CS-Ma**	1.23 A	0.52 C	0.37 AB	0.71 ABC	0.20 AB	0.32 A	0.43 AB	0.15 AB
	CS-Me	1.21 A	0.52 C	0.39 A	0.74 A	0.21 A	0.31 A	0.42 B	0.18 AB
	CS-Br	1.22 A	0.52 C	0.38 AB	0.73 AB	0.20 AB	0.31 A	0.42 B	0.14 AB
	CR-2	1.16 B	0.55 AB	0.37 B	0.68 C	0.18 B	0.29 A	0.44 AB	0.12 B
	CR-3	1.20 AB	0.56 A	0.37 B	0.68 BC	0.17 B	0.28 A	0.45 A	0.17 AB
	CR-3D	1.17 B	0.54 B	0.39 A	0.69 ABC	0.21 A	0.28 A	0.45 A	0.20 A
	CV (%)	1.54	1.35	2.34	3.72	6.18	6.0	3.42	23.26

*Equal letters indicate an absence of statistical differences by Tukey test ($p<0.10$). B_d: Soil Bulk density (Mg m^{-3}); TP: Total porosity (m^3 m^{-3}); FC: Water content at field capacity (m^3 m^{-3}); FC/TP: Relative saturation at field capacity (dimensionless); AW: plant available water (m^3 m^{-3}); θ_{PR}: soil water content in which penetration resistance reaches 3.5 MPa (m^3 m^{-3}); θ_{Air}: soil water content in which aeration is minimally adequate (m^3 m^{-3}) and ε_a: air filled porosity at field capacity (m^3 m^{-3}).

The AWC exhibited a similar behavior to the B_d, FC and FC/TP for the 0-10 cm layer, but indicated a higher water availability to plants under crop rotation (CR-2 and CR-3) in comparison with the crop succession treatment (CS-Br). The LLWR (Figure 1) was 267% higher under CS-Me than under CS-Ma.

Differences in water availability, measured by both the AWC and LLWR, were strongly influenced by soil management, especially within 0-10 cm soil layer (Figure 2). Under CS-Ma, the LLWR was lower than the AWC, while the LLWR was higher than the AWC in the CS-Me (Figure 2). Therefore, we can state that the use of the AWC for plant water access in surface soil under CS-Ma and CS-Me would result in overestimated and underestimated values, respectively.

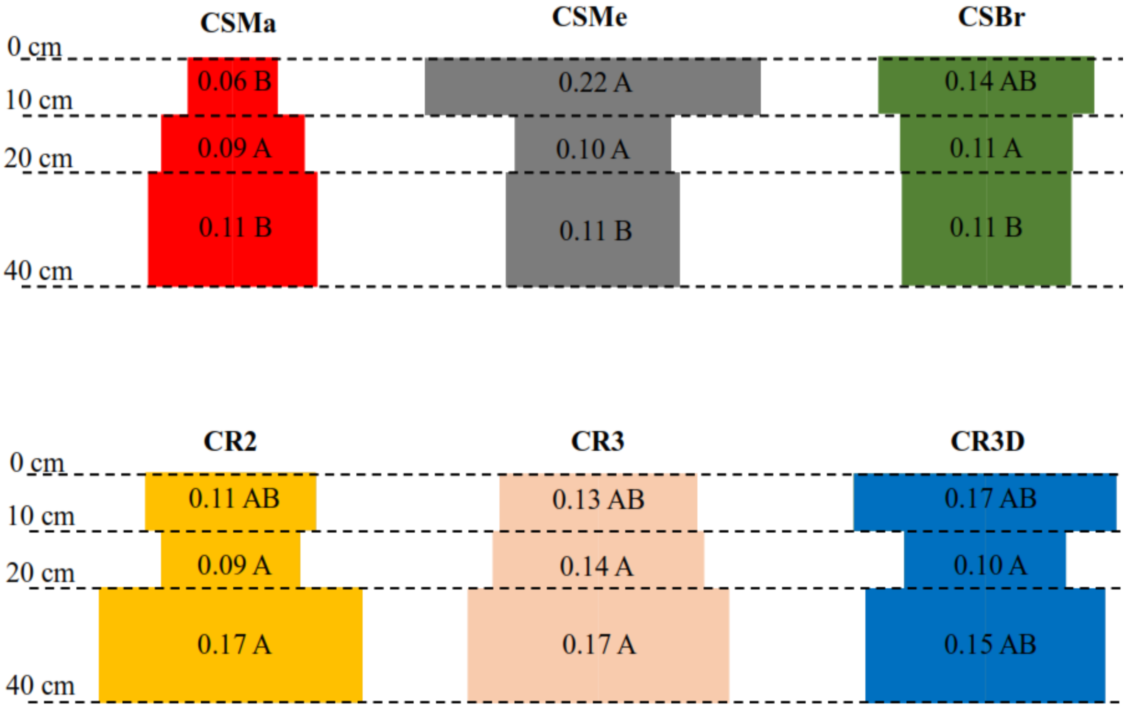


Figure 1. The least limiting water range (LLWR; $m^3 m^{-3}$) in three layers of a Rhodic Ferralsol under different soil management treatments. The width of the colored bars and the values inside refer to the LLWR of each treatment layer. Different uppercase letters indicate a statistical difference between treatments by Tukey test ($p<0.10$). CV (%) equal to 41.44; 29.62 and 20.75 for the 0-10, 10-20 and 20-40 cm layers, respectively.

Restricted root penetration could be responsible for decreasing the LLWR in comparison with the AWC in the 0-10 cm layer under CS-Ma, while misrepresentation of the upper water content limit by the FC provided a lower AWC in comparison with the LLWR under CS-Me. The WP only limited the LLWR in the 0-10 cm layer of the CS-Me treatment. This finding suggests that soil penetration resistance was more widely limiting to root growth when the soil was dry than WP. Bengough *et al.* (2011) indicated that penetration resistance was the main factor affecting plant growth, as was found by Tormena *et al.* (2017) and other studies in Brazil (Betioli Júnior *et al.*, 2012; de Lima *et al.*, 2012).

In the 0-10 cm layer under CS-Ma there was a greater part of the AWC outside of the LLWR limits in comparison with the overlapping part of both. This portion of water therefore was unavailable for plants to access (Figure 2), indicating that an expressive portion of water previously assumed as available for plants in the surface soil under CS-Ma is in fact unavailable due to excessive soil penetration resistance. In the CS-Me treatment, the AWC was integrally available as indicated by the overlap with the LLWR.

This may be a result of the effect of the millet radicular system on the soil structure in the 0-10 cm layer, reducing the penetration resistance of the soil. These results are in line with Nascente e Stone (2018) who found soil physical quality improvements provided by crop rotation involving millet, associated with the beneficial effect of grasses roots on soil structural and physical amelioration.

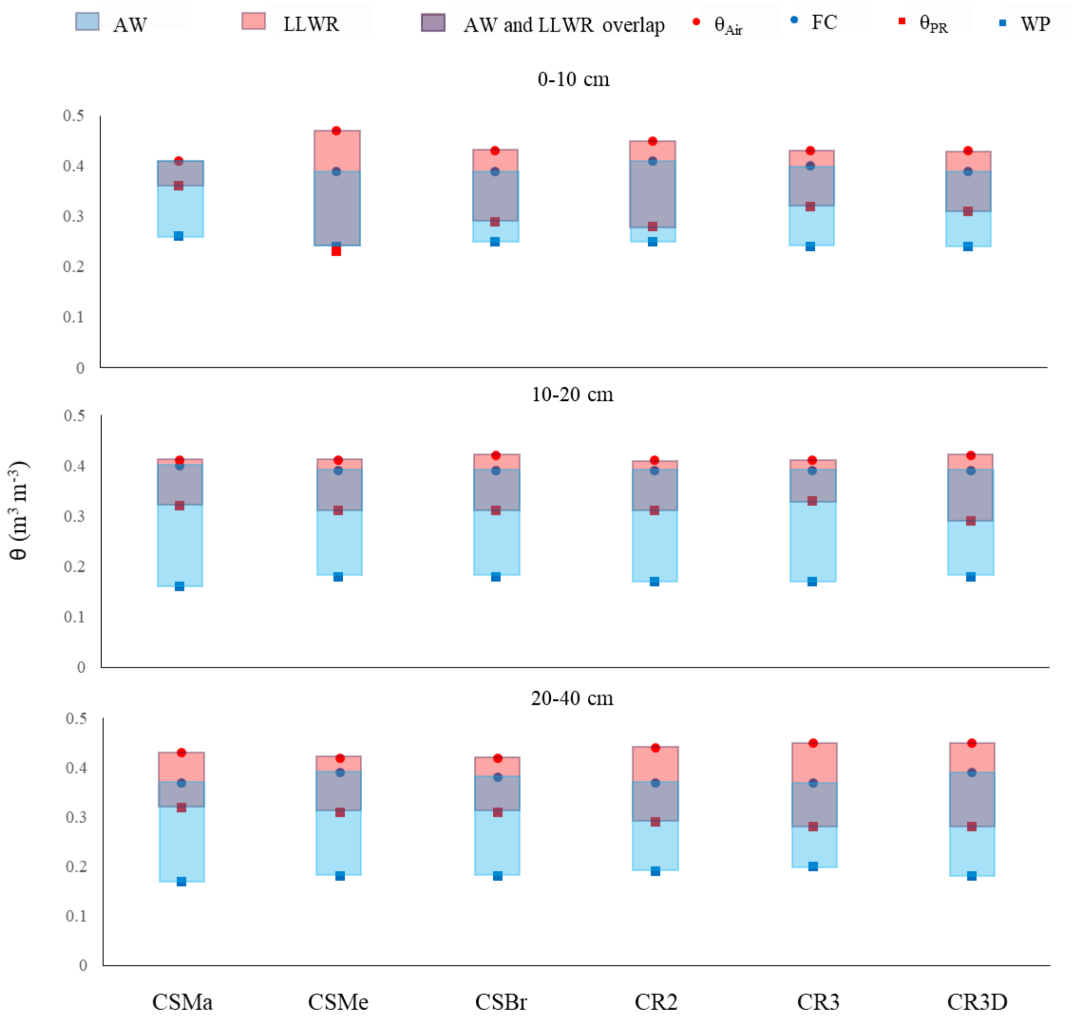


Figure 2. Water content (θ) limits and overlap of available water to plants (AW) and the least limiting water range (LLWR) in three layers (0-10, 10-20 and 20-40 cm) of a Rhodic Ferralsol under three crop succession (CS-Ma, CS-Me and CS-Br) and three crop rotation (CR-2, CR-3 and CR-3D) treatments.

We found that air-filled porosity under CS-Ma was reduced within the 0-10 cm layer, because θ_{Air} under CS-Me and CR-2 overcame that under CS-Ma (Table 2; Figure 2). Average Ka in the CS-Ma soil was also lower than those under CS-Me, CR-3 and CR-3D in the 0-10 cm soil layer (Figure 3). The 0-10 cm layer under CS-Ma was the only case where Ka<1 μm^2 indicating that excessive soil compaction under soybean-maize succession provided a soil impermeable to gas fluxes (McQueen e Shepherd, 2002). On the other hand, ε_a did not show differences among treatments for the 0-10 cm and 10-20 cm soil layers (Table 2).

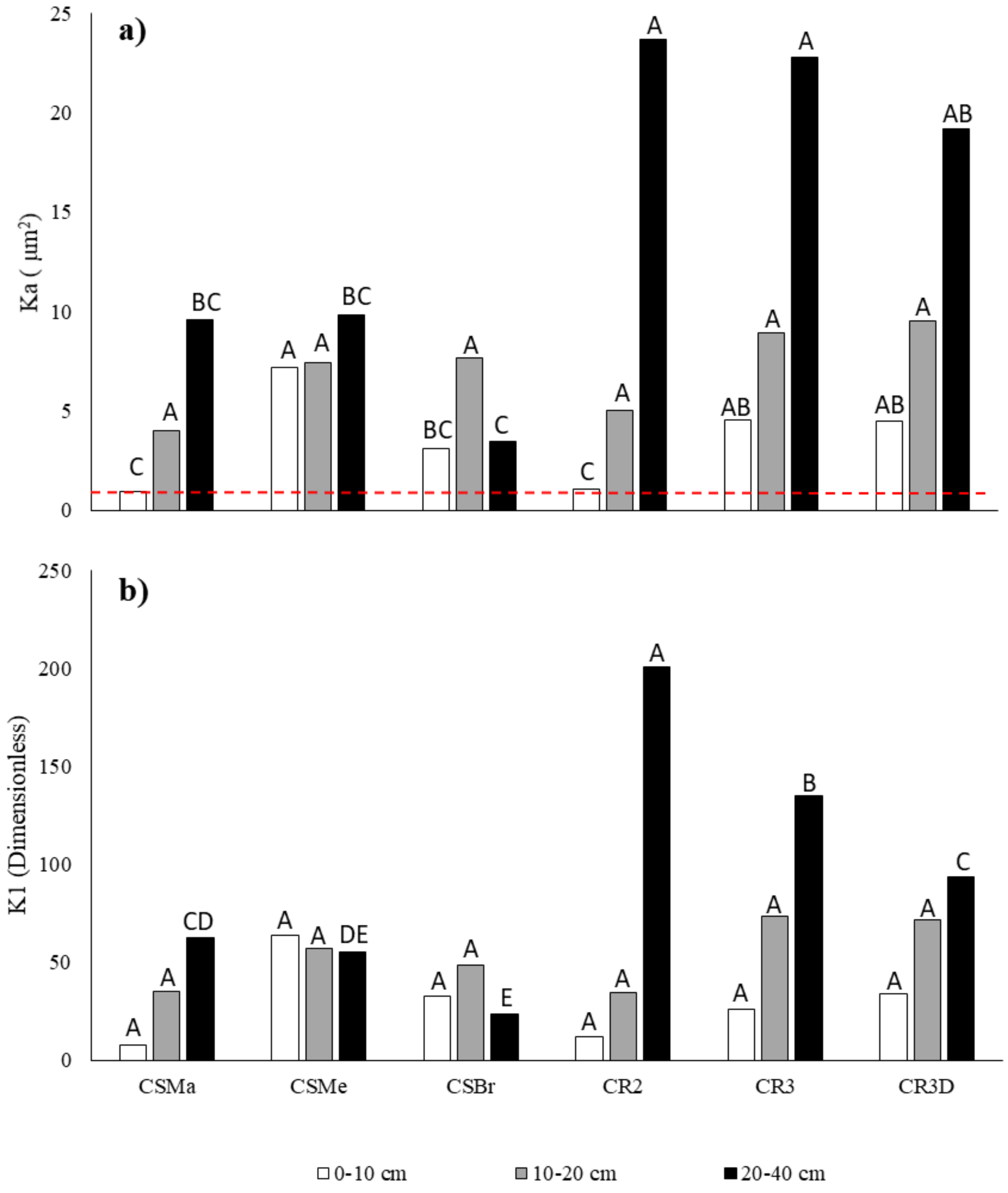


Figure 3. a) The soil air permeability (Ka; μm^2) and b) pore continuity index (K1; dimensionless) from three layers of a Rhodic Ferralsol under different soil treatments. Different uppercase letters indicate a statistical difference between treatments by Tukey test ($p<0.10$). CV (%) of Ka corresponds to 38.31, 88.13 and 38.33 for the 0-10, 10-20 and 20-40 cm layers, respectively, while CV (%) of K1 corresponds to 98.33, 84.52 and 19.69 for the 0-10, 10-20 and 20-40 cm layers, respectively.

Penetration resistance under CS-Ma, in turn, reached critical levels in wetter conditions than under CS-Me (Table 2; Figure 2). Nevertheless, poor soil physical quality in the interrow of the soybean crop under no-tillage is probably minimized by furrow opening. Results from Anghinoni *et al.* (2017) and Ferreira *et al.* (2016) indicated differences between soil physical quality in the row and interrow for the 0-10 cm layer under NT, due to improved aeration and soil pore system functionality under the plant row.

Decreased LLWR in comparison with AWC, within the 10-20 cm layer of all the treatments, was associated with excessive soil penetration resistance to root growth, since θ_{PR} was always higher than the WP as can be seen in Figure 2. In the 10-20 cm layer, only B_d, FC, and AW were different among the treatments (Table 2). The average B_d values under CS-Ma was no different to that under CR-2; however, it exhibited increased B_d and FC compared with all of the other treatments within this soil layer. There was an increase in B_d under CR-2 in comparison with CS-Me, CS-Br and CR-3, while the FC and AWC displayed similar behavior in the 10-20 cm layer; the CS-Me, CS-Br and CR-3D treatments had lower FC and AW than CS-Ma, while other comparisons were not significant ($p<0{,}1$). These results indicate impaired soil physical quality not only for the 0-10 cm, but also in the 10-20 cm layer under the traditional soybean/maize crop succession. However, the absence of differences among the remaining variables, including the LLWR, demonstrated that soil physical degradation in the 10-20 cm layer under CS-Ma affected soil physical properties related to plant growth parameters such as the LLWR, θ_{PR} and θ_{Air}.

All soil physical properties were influenced by the treatments at the deepest layer (20-40 cm), where B_d was lower in CR-2 and CR-3D in comparison with the crop succession treatments. Overall comparisons for this layer indicate a lower B_d under crop rotation treatments. In addition, TP was lower under crop succession treatments when compared with those under crop rotation within this layer. The 20-40 cm soil under CR-3 also had a higher TP compared with CR-3D. Both the FC and AWC also demonstrated similar behavior to the one observed for TP and B_d in the 20-40 cm layer. It was verified that the 20-40 cm soil layer under CS-Me and CR-3D had increased water retention at Ψ=-0,001 MPa and AWC when compared with CR-2 and CR-3. As for TP, a contrast in the FC/TP was observed among crop rotation and succession treatments for the 20-40 cm soil layer, which indicated that the porosity of CR-2 and CR-3 was excessively occupied by water when compared with CS-Me, as was also observed for CS-Br in comparison with CR-2.

Differences in the soil physical quality under crop rotation versus the crop succession treatments were also measurable for the LLWR of the 20-40 cm layer. Some crop rotations (CR-2 and CR-3) had a LLWR 54% higher than that measured in the crop succession production systems. These results, for B_d, TP and the FC/TP, indicate that increased root access to this layer primarily caused improved soil physical quality in the crop rotation treatments. Similar results were also described by Calonego *et al.* (2011) and Anghinoni *et al.* (2019).

Figure 2 indicates the differences in the AWC and LLWR caused primarily by the overestimation of the AWC. As discussed above, the FC may be an inadequate upper limit for water availability for plants, especially in deeper layers where soil water content takes longer to decrease (Reynolds, 2018), maintaining water content nearer to soil saturation longer than in the surface layers. The use of θ_{Air} as an upper limit of the LLWR added the effect of aeration improvements, caused by the crop rotation treatments, into the LLWR for the 20-40 cm layer, visible as the reddish area of the bars in Figure 2. The reddish area of the bars of the crop succession treatments was 62% lower than that under the crop rotation treatments in the 20-40 cm soil layer, indicating that the use of the FC as the upper limit of the LLWR may result in its overestimation, mainly because an excessive portion of water is considered unavailable due to restricted aeration.

Despite the fact that the θ_{PR} of the 20-40 cm soil layer was not statistically different among the treatments, Figure 2 indicates that a lower soil penetration resistance provided an increased LLWR within this layer in the crop rotation treatments. The limits and behavior of the LLWR of the 10-20 cm layer indicated no influence of the treatments. An absence of differences in the soil physical quality of the 10-20 cm layer under NT has already been described by Anghinoni *et al.* (2019), Ferreira *et al.* (2016) and Betioli Júnior *et al.* (2014) in Brazilian Oxisols under long-term no-tillage systems.

The average values for Ka and K1 indicated an expressive effect of crop rotation on soil aeration and pore continuity/connectivity in the 20-40 cm layer. The Ka values corroborated with the LLWR, since CR-2 and CR-3 had improved Ka in comparison to crop succession. The average values of Ka in CR-3D were only superior to CS-Br for the 20-40 cm layer. Besides the CS-Ma and CR-3D comparison, K1 in the crop rotation treatments was also higher than under crop succession within the 20-40 cm layer. Pronounced differences in K1 and Ka for this layer, on the other hand, were verified between CS-Br and CR-2, with Ka and K1 values 590% and 740% higher under CR-2, respectively. It appears therefore that the crop rotations were more inclined to promote improved physical conditions for plant growth in the 20-40 cm layer, mainly because soil aeration and pore continuity were positively affected. Besides contributing to aeration, increased pore continuity may contribute to root penetration and provide alternative routes for root elongation through compacted soil, as suggested by Bengough *et al.* (2006). Colombi *et al.* (2017) found that macropores attracted roots and were used for root growth through the soil, improving crop yields, while Anghinoni *et al.* (2019) reported an increased cotton yield when continuous and connected pores improved root access to deeper soil in an experiment 10 m in distance from the current experimental site.

Despite the positive effects of crop rotation on the TP, θ_{Air} and Ka, it appears that increased air-filled porosity (Table 2) was not the cause of the air permeability improvements within the 20-40 cm layer. Once Ka is affected by ε_a and pore continuity (Groenevelt *et al.*, 1984), it can be concluded that pore continuity may be leading improvements in aeration at this deepest layer.

The total amount of available water within the soil profile (0-40 cm) under CS-Ma was 32% less than all other treatments, as indicated by the LLWR in Figure 1. The decrease in the LLWR of the CS-Ma soil profile was affected the most by the soil physical quality of the surface layer (0-10 cm) in which the LLWR under CS-Ma was 61% lower when compared with all the remaining treatments. In all the treatments and layers, and especially the surface layer (0-10 cm), the FC/TP was higher than its optimal value (0.66) described in literature. Hence, the FC/TP mainly indicates suboptimal conditions for plant growth, due to poor soil aeration in the interrow zone of NT soybean, especially in the 0-10 cm layer.

The more pronounced influence of crop rotation on the soil physical quality was related to soil aeration and pore continuity (θ_{Air}, Ka and K1), positively affecting the LLWR, and contrasting the soil physical quality of the crop rotation and crop succession treatments in the 20-40 cm layer. While differences in the soil physical quality of the subsoil appeared to be less related to the soil's resistance to root penetration, soil physical quality of the surface soil was highly impacted by the negative effects of penetration resistance in dry soil. Similar results were found by Anghinoni *et al.* (2019), indicating that after seven years of cultivation, crop diversity enhanced the soil physical quality of the subsoil, and especially the LLWR, positively affecting cotton yields during two cropping seasons in central Brazil. As stated by Anghinoni and colleagues, the improved soil physical quality of the subsoil may enhance plant resilience during water stress periods, such as dry spells. Hansel *et al.* (2017) found that root growth deeper into the soil improved plant drought tolerance, positively affecting yields. Gaudin *et al.* (2015) found that increased crop diversity positively influenced soybean and maize yield stability during critical cropping seasons and attributed those results to soil amelioration caused by root system diversity and soil organic matter accumulation.

In fact, soil air permeability, TP and pore continuity (K1) were the studied variables most affected by the treatments, as seen in Figure 4. The K1index for the 20-40 cm layer was the variable with the highest ANOVA F value (46.63), followed by the TP within the same layer (F=21.94). The soil physical quality of the 20-40 cm soil layer was the most influenced by the treatments, since the B_d, FC, TP, AW, LLWR, Ka, K1, θ_{Air} and FC/TP highlighted significant differences within this layer, followed by B_d, LLWR, Ka and θ_{Air} in the 0-10 cm layer.

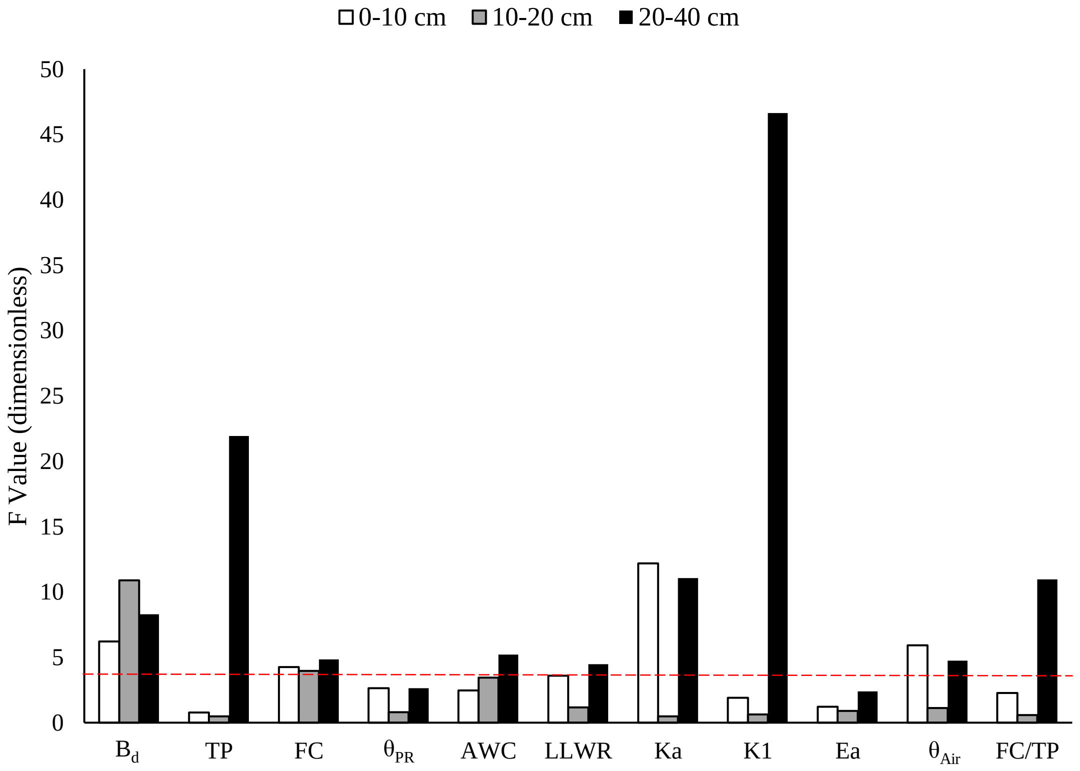


Figure 4. ANOVA F value of each variable studied for the three soil layers (0-10, 10-20 and 20-40 cm). The red dotted line represents the significant F value equal to 3.58, and values above it indicates statistical significance by ANOVA. Bd: Soil Bulk density; TP: Total porosity; FC: Water content at field capacity; FC/TP: Relative saturation at field capacity; AW: plant available water; LLWR: least limiting water range; θPR: soil water content in which penetration resistance reaches 3.5 MPa; θAir: soil water content in which

aeration is minimally adequate; Ka: Soil air permeability; K1: Soil pore continuity index and Ea: air filled porosity at field capacity.

Pore connectivity of the 20-40 cm soil layer was the soil physical quality property most influenced by the treatments – because of differences in plant root access to the subsoil – which consequently affected air permeability, Ea and θ_{Air}. Our results are in line with Colombi *et al.* (2019) who found evidence that improved gas transport in the soil was positively related to soil organic carbon content, both influenced by root growth. The results described by Anghinoni *et al.* (2019) showed that the improved soil physical quality in the 20-40 cm layer of an Oxisol from the *Cerrado* was due to increased root growth, which created continuous pores through soil profile and favored root growth and air supply within that layer. Bacq-Labreuil *et al.* (2018) also concluded that plants increased macroporosity and pore connectivity of clayey soils through root growth. Pore connectivity appears to be the soil capacity property most sensitive to conservation agriculture. Root quantity and diversity may improve aeration because root growth creates “large avenues” into the soil, allowing good aeration and root access to deep layers. Notwithstanding, effects of a compacted surface soil layer under CS-Ma were also visible through other variables as a result of a hostile environment to root growth, it was visible using the LLWR, θ_{PR}, θ_{Air} and Ka.

CONCLUSIONS

Overall crop succession damaged soil physical quality through the soil profile when compared with crop rotation. Nevertheless, succession of soybean and millet resulted in increased soil physical quality of the 0-10 cm soil layer after 9 years of cultivation. The main farming system in Brazilian farmlands (CS-Ma) exhibited poor soil physical quality in the surface layer, caused by soil compaction. Increases in crops diversity would highly benefit Brazilian soybean producers through increased resilience of crops to environmental risks because of improved soil physical quality. crop rotation was associated with an increased soil physical quality through the soil profile, especially within the 20-40 cm layer, as a result of improved soil aeration, pore continuity and water availability. Pore connectivity was the soil property most affected by the treatments and linked to increased root access. Further to this, aeration-related soil physical quality indicators were the most affected by differences in root access to the subsoil, mainly because of improved soil pore connectivity and continuity. The AWC underestimated the amount of plant accessible water in soil when compared with the LLWR due to the misrepresentation of the soil water content limits by the AWC. The LLWR was impaired by penetration resistance when the soil was dry, and by the air-filled porosity in moist soil.

CHAPTER 2

CONSERVATION AGRICULTURE STRENGTHEN SUSTAINABILITY OF BRAZILIAN GRAIN PRODUCTION AND FOOD SECURITY

Resumo: A sustentabilidade da agricultura brasileira tem sido abordada com frequência em debates sobre as influências antrópicas no ambiente. A sustentabilidade da produção agrícola é fundamental para atender à crescente demanda por alimentos, fibras e energia e envolve componentes econômicos e ambientais da agricultura. Testamos, neste estudo, a hipótese de que a agricultura conservacionista contribui para a sustentabilidade da produção brasileira de soja (*Glycine max* (L.) Merril) através de efeitos positivos em um ou mais dos seguintes itens: qualidade do solo, rendimento de grãos e qualidade nutricional, e rentabilidade do agricultor em longo prazo. Os resultados demonstraram que a agricultura conservacionista intensificou o sequestro de carbono, a qualidade física e principalmente biológica do solo, o que causou maior rendimento, conteúdo de proteínas e flavonoides nas sementes de soja, bem como maior lucro do agricultor. Por sua vez, a sequência de cultivo mais utilizada em sistemas de produção de soja no Brasil, a sucessão anual de soja e milho (*Zea Mays*), prejudicou a qualidade física do solo, e por isso, a segurança alimentar e a sustentabilidade agrícola. A hipótese lançada foi aceita, de forma que a sustentabilidade da produção brasileira de soja pode ser aumentada substituindo a sucessão anual de soja e milho por rotações de culturas envolvendo culturas de cobertura.

Palavras chave: Qualidade do solo; sequestro de carbono; flavonoides; proteína; Brasil.

Abstract: Sustainability of Brazilian agriculture has been frequently addressed in debates about human influences on the environment. Sustainability of agricultural production is critical to meet the growing demand for food, fiber and energy, and involves economic and environmental components of agriculture. We tested the hypothesis that conservation agriculture contributes to sustainability of Brazilian soybean (*Glycine max* (L.) Merril) production through positive effects on one or more of the following: soil quality, grain yield and nutritional quality and farmer profitability in long term. We found that conservation agriculture enhanced carbon sequestration, physical and especially biological quality of soil, which caused improved soybean grains yield, protein and flavonoids content and farmer profit. In turn, the most expressive cropping sequence within Brazilian farmlands, the annual soybean and maize double crop (*Zea Mays*), prejudiced soil physical quality which harmed food security and agricultural sustainability. The hypothesis was accepted as long as sustainability of Brazilian soybean production can be increased by replacing the annual succession of soybean and maize by complex crop rotations involving cover crops in the rotation cycle.

Keywords: Soil quality; carbon sequestration; flavonoids; protein; Brazil.

INTRODUCTION

Agricultural sustainability depends on economic, social and environmental components of agricultural production systems (Purvis *et al.*, 2019), and is critical to meeting the growing demand for food, fiber and energy. Conservation agriculture is based on practices that contribute to agricultural sustainability, such as minimal or no soil disturbance, crop rotation with diversified and high biomass production providing better energy efficiency, improved nutrients harnessing and usage and suitable soil quality (Kassam *et al.*, 2019). conservation agriculture has, therefore, been positively associated with improved soil physical functionality, carbon sequestration and enzymes activity in soil (Tivet *et al.*, 2013; Sá *et al.*, 2014; Lehman *et al.*, 2015; Moraes *et al.*, 2016; Nunes *et al.*, 2018; Anghinoni *et al.*, 2019; Mendes *et al.*, 2019). Under Brazilian tropical farmlands, conservation agriculture is critical to sustaining soil organic carbon (SOC) pools (Rusinamhodzi, 2015) and has facilitated the restoration of degraded areas under the Brazilian *Savana* – the *Cerrado* biome – to productive agricultural lands (Kassam *et al.*, 2019).

Since the 1970's, Brazilian agriculture has increased, along with the agricultural production, which has made Brazil as one of the main world agricultural exporters, being the larger producer of sugarcane, orange juice and coffee and soybeans (*Glycine max* (L.) Merril)(Picoli *et al.*, 2018; USDA, 2019). Agricultural intensification arouses concerns about agronomic and environmental issues within farmlands because of soil degradation (Banerjee *et al.*, 2019). Therefore, sustainability of agricultural production, especially in

Brazil, has been frequently addressed in debates about human influences on the environment.

Climate instability is often associated to uncertain food supply, while climate-smart agriculture is addressed as a tool to ensure agricultural resilience in a long-term scenario where climatic instability is critical to food security (Wheeler e von Braun, 2013), and simultaneously conserving and enhancing environmental capabilities in farmlands. Liebig *et al.* (2014) observed that increased crop diversity fostered greater and more stable crop yields, improved nutrient and water-use efficiencies, and increased profit margin compared to that for the less diverse cropping systems. Soybeans grains have high protein content (around 40%), even though it is determined by the interaction of genotype and environment (Miransari, 2016). Flavonoids (FLAV) are part of the three major phenolic compounds for human nutrition (Shahidi e Naczk, 2003). Producing soybean with high nutritional value, such as high protein and flavonoids contents, may positively contribute to alleviate malnutrition and food-related diseases (Dubey *et al.*, 2019), and therefore positively affect food security over time.

Thus, the present study was designed to test the hypothesis that conservation agriculture contributes to sustainability of Brazilian soybean production through positive effects on one or more of the following: soil quality, grain yield and nutritional quality and farmer profitability. The specific objectives of the study were to measure integrated soil quality indicators such as the least limiting water range (LLWR; physical), soil P content (chemical) and β-glucosidase enzyme activity (biological) as well as soybean grains yield, protein and flavonoids contents, the above ground biomass of crops prior to the soybean cultivation, and estimated profitability in four long-term soybean production systems.

MATERIALS AND METHOD

Experiment description

This study was performed at the experimental farm of the Mato Grosso Foundation (Fundacao MT) in Itiquira county, Mato Grosso state, central Brazil (170°09′S, 540°45′W, 490 m above sea-level). The regional climate is classified as tropical with a dry winter (Aw) according to the Köppen classification. The average annual rainfall and temperature are 1600 mm and 22ºC, respectively. The soil is classified as Rhodic Ferralsol according to the WRB (2006), or Latossolo Vermelho distrófico according to the Brazilian classification system (Santos *et al.*, 2013). Soil texture analysis indicated a clayey texture class (567 g kg^{-1} clay and 386 g kg^{-1} sand) for the 0.0-0.1 m layer and a very clayey texture class at the 0.1-0.2 m and 0.2-0.4 m depths (613 g kg^{-1} clay, 358 g kg^{-1} sand; and 724 g kg^{-1} clay, 254 g kg^{-1} sand, respectively).

The experiment began in 2008 at a commercial farm that had been cultivated with soybean and maize for the last 25 years. The experiment was designed to study the impact of different soybean cropping systems on soil quality. Prior to establishing the experiment, sub-soiling was done to 40 cm depth to loosen compacted soil layers. Each plot was 600 m^2 (20 x30 m), and eight treatments involved soil tillage and crop rotation in a complete randomized blocks design with four replications. Four treatments involving no-till selected for this study were: soybean monoculture (Mo), soybean succession with maize (*Zea Mays)* and brachiaria (*Urochloa ruziziensis*; Ma and Br treatments, respectively), and a crop rotation treatment (Crot) involving soybean, maize, brachiaria and crotalaria (*Crotalaria ochroleuca*) (Table 1). In the treatment Crot, brachiaria was cultivated during eighteen months, and mowed at flowering stage to 20 cm height with a tractor-mounted mower.

Table 3.Crop sequences of different soybean production systems in central Brazil.

Treatment	Year 1	Year 2	Year 3
Mo	Soybean/Fallow	Soybean/Fallow	Soybean/Fallow
CS-Br	Soybean/Brachiaria	Soybean/Brachiaria	Soybean/Brachiaria
CS-Ma	Soybean/Maize	Soybean/Maize	Soybean/Maize
Rotation	Soybean/Maize+Brachiaria	Brachiaria	Soybean/Crotalaria

Soybean: *Glycine max* (L.) Merril; Maize: *Zea Mays*; Brachiaria: *Urochloa ruziziensis* and Crotalaria: *Crotalaria Ochroleuca*. In each year, crops before and after slashes were cropped during the summer and winter, respectively. Maize+brachiaria: Maize intercropped with brachiaria.

Each experimental plot consisted of 44 rows, spaced 45 cm apart for cultivation of soybean or maize. Both soybean and maize were seeded with a drill, equipped with cutting discs for placement of seed and fertilizers. When intercropped with maize, brachiaria seeds were sown between the maize row, and were mixed with the fertilizer. When cropped individually, millet, crotalaria and brachiaria were sown using a seeder for small seeds (SEMEATO TDAX 3500), at a spacing of 17 cm between the rows. If needed, phosphorus (P) was applied uniformly across all treatments, in the furrow while seeding of soybean or maize. The application of lime, fertilizers, and agrochemicals were performed according to the regional recommendations for each crop (EMBRAPA, 2013).

Three crops of soybean, seeded at the beginning of the rainy season of the 8th, 9th and 10th year after the on-set of the experiment were studied, and named as CS8, CS9 and CS10, respectively. Soybean crops were seeded on 4th November 2015, 24th October 2016 and 30th October 2017 in CS8, CS9 and CS10, respectively. Total precipitation received during the soybean growing cycle was 1120, 1268 and 1943 mm for the CS8, CS9 and CS10, respectively.

Measurements of plant parameters

Soybean plants were harvested manually from 7.2 m^2 area at maturity (Fehr e Caviness, 1977), threshed, seeds separated from straw, and bagged Soybean grain yield (Yield) was computed by equation 1:

$$\text{Yield} = \left(\frac{\text{GM}}{7.2}\right) \text{x } 10.000 \qquad (1)$$

where Yield is expressed in (Kg ha^{-1}), GM is the mass of grains harvested in an area of 7.2 m^2 (kg), 7.2 m^2 is the harvested area and 10.000 is the conversion coefficient from kg m^{-2} to kg ha^{-1}.

Total N concentration in grains was determined by the Kjeldahl method, and converted to protein content (PROT) (Parkinson e Allen, 1975) by multiplying with 6.25. Concentration of FLAV was measured by spectrophotometrically (Zhishen *et al.*, 1999). Results were expressed in milligram catechin equivalents per gram of ground seed fresh weight.

Biomass dry weight (DW) was measured at the flowering stage by harvesting all above ground biomass from 1.0 m^2 randomly chosen quadrant in each plot. Samples were oven dried and biomass dry weight was reported as kg ha^{-1}.

Profitability

The mean profit of each cropping season was computed by using the data of the Mato Grosso Institute of Agricultural Economics (IMEA, 2015; 2016; 2017) for production costs of soybean in the southern region of the Mato Grosso State. The soybean production costs were expressed in equivalent weight of soybeans per hectare (kg ha^{-1}) to minimize the impact of temporal fluctuations in prices. Thus, the profit was computed as the difference in soybean yield and production costs per hectare, both expressed in the same unit.

Soil Quality Assessment

Soil quality was assessed for the 0-20 cm layer. An undisturbed core (215 cm^3) and a bulk soil sample were obtained for 0-10 and 10-20 cm depths from each plots between 5-10th February 2017, ~ nine years after initiating the experiment. The LLWR was measured following the method by Silva *et al.* (1994). It was computed as the difference between the upper limit (e.g., the soil water content (θ) in which the air-filled porosity reaches 0.10 $m^3\ m^{-3}$, which, if exceeded, may restrict air supply to plants and microbe respiration) and the lower water content limit of the soil. The latter is defined as the highest water content value corresponding to the wilting point (WP) or by the soil water content in which the penetration resistance reaches the critical value for root growth (θ_{PR}). To obtain $\theta_{PR,}$ the samples were submitted to a drying process at room temperature and at least 6 penetration resistance (PR) measurements were performed in each sample during the drying process. PR measurements were made using a bench penetrometer equipped with a 4 mm wide and 30° semi-angle penetration cone. Cone penetration speed was constant (0.01 m min^{-1}), and the average PR for each sample was obtained. After that, samples were weighed to obtain the soil water content for each PR measurement. PR measurements of each sample were used to construct a soil PR curve as a function of soil water content. The data for PR f(θ) were fitted to an exponential model using the PROC NLIN procedure of SAS (Institute, 2002) that followed equation 2:

$$PR = a\theta^{b} \tag{2}$$

Where, PR is penetration resistance (MPa), θ is soil water content ($m^3\ m^{-3}$), and a and b are the fitted coefficients.

The soil water content at which penetration resistance reached the limiting value was estimated with the fitted equation. 3.5 MPa as used herein as the limiting θ_{PR} value, as established by Moraes *et al.* (2014) for soil under long-term NT, and also used by Anghinoni *et al.* (2019) in a study carried out close to this experiment.

θ_{Air} represents a soil water content limit in which, when exceeded, soil aeration may restrict air supply to plants and microbe respiration. It was obtained by using equation 3:

$$\theta_{Air} = TP - 0.1 \tag{3}$$

The WP was obtained using a WP4-T Dewpoint potential meter as described by Campbell *et al.* (2007) and Leong *et al.* (2003). The θ_{PR} was estimated for each sample by performing subsequent measurements of penetration resistance along with soil drying.

Disturbed soil was used for measurement of soil organic carbon (SOC) and exchangeable P contents. Soil exchangeable P was extracted using Mehlich-1 solution, and SOC was determined by dry combustion (Nelson e Sommers, 1996).

After measuring the LLWR, SOC and exchangeable P separately for 0-10 and 10-20 cm layers, an average value of both depths was computed and reported for the 0-20 cm layer.

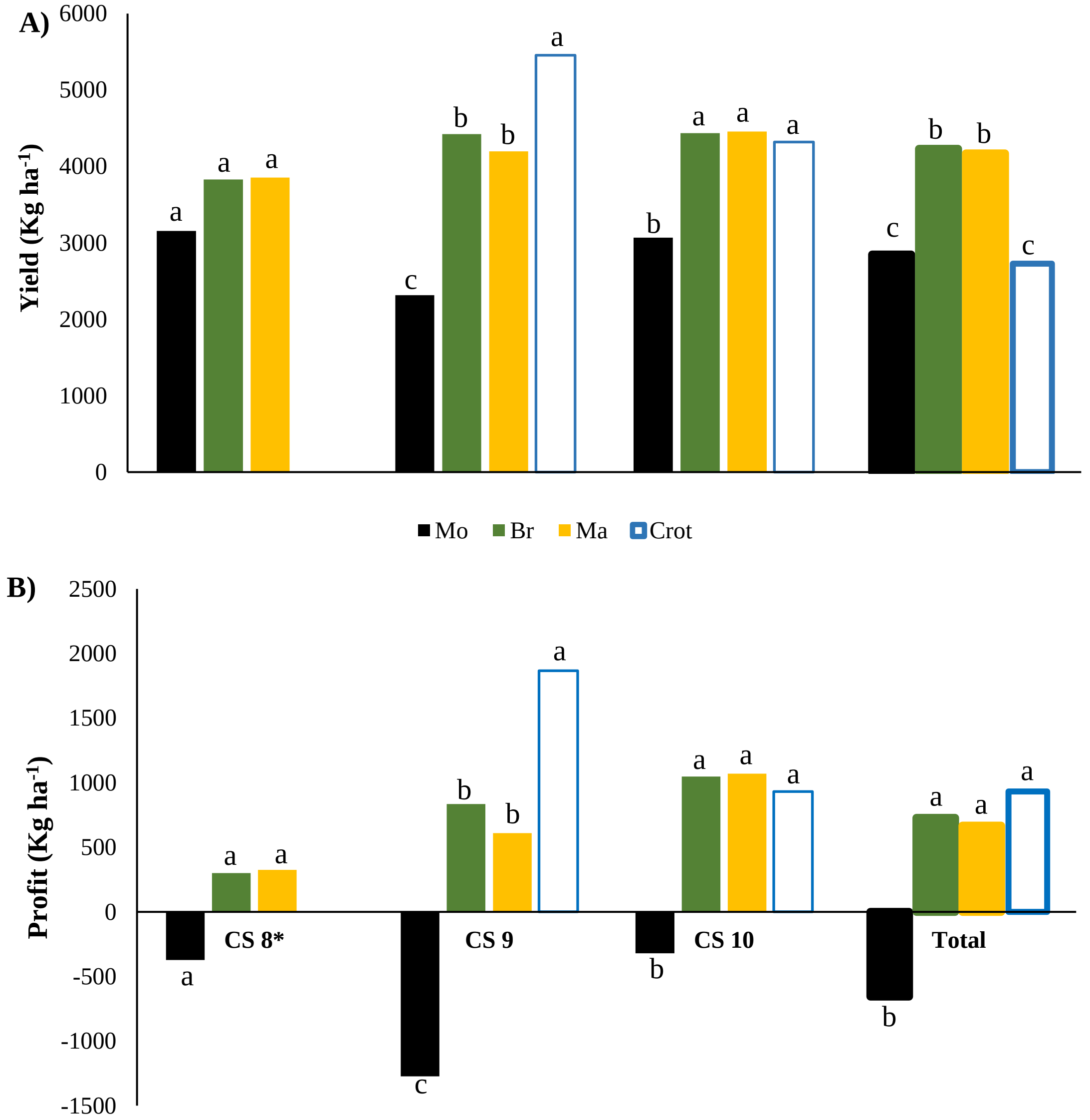
Soil biological quality was assessed by measuring the β-glucosidase activity according to the protocol proposed by Mendes *et al.* (2019), because of its role in the C cycle. In each of the treatments plots, composite soil samples were obtained for 0 to 10 cm depth in December 2015 at the soybean flowering stage. The β-glucosidase (E.C. 3.2.1.21) activity was determined according to the protocol proposed by Tabatabai (1994). Due to the short incubation period (one hour), toluene was omitted from the assays.

Statistical analysis

Data were submitted to homoscedasticity by the Levene test (α=0.05) prior to computing the ANOVA using the SAS software (Institute, 2002). Univariate comparisons were performed using the Tukey´s test (α=0.05) for a complete random block design. The principal component analyses (PCA) was performed to determine the correlations among soil, BW and soybean variables using Statistica PL (version 10.0, StatSoft Inc., Tulsa, USA)

RESULTS

The soybean grain yields and the profits of the three cropping seasons studied (8th, 9th and 10th) and their average value are shown in Figure 1A and 1B. In the 8th cropping season, crop rotation included brachiaria as cover crop and, because of that, no soybean yield was obtained under the crop rotation (Crot) in that cropping season. The 9th and 10th cropping seasons indicated lower Yield under monoculture (Mo) in comparison to those for the other treatments, while the 8th cropping season exhibited no yield differences among treatments. Crop succession (CS-Br and Ma) treatments were characterized by a 86% and 45% higher yield than that under monoculture for the 9th and 10th cropping seasons, respectively. Higher yields under crop rotation were also observed for the 9th cropping season, in comparison to all other treatments.



C)	CS8	CS9	CS10	Total
Yield	1.54^{ns}	64.26*	14.64*	32.29*
Profit	1.24^{ns}	75.84*	17.65*	24.73*

Figure 5. Experimental soybean grain yield (Yield; A) and profit (B) during the 8th, 9th and 10th cropping seasons (CS8, CS9 and CS10, respectively) and their total means in a monoculture (Mo), two crop succession schemes (CS-Br and Ma) and a crop rotation scheme (Crot) in central Brazil. C: F statistic of ANOVA testing. Different letters indicate statistical difference by the Tukey test (α=0.05). *No soybean cultivation under Crot in CS8 resulted in Yield absence for the referred treatment. Each bar refers to a mean of four samples in CS8, CS9 and CS10.

However, costs of soybean production (expressed in terms of the equivalent soybean amount) are not deducted from the Yield, which impacts economical sustainability of soybean production as differences in profit per unit area. As indicated by Weil e Kremen (2007), the establishment of cover crops in agricultural lands, as in diversified cropping systems, is not widely adopted because of additional expenses to the already risky business of farming. Thus, it is not only important to study parameters related to the efficiency of grain production (i.e. Yield), but also the profit margin associated with each agricultural management practice, aimed at maximizing the profit margin for the farmers. Figure 1B depicts the data calculated from the differences of Yield and soybean production costs, expressed in kg ha^{-1} of soybean grain, and denominated as Profit.

The lower Yield under monoculture resulted in financial losses in every cropping season (Figure 1B). For the monoculture soybean, the profit was lower than that under other treatments at the end of the 9th and 10th cropping seasons. Despite having no soybean cultivation in the cropping season 8, crop rotation produced similar profit at the end of the three cropping seasons when compared to succession of soybean/braquiaria and soybean/maize double-cropping (Figure 1B). These results indicate that crop rotation produced profits similar to those for double-cropping treatments, because of lower accumulated production costs along the three cropping seasons associated with higher Yield when soybean was cultivated during the two other cropping seasons.

Average values for soil quality (LLWR, β-glucosidase, SOC and P), soybean nutritional quality (FLAV and PROT) and soil cover biomass dry weight (DW) are shown in Table 2. Soil physical quality, as indicated by the LLWR, was more at the 0-20 cm depth under soybean/maize double-crop in comparison to soybean monoculture. The soybean/maize double cropping system receives machinery traffic for planting and harvesting operations two times a year while soybean monoculture only receives early machinery traffic for soybean planting and harvesting. The differential traffic patterns justify why the LLWR of 0-20 cm depth under monoculture was approximately 140% higher than that under soybean/maize double cropping, which may be a direct effect of low traffic incidence in that treatment. Increased traffic in soybean/maize double-crop may have negatively affected soil physical quality through formation of a compacted layer at the 0-20 cm depth. The latter inhibited soil functionality and plant growth either through unfavorable water holding capacity, aeration or soil penetration resistance or by negatively affecting the LLWR. Keller *et al.* (2019) reported that historical increase in machinery weight and traffic intensity caused detrimental conditions for plants growth due to soil compaction. Compaction-induced loss of soil physical quality under no-till was also described by Moreira *et al.* (2016) in Brazilian soils.

Table 4. Soil variables (LLWR, β-glucosidase, P and SOC), soybean grains nutritional quality, as well as aboveground biomass weight of cover crops produced on the previous cropping season to the studied of different soybean production systems in Central Brazil.

Treatments	**LLWR**	**β-glucosidase**	**P**	**SOC**	**FLAV**	**PROT**	**DW**
Mo	0.19 a	30.07 c	16.25 a	16.06 bc	1.74 b	33.06 c	0.00 c
CS-Br	0.13 ab	132.41 a	11.25 b	17.41 ab	2.25 a	36.85 b	13.40 a
CS-Ma	0.08 b	64.68 bc	12.88 ab	14.42 c	1.75 b	33.90 c	9.70 b
Crot	0.13 ab	114.80 ab	10.00 b	18.27 a	2.41 a	41.62 a	12.71 ab
F statistic	7.34*	11.57*	12.12*	18.90*	20.87*	48.49*	81.49*

LLWR: mean least limiting water range of the 0-20 cm layer (m^3 m^{-3}); β-glucosidase: activity of the enzyme within 0-10 cm soil layer (mg *p*-nitrophenol kg^{-1} soil h^{-1}); P: mean phosphorus content within 0-20 cm soil layer (mg dm^{-3}); Soil organic carbon (SOC; g dm^{-3}); FLAV: soybean seeds Flavonoid content (milligram catechin equivalents per gram of seeds fresh weight); PROT: soybean seeds protein content (%) and DW: above ground dry weight of cover crops biomass produced on the ninth cropping season (Mg ha^{-1}). Different letters indicate means statistical differences by the Tukey test (α=0.05). Each value is a mean derived from four samples.

While soybean monoculture optimized the LLWR, the average values of β-glucosidase indicated poor biological quality when compared to that for the soybean succession with brachiaria as a double-crop. Biological quality appeared to be directly linked to soil cover biomass produced prior to soybean 9th cropping season (CS9) as well as to SOC, since the highest soil cover biomass weight was measured in soybean/braquiaria succession and the lowest in the soybean monoculture. Furthermore, there occurred an increase in SOC contents in 0-20 cm layer under crop rotation. Soybean/maize double-crop and the crop rotation treatments were characterized by a higher soil cover biomass prior to the soybean cropping season than that under soybean monoculture, because of fallow that preceded the monoculture on the 9th cropping season. These results may be directly linked to the positive effect of soil cover by plant residues on soil biological quality and SOC accumulation. McDaniel *et al.* (2014) reported that crop rotations involving cover crops improved soil quality, especially when compared to that under monoculture. Gentile *et al.* (2011) also reported the positive but rather a transient effect of plant residues on soil biological quality.

The soil P content was higher at the 0-20 cm depth under soybean monoculture as compared to that for the soybean/braquiaria double-crop and the crop rotation. Lower

P extraction through no or decreased biomass production, as indicated by DW or even by lower Yield, may indicate that higher P content in soil under monoculture may be a result of low P extraction by crops, and not because of an impaired effect of soybean monoculture on soil P availability. Soybean/braquiaria double-cropping system and the crop rotation also had the maximum BW but lower P content, indicating that higher nutrient uptake by total aboveground biomass and Yield might have strongly influenced the soil P contents.

The FLAV content in soybean grains was higher under soybean/braquiaria double-crop and in crop rotation than those for soybean monoculture and soybean/maize double-crop. However, the protein content in soybean grains for crop rotation was higher than those for all other treatments. The protein content was also lower for monoculture and soybean/maize double-crop than that for soybean/braquiaria. Nutritional quality of soybean grains, as indicated by protein and FLAV content, was also negatively affected by soybean monoculture or double-cropping with maize. These results not only highlight the detrimental effects of soybean monoculture on food security, but also indicate that the currently prevailing soybean production system of Brazilian farmlands has similar food quality outputs as is that for the soybean monoculture.

Figure 2 depicts the distribution of each soybean production system on the principal components 1 and 2, with soil, soil cover dry weight and soybean grain indicators, as explanatory variables. The two main axis of the PCA explained 84% of the total data variance. PC1 separated P, on the positive side, from all soybean grain variables (Yield, FLAV and PROT), soil cover dry weight and soil biological quality indicator β-glucosidase. The data show that PC1 represents the characteristics that are directly proportional to the soil P content and inversely proportional to the soybean yield and nutritional quality, soil biological quality and above ground biomass dry weight of cover crops produced on CS9. The PC2, on the other hand, represents the characteristics that are inversely related to soil physical quality because the LLWR was located on the negative extreme of that axis. Thus, treatments distributed on the quadrant I represent low soybean grains yield, flavonoids and protein contents, soil cover biomass dry weight and poor biological and physical quality, but a high soil P content. In contrast, treatments in quadrant III represent high soil physical and biological quality and SOC content, as well as improved soybean yield and nutritional quality and increased soil cover biomass dry weight, but adverse soil chemical quality.

The data presented in Figure 2 indicate that amount and nutritional value of soybean grains produced were positively related to soil biological quality and biomass production preceding the cropping season, but negatively correlated with soil P content. Such a trend may be due to the already discussed low uptake of soil P, especially that by soybean monoculture. These results also indicate that soil biological quality expressed by β-glucosidase activity had a stronger effect on soybean grain nutritional quality and yield, than that by soil chemical quality measured by exchangeable P. These results are in accordance with those reported by Pascual *et al.* (2000), García-Ruiz *et al.* (2008), Alves de Castro Lopes *et al.* (2013) who also reported that soil biological parameters act as early warning indicators of the management effects on soil quality.

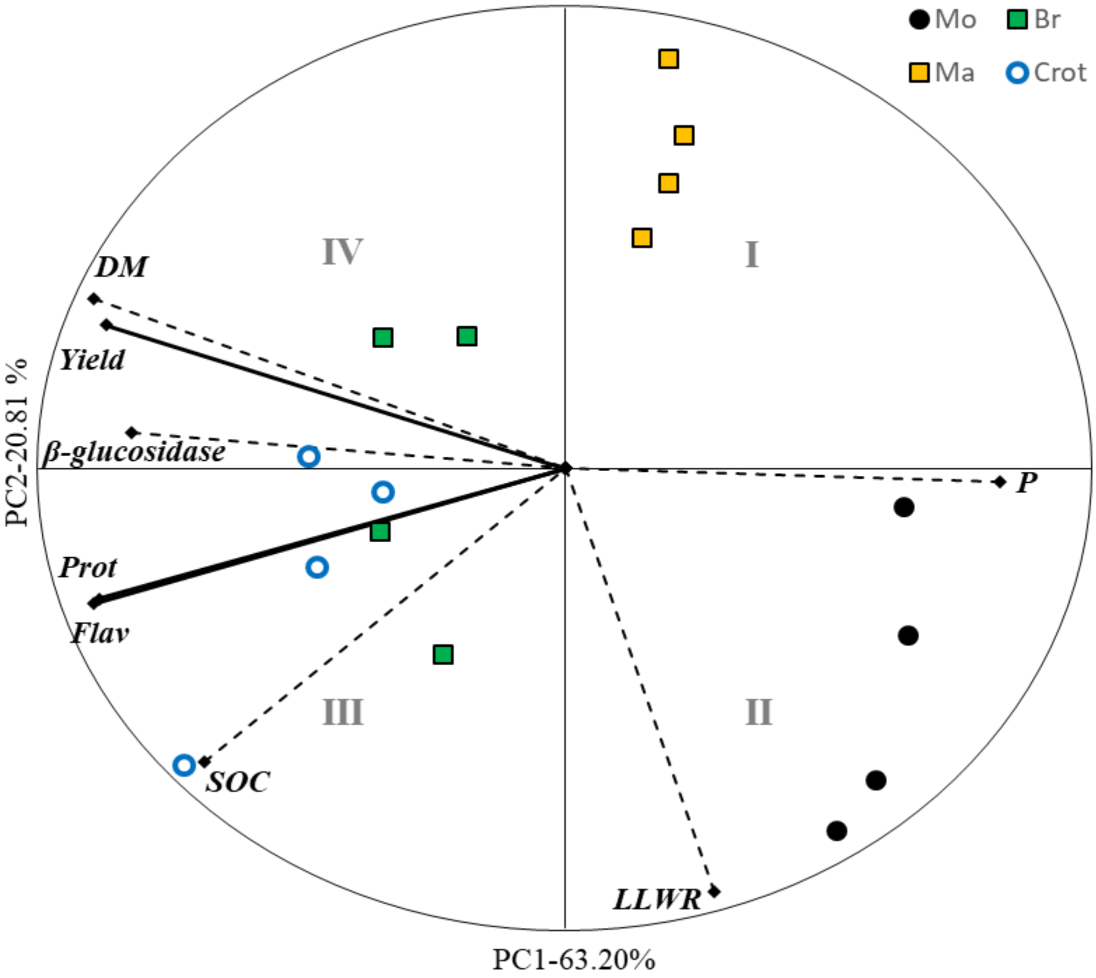


Figure 6. Principal component analysis of soil variables, represented by the least limiting water range (LLWR), soil phosphorus content (P) , β-glucosidase activity and soil organic carbon (SOC), and soybean grain yield (Yield), flavonoid (FLAV) and protein (PROT) content, as well as aboveground biomass dry weight produced on the previous cropping season to the studied (DM), under soybean (Glycine max (L.) Merril) monoculture (Mo), soybean succession with brachiaria (Urochloa ruziziensis, CS-Br) and maize (Zea Mays,

CS-Ma), and a crop rotation scheme (Crot) in central Brazil. Dashed lines represent soil-related variables and bold lines represent soybean grains-related variables.

Treatments distribution on the PCA indicated that soybean monoculture (predominant in quadrant II) was distinct from other treatments, especially because of its higher soil chemical (e.g. higher P content) and physical quality (higher LLWR). However, soybean monoculture had the lowest soil biological quality among all treatments (Table 2; Figure 2). Differences in soil physical quality were predominantly caused by soil compaction under soybean/maize succession, which was thus located in the extreme positive coordinates of PC2. These results indicate that soybean and maize double-cropping, a predominant cropping system of the Brazilian farmlands, may compromise sustainability of soybean production and food security through negative effects on soybean yield, farmer profitability and soil quality, with a stronger effect on soil physical quality and carbon sequestration. Further, the negative effect of soil quality on food security observed in soybean monoculture may be attributed to poor soil biological quality.

Soybean/braquiaria double crop and the crop rotation were distributed on the negative side of the PC1 axis of Figure 2, indicating increase in soil biological quality of those treatments. The latter may be attributed to improved yield and nutritional value of soybean grains despite lower soil chemical quality. The predominant distribution of crop rotation treatments along the quadrant III (Figure 2) indicate the best physical and biological conditions of 0-20 cm soil, which resulted in higher soybean yield, protein and flavonoids grain contents among treatments (Figures 1, 2 and Table 2). Figure 3 highlights the positive effect of crop diversity on the visual roots abundance within undisturbed soil cores of this study.

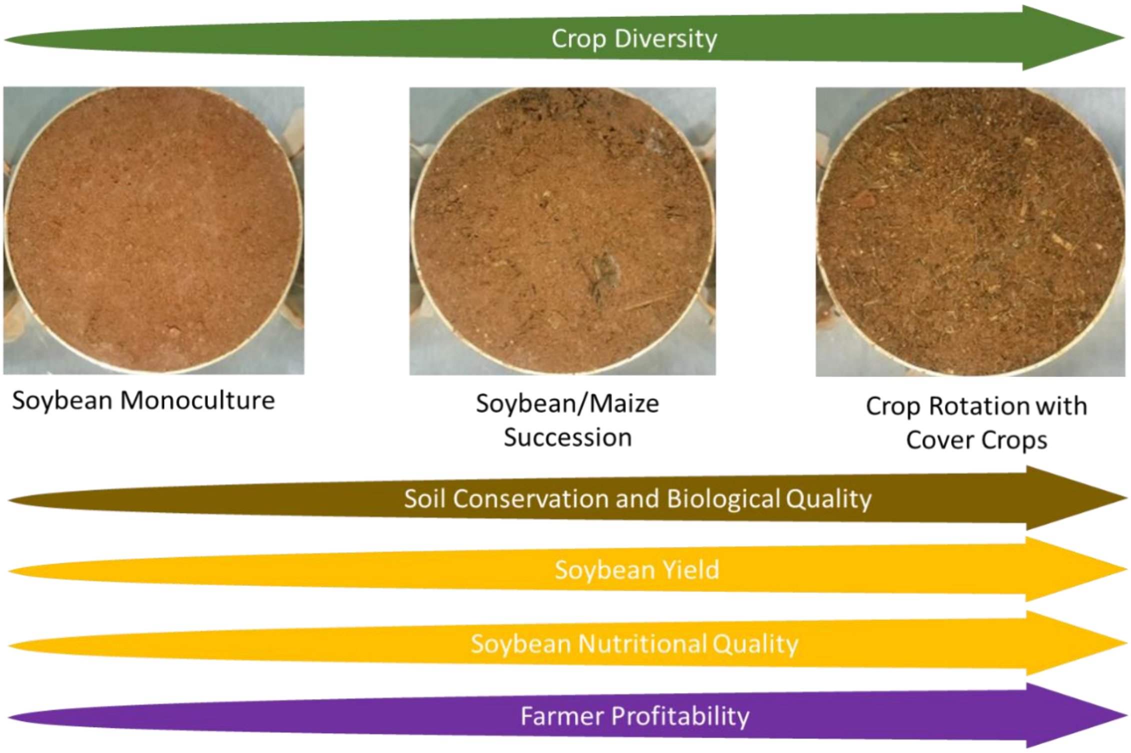


Figure 7. Effect of the cropping sequence diversity on visual abundance of roots and soil color within undisturbed soil samples from a Rhodic Ferralsol and on sustainability aspects of soybean production in central Brazil.

DISCUSSION

The most diversified cropping system (Crot) resulted in same or higher soybean grain yield than the traditional cropping system in Brazil – the soybean and maize double-cropping. Despite having soybean cultivated in only two out of the 3-years cropping cycle, the crop rotation resulted in statistically identical profit than that obtained by cultivating soybean in all cropping seasons under less diversified cropping sequences (Figures 1, 2 and 3). These results not only indicate the spared efficiency for soybean cropping under a diversified sequence, but also that crop rotations potentially decrease inherent risks related to production under stressed or uncertain conditions, contributing to stability on food production. That is because same or higher profit would be achieved through less cropping seasons, which involve production uncertainty to some degree (Weil e Kremen, 2007), because of the negative effects of droughts, pests or other adverse events during the cropping season.

Even though no measurements of greenhouse gas (GHG) emissions were performed in this study, we found that the crop rotation had increased soil organic carbon levels when compared to the soybean/maize double cropping system and the monoculture. It is then fair to state that transitioning soybean production from soybean/maize double-cropping to conservation agriculture might contribute to achieve sustainability in Brazilian farmlands in full, through the ‘triple wins’ indicated by Lipper *et al.* (2014), contributing to (1) increased yields coupled with increased incomes; (2) increased resilience to climatic events; and (3) decreased GHG emissions. Positive effects of crops diversity were predominantly associated to soil biological quality. Even if there is criticism on the efficiency of conservation agriculture to decrease poverty among low-income farmers (Hellin e Fisher, 2019), our data indicate that conservation agriculture practices foster soybean production sustainability in central Brazil by improving soil quality – especially biological quality – guaranteeing farmer’s profitability while advancing food security. Not only the quantitative aspect of soybean grain production (Yield), but also qualitative (flavonoids and protein grains content) parameters were positively associated with crop diversity and soil cover biomass of the cropping system because of higher soil biological quality. Higher protein and flavonoids content in soybean grains may also be associated to improved physiological quality of soybean seeds once the latter act on reactive oxygen species sequestration, which are produced by sun ultraviolet radiation, by delaying or preventing seeds deterioration (Pietta, 2000).

Soybean monoculture stood out from the other treatments in a poor way. Lower yields and nutritional quality of soybean grains produced under soybean monoculture, coupled with decreased farmer profit, appeared to be a result of prejudiced soil quality – especially soil biological quality. Wu *et al.* (2008) **reported** that crop rotations positively influenced soil microbial diversity, while Xuan *et al.* (2012) indicated that crop diversity determined rice (*Oryza sativa*) yield because of positive effects of soil biological quality. Soybean monoculture was a common practice during the 1970s when annual tillage-based cropping systems were predominant in Brazilian farmlands (Batlle-Bayer *et al.*, 2010). At present, however, NT is widely adopted in Brazilian farmlands for soybean cultivation, is based on the double-cropping of soybeans and maize (*Zea Mays*) within each year, where the first is grown on the summer season and maize is grown on the late season (Arvor *et al.*, 2012; Spera *et al.*, 2014; Abrahão e Costa, 2018). This change was mostly driven by landowner’s avoidance to adverse impacts in soil quality and increased production costs of the traditional fallow and tillage-based mechanized crop production systems (Sá *et al.*, 2014). This double-cropping scheme involves cultivation of two cash-crops in a year, which attract farmers attention because of its potential profitability, but negative effects of agricultural intensification have already been described by Banerjee *et al.* (2019).

Our data indicate that negative effects of compacted soil under soybean/maize succession were not restricted to the resulting product of the chain, such as soybean grains yield and nutritional quality, but also to the decreased capacity of that to promote resilience to environmental stresses because of low soil quality (Lal, 1997; Anghinoni *et al.*, 2019). Therefore, we demonstrated that, beside improvements on the efficiency of the Brazilian cropping system since the 1970's, which was accompanied by soil biological quality improvements, future agricultural sustainability of soybean-based cropping systems in Brazil depends on crop diversification, and will probably be accompanied by improvements in soil physical quality because of the abandonment of the soybean/maize double-crop.

The high soil chemical quality, as indicated by the soil P content, did not positively affect food production and nutritional quality of soybean when under an environmentally poor production system (soybean monoculture), because of low soil biological quality. Similarly, low soil chemical quality did not reduce yield and nutritional quality of soybean grains in diversified production systems with high plant biomass production and maintenance (Figure 2), such as the crop rotation involving cover crops, through positive effect of the latter on soil biological quality. Under the experimental conditions described herein, soil chemical quality did not affect directly soybean variables (Yield, PROT and FLAV) because soil biological quality occulted its effect. Thus, it is justified to state that soil biological quality was more important than soil chemical quality to achieve high soybean grains Yield, optimal nutritional content (FLAV and PROT) and profitability. Dotaniya *et al.* (2019) also stated that soil nutrients availability to plants is affected by its physical and biological properties. The availability of plant nutrients in soil depends on soil biological activity, through action of enzymes. Therefore, soil chemical quality, as indicated by soil P content, had minimal impact on improving soybean grains and nutritional quality.

CONCLUSIONS

The data support the acceptance of the established hypothesis once our results evidenced that sustainability of the soybean production in central Brazil can be enhanced by adopting a highly diversified cropping system, resulting in higher grains yield, nutritional quality of grains, improved soil quality and carbon sequestration with similar or greater farmer profitability (Figure 3).

We found that, under experimental conditions, soil biological quality was positively affected by conservation agriculture and acted as the main driver for food security in soybean-based production systems in central Brazil, followed by soil physical quality. Meanwhile, soil chemical quality effects on soybean grain production and nutritional quality was marginal when compared to the soil biological quality effects on the latter.

Sustainability of Brazilian soybean production can be increased by replacing the annual soybean and maize double cropping by complex crop rotations involving cover crops in the rotation cycle, due to increases in soil physical quality and followed by increases in soil biological quality.

We found that the predominant soybean cropping system in Brazil – the soybean and maize double cropping – negatively affects soil physical quality, and therefore prejudices food security. Therefore, sustainability of Brazilian soybean production can be increased by replacing the annual soybean and maize double cropping by complex crop rotations involving cover crops in the rotation cycle, especially because of improvements in soil physical quality.

CONCLUSÕES GERAIS

A hipótese desta tese foi aceita, uma vez que houveram expressivas diferenças na qualidade do solo, principalmente nos componentes físicos e biológicos, entre os diferentes sistemas de produção de soja estudados.

Os sistemas de produção de soja mais diversificados, principalmente aqueles compostos com a cultura da braquiária, apresentaram maior qualidade física do solo resultante da ação das raízes em camadas superficiais ou em camadas mais profundas, bem como maior qualidade biológica do solo. Com isso, a resiliência dos sistemas de produção de soja culturalmente diversificados foi intensificada, o que resultou em maiores produtividade e qualidade nutricional das sementes de soja.

O sistema de produção anual de soja em sucessão ao milho promove degradação física do solo, principalmente na camada superficial (0-10 cm) e, em menor grau, degrada também a qualidade biológica do solo, aumentando a suscetibilidade da soja aos estresses ambientais e diminuindo seu potencial produtivo e alimentar.

A adoção das novas tecnologias de produção de soja relacionadas a diversificação da produção agrícola, tal como a integração entre lavoura, pecuária e silvicultura, podem beneficiar expressivamente a sustentabilidade da produção de soja no Brasil por meio de melhorias na estabilidade da produção, na produtividade e na qualidade nutricional dos grãos de soja produzidos.

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