University of São Paulo
"Luiz de Queiroz" College of Agriculture

Agricultural expansion affects soil quality indicators in the MATOPIBA region: Brazil's new agricultural frontier

Jorge Luiz Locatelli

Dissertation presented to obtain the degree of Master in Science. Area: Soil and Plant Nutrition

Piracicaba
2021

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
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"Essentially, all life depends upon the soil… There can be no life without soil and no soil without life; they have evolved together."

Dr. Charles E. Kellogg

CONTENTS

RESUMO

Expansão agrícola afeta indicadores de qualidade do solo na região de MATOPIBA: a nova fronteira agrícola do Brasil

O aumento global da demanda por recursos básicos tem causado a intensificação e a expansão da agricultura. No Brasil, isso tem ocorrido na região do MATOPIBA (região nordeste), considerada a nova fronteira agrícola do país. Entretanto, devido as condições locais de solo e clima e dos efeitos promovidos pela mudança do uso da terra (MUT), a sustentabilidade do desenvolvimento agrícola na região tem sido questionada. A hipótese testada nesse estudo foi de que a expansão agrícola na região induz a degradação do solo. Diante disso, foi conduzido um estudo de campo em uma área representativa da região do MATOPIBA, onde foi avaliado os efeitos da MUT na dinâmica da matéria orgânica do solo (MOS) e nos principais indicadores da qualidade física do solo. A amostragem foi realizada em três usos: mata nativa - Cerrado (MN), pastagem (PA) e cultivo anual (CA). Os solos foram classificados como *Typic Haplustox* (Soil Taxonomy*)*, e Latossolo Amarelo distrófico na área de PA e Latossolo Vermelho Amarelo nas áreas de MN e CA, segundo o Sistema Brasileiro de Classificação de Solos. Amostras deformadas e indeformadas foram coletadas até 1 m de profundidade, e foram avaliados atributos relacionados a MOS, como teor de carbono (C) e nitrogênio (N) totais, C das frações obtidas por meio do fracionamento físico da MOS, e o índice de manejo de carbono (IMC). Atributos físicos foram avaliados até 30 cm, sendo indicadores da compactação do solo, distribuição de poros, fluxos de ar e água, e estabilidade de agregados. Os resultados mostraram que a conversão de MN para PA extensivo reduziu os estoques totais de C e N, os teores de C contido nas frações da matéria orgânica associada aos minerais (MOAM) e da matéria orgânica particulada (MOP), e o IMC. Além disso, a conversão para PA resultou na compactação do solo, que consequentemente reduziu o espaço poroso e os fluxos de ar e água, atingindo os níveis críticos para o crescimento das plantas. Por outro lado, a conversão da MN para CA não afetou os estoques totais de C e N. Houve um decréscimo nos estoques de C associados à fração da MOAM, mas o aumento do C na MOP foi capaz de compensar tais perdas. O aumento observado nos teores de C na MOP resultou em um acréscimo no IMC, indicando o aumento da qualidade da MOS. Apesar dos efeitos positivos na dinâmica da MOS, a conversão de MN para CA não promoveu o mesmo efeito nos indicadores físicos avaliados. Embora os níveis críticos para o crescimento das plantas não tenham sido atingidos, o estabelecimento do CA favoreceu a compactação do solo, reduziu o espaço poroso, a condutividade hidráulica saturada do solo e a estabilidade de agregados (comparado a MN), o que aumenta a suscetibilidade do solo a erosão. Em geral, os resultados obtidos indicam a necessidade urgente da adoção de práticas conservacionistas para o manejo das áreas na região do MATOPIBA. A qualidade do solo em áreas de PA pode ser substancialmente melhorada por meio da adoção de técnicas de pastejo otimizadas (e.g., controle de taxa de ocupação, pastejo rotacionado) e da melhoria da fertilidade do solo (especialmente N). Do mesmo modo, a rotação de culturas e o controle de tráfego de máquinas podem ser opções viáveis para a melhoria do manejo das áreas de CA, reduzindo os efeitos negativos induzidos pela MUT, e favorecendo a provisão de serviços ecossistêmicos na região.

Palavras-chave: Qualidade do solo, Matéria orgânica, IMC, Física do solo, Cerrado, MATOPIBA

ABSTRACT

Agricultural expansion affects soil quality indicators in the MATOPIBA region: Brazil's new agricultural frontier

The global increase in demand for primary resources has caused the intensification and expansion of agriculture. In Brazil, this has occurred in the MATOPIBA region (northeast region), considered the new agricultural frontier in the country. However, due to local soil and climate conditions and the effects promoted by land-use change (LUC), the sustainability of agricultural development in the region has been questioned. The tested hypothesis in this study was that agricultural expansion in the region leads to soil degradation. Therefore, a field study was conducted in a representative area of the MATOPIBA region, where the LUC effects in the soil organic matter (SOM) dynamics and the main soil physical quality indicators were evaluated. The sampling process was carried out in three uses: native vegetation - *Cerrado* (NV), pasture (PA) and cropland (CA). Soils were classified as Typic Haplustox (Soil Taxonomy) and as *Latossolo Amarelo distrófico* in the PA area, and *Latossolo Vermelho Amarelo distrófico* in NV and CL areas (*Sistema Brasileiro de Classificação de Solos*). Disturbed and undisturbed samples were collected up to 1 m, and attributes related to SOM were assessed, such as total carbon (C) and nitrogen (N) content, C of the fractions obtained through the physical fractionation of SOM, and the carbon management index (CMI). Physical attributes were obtained up to 30 cm, being indicators of soil compaction, pore distribution, air and water fluxes, and aggregate stability. The results showed that the conversion from NV to extensive PA reduced the total C and N stocks, the C content from the mineral-associated organic matter (MAOM) and of particulate organic matter (POM) fractions, and the CMI. Besides, the conversion to PA resulted in soil compaction, which consequently reduced porous space and air and water fluxes, reaching the critical levels for plant growth. On the other hand, the conversion from NV to CL did not affect the total C and N stocks. There was a decrease in the C stocks from the MAOM fraction, but the increase in C in POM was able to offset such losses. The increase observed in C levels in POM improved the CMI, indicating an increase in the SOM quality. Despite the positive effects in the SOM dynamics, the conversion from NV to CL did not promote the same impact on the assessed physical indicators. Although the critical levels for plant growth have not been reached, the establishment of CL favored soil compaction, reduced porous space, saturated hydraulic conductivity of the soil, and aggregate stability (compared to NV), which increases soil's susceptibility to erosion. Overall, the results obtained indicate the urgent need to adopt conservationist practices for the management of areas in the MATOPIBA region. Soil quality in PA areas can be improved by adopting optimized grazing techniques (e.g., stocking rate control and rotational grazing) and improving soil fertility (especially N). Likewise, crop rotation and machine traffic control can be viable options for improving the management of CL areas, mitigating the negative effects induced by the LUC, and supporting the provision of ecosystem services in the region.

Keywords: Soil quality, Organic matter, CMI, Soil physics, *Cerrado*, MATOPIBA

1. GENERAL INTRODUCTION

The last estimates from the United Nations pointed that the global population will reach 9.7 – 12.7 billion inhabitants by 2100 (UN, 2019) and at this pace, current food production will have to double over the next three decades to guarantee food security (Tilman et al., 2011). Historically, this growing demand for resources transformed agriculture in the world, which triggered a process marked by the intensification and the expansion over new areas (Pellegrini and Fernández, 2018). Brazil's case is an excellent example of this process. Until the mid-70s, Brazilian agriculture was very incipient, careless of technologies, and characterized by low productive systems (Boddey et al., 2003). This scenario completely changed after the "green revolution", where Brazil was about to become an important player in the global food production scenario (OECD-FAO, 2015; Dias et al., 2016). However, the advancing of agricultural activity and the disturbance induced by the removal of the native forest areas has been the cause of important changes in environments' equilibrium, causing land degradation (Foley et al., 2005; Newbold et al., 2015). In this sense, it becomes mandatory to understand the agricultural expansion effects, aiming to alleviate possible negative impacts and thus contribute to more efficient agricultural production systems.

Brazil was globally recognized as an important food exporter, mainly after expanding agriculture over the *Cerrado* region (Rada, 2013). Nowadays, *Cerrado*'s agricultural area covers ~ 85 million hectares and contributes with ~ 50% of the country's soybean production (Carneiro Filho and Costa, 2016; INPE, 2015), configuring one of the most important regions in the national scope of the agricultural sector. More recently, the expansion of the activity over new areas has been observed in the Brazilian northeastern, more specifically in the MATOPIBA region, which is considered the Brazilian new agricultural frontier. In the 2019/2020 crop season, the region contributed with ~ 10% of the national grain production (CONAB, 2020), and future estimates indicated a further increase of 30% in the cultivated area and 54% in the grain production, highlighting the expansion potential of the region (MAPA, 2019).

The MATOPIBA region extends over ~ 73 million hectares, that covers part of the states of Maranhão, Tocantins, Piauí and Bahia (collectively MATOPIBA) (Zalles et al., 2019). The region falls within the *Cerrado* biome, in which soils are highly weathered (low activity of clay fraction), presenting low natural fertility and high acidity (Lopes and Guimarães Guilherme, 2016). An additional limiting factor for the region is the predominance of sand in the mineral fraction of soils (Donagemma et al., 2016), which increases soil susceptibility to degradative processes, since these soils have a low water storage capacity, soil organic matter (SOM) content, and are more sensitive to compaction and erosive processes (Huang and Hartemink, 2020; Yost and Hartemink, 2019). Furthermore, the high mean annual temperature and the short-time rain season of the region are additional characteristics that may limit proper plant growth, especially under poorly managed systems (Alvares et al., 2013; Klink and Machado, 2005). These specific characteristics have raised some concerns regarding the sustainability of the agricultural development in the region over time, and the risk of environmental degradation.

The LUC from native forests to agricultural areas usually reduces soils' natural capability to promote broader ecosystem functions (Fu et al., 2015). The disturbance induced by the forest removal and the lack of best management practices associated with the following use in these areas frequently causes soil degradation (Borrelli et al., 2017). The conversion from native vegetation (NV) to cropland (CL) and pasture (PA) areas (commonly observed in the MATOPIBA region; Zalles et al., 2019) is frequently linked to poor soil fertilization (especially N), lack of grazing control, low biomass input, and soil disturbance (i.e., loss of structural stability), which leads to SOM depletion (Carvalho et al., 2010; Conant et al., 2017; Don et al., 2011; Gmach et al., 2018). Soil organic matter depletion decreases soil nutrient cycling (Tiessen et al., 1994), soil biological diversity and activity (Lange et al., 2015), and directly affects soil physical properties such as soil water holding capacity, resistance to compaction, structure and stability, and consequently soil resistance to erosion (Mujdeci et al., 2017; Six et al., 2002).

Several studies conducted worldwide have adopted different approaches to assess these changes in soil quality status, exploring various soil quality indicators (Bünemann et al., 2018). Soil organic matter, due to its close relationship with multiple soil functions (e.g., chemical, biological and physical aspects) (Huang and Hartemink, 2020; Lange et al., 2015; Tiessen et al., 1994) has been widely used for this purpose (Bünemann et al., 2018). Besides, because SOM is a heterogeneous matrix of organic compounds, changes induced by soil disturbance in its constituents typically occurs at different extents and time (Lavallee et al., 2020; Lehmann and Kleber, 2015), configuring an important predictor of soil quality changes. Furthermore, regarding soil physical health, several indicators related to soil compaction, pore size distributions, and water and air fluxes have been selected as proxies for soil physical quality alterations (Cavalcanti et al., 2020; Cherubin et al., 2016), being successfully applied in field study evaluations.

In the MATOPIBA region, however, due to the recent agricultural expansion, little is known about the extent of the LUC effects over soil quality indicators. Due to the specific conditions found in the region, we assumed that changes in SOM and soil physical properties could reach critical levels for proper plant growth, leading to soil quality loss, directly constraining environmental equilibrium. Therefore, we conducted a field study experiment to assess the effects of the agricultural expansion in the region over SOM dynamics and soil physical indicators, following the most common LUC scenarios in the region: from NV to PA, and from NV to CL (Zalles et al., 2019). We organized this study into four parts. First, we present a brief introduction regarding the study region and the purpose of our research. Second, we address the LUC effects on SOM dynamics, including total C and N stocks, particle-size fractions of SOM, and a brief assessment of SOM quality through the carbon management index. Third, we provide an evaluation of the LUC effects on the soil's physical properties, following indicators related to soil compaction, pore size distribution, air and water fluxes, and soil structure and stability. And finally, in the fourth, we present the final considerations of this study.

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2. SOIL ORGANIC MATTER POOLS AFFECTED BY CROPLAND AND PASTURE EXPANSION IN BRAZIL'S NEW AGRICULTURAL FRONTIER

ABSTRACT

Land-use change (LUC) is recognized as one of the major causes of soil carbon (C) depletion. Recently, the so-called MATOPIBA region (northeastern Brazilian region) has experienced an accelerated agricultural expansion. However, little is known about the qualitative and quantitative impacts of LUC in soil organic matter (SOM) dynamics in this region, and there is a growing interest to quantify the potential trade-offs associated with agricultural expansion and soil health. In this sense, we attempted to assess the magnitude that the agricultural expansion affects soil C and nitrogen (N) dynamics in the most common LUC scenarios in the MATOPIBA region: from native vegetation (NV: the *Cerrado* biome) to extensive pasture (PA) and cropland (CL) under no-tillage. Soil samples were collected in three adjacent areas (i.e., NV, PA, and CL) up to 1-m of depth. We measured the changes in the total C and N stocks, and we performed the particle-size fractionation of SOM, obtaining particulate organic matter (POM) and mineral associated organic matter (MAOM) fractions. Additionally, the carbon management index (CMI) was used to evaluate SOM quality changes. The conversion from NV to extensively managed PA decreased the C and N stocks by ~ 28 and 0.5 Mg ha^{-1} in the 0-100 and 0-50 cm layers, respectively. The C depletion occurred in both the POM and MAOM fractions, which reduced by 36 and 34% compared to the NV, respectively (0-100 cm). This C decrease led to the smallest CMI values (75%) for the 0-30 cm layer. Contrarily, the conversion from NV to CL under no-tillage did not induce changes in the total C and N stocks (0-100). A slight decrease in the stocks in the MAOM fraction was observed, but an increase in the POM fraction in the upmost soil layers sustained total C stocks at the same levels observed in NV. The increase in the POM stocks in the upmost layers led to the highest CMI (137%) for the 0-30 cm layer, indicating that the conversion from NV to CL had positive effects on SOM quality. Our results revealed that PA expansion in the region has caused substantial losses of C and N, and decreased SOM quality. On the other hand, CL under no-tillage did not change quantitatively C and N stocks and even improved SOM quality. The adoption of no-tillage showed to be an important sustainable practice for keeping soil health and related ecosystem services in the MATOPIBA region.

Keywords: Soil organic matter; carbon management index; no-tillage; soil health; *Cerrado*

2.1. Introduction

Soil is the largest carbon (C) reservoir among terrestrial ecosystems (~ 3600 Pg within 2-m soil depth), storing 4.4 and 5.8 more C than atmosphere and vegetation, respectively (Lal, 2018; Plaza et al., 2018). Thus, even small changes in soil C levels, most found as organic matter, may lead to substantial alterations in the global C dynamics (Lal, 2020). Land-use change (LUC) and poor management of soil are considered the main factors associated with soil C loss, being attributed to them a global C depletion of ~ 133 Pg (1 m soil depth) over the last 12000 years (Sanderman et al., 2017). In Brazil, LUC accounts for the largest proportion of carbon dioxide emissions (Albuquerque et al., 2020), mostly attributed to the agricultural expansion over new areas such as in the MATOPIBA region, the newest agricultural frontier of the country. However, little is known about how different land uses (e.g., crops and pasture) have impacted soil organic matter (SOM) dynamics and what is the extension of these changes on C pools over time in this region, being essential a further comprehension of these changes to minimize human-induced pressure on the environment.

The MATOPIBA region is located in the northeastern part of Brazil, covering approximately 73 million hectares that includes part of the states of Maranhão, Tocantins, Piauí, and Bahia (collectively MATOPIBA) (Zalles et al., 2019). The agricultural expansion in this region has reached a stunning rhythm in the last decades, driven mainly by soybean cultivation (production increased from ~ 260 tons in 1990 to ~ 14 million tons in 2018) (IBGE, 2018; Araújo et al., 2019), and future estimates indicate a further increase of 30% in the cultivated area and 54% in grain production over the next 10 years (MAPA, 2019). The region is within the *Cerrado* biome, which soils are highly weathered, characterized by a low activity of the clay fraction, acidic pH, and low natural fertility (Lopes and Guimarães Guilherme, 2016). Additionally, soils in the MATOPIBA region (predominantly composed of Oxisols and Entisols) present high sand content (usually > 60%) (Donagemma et al., 2016), which makes soil management even more challenging given the soil's natural low water holding capacity, high vulnerability of erosion processes, and susceptibility of losing SOM (Huang and Hartemink, 2020). Soil organic matter, in particular, plays a key role in soil quality due to its capacity to affect soil chemical, physical, and biological properties (Huang and Hartemink, 2020; Lange et al., 2015; Mujdeci et al., 2017; Tiessen et al., 1994). These natural soil characteristics associated with the recent agricultural expansion may increase soil C depletion, increasing soil C emissions, and compromising the sustainable productivity of the region in the long term.

Overall, conversion from native vegetation (NV) to agriculture leads to C loss (Don et al., 2011; Guo and Gifford, 2002; Wei et al., 2014). In addition to the potential of increasing carbon dioxide in the atmosphere, SOM depletion also degrades several soil functions and soil health, leading to a lower nutrient cycling (mainly P and N) (Tiessen et al., 1994), water holding capacity (Rawls et al., 2003), soil resistance to compaction (Mujdeci et al., 2017), aggregate stability and consequently soil resistance to erosion (Six et al., 2002), thus reducing soil capability to promote plant growth. The magnitude of these changes and the capacity of soil to recover SOM levels are highly dependent on the following use and management (Wiesmeier et al., 2019). In a meta-analysis performed in the tropical region, Don et al. (2011) showed that LUC from NV to cropland (CL) and pasture (PA) caused a C depletion of ~ 25 and 12%, respectively, mostly driven by the decrease in biomass-C inputs and degradation of soil structure (i.e., reducing physical protection of soil C). On the other hand, the adoption of practices such as no-tillage/reduced tillage associated with crop diversification, deep-rooting crops, proper fertilization and grazing control have shown promising results on soil C sequestration in several long-term studies (Abdalla et al., 2018; Corbeels et al., 2016; Ferreira et al., 2021; Silveira et al., 2013; Tiefenbacher et al., 2021). However, due to specific inherent characteristics (e.g., highly weathered and high sand content) of soils in MATOPIBA region, sustain or enhance soil C stocks are still more challenging, requiring special attention for soil management and crop production.

Because SOM is a continuum of progressively decomposing organic compounds that interacts with distinct energy levels with the soil mineral matrix (Lehmann and Kleber, 2015), LUC may not cause a uniform effect upon SOM constituents. Overall, as SOM interacts with soil minerals, C is more efficiently protected against microbial metabolism and less responsive to management changes (Kögel-Knabner et al., 2008; Lavallee et al., 2020). Thus, fractioning SOM into components that have similar formation, persistence, and functioning may provide a better understanding of LUC impacts in SOM dynamics. The physical fractionating of SOM into particulate organic matter (POM) and mineral-associated organic matter (MAOM) (Cambardella and Elliott, 1992) have been advocated as one of the most promising approaches to this matter (Cotrufo et al., 2019; Lavallee et al., 2020; Sá and Lal, 2009), given the simplicity and practicality for obtaining SOM fractions and their sensitiveness of soil management in the short and long term. Additionally, qualitative changes in SOM can be inferred through the carbon management index (CMI), proposed by Blair et al. (1995). This index is based on the relationships between the labile and non-labile fractions of the SOM and has been widely used as an integrative approach and sensitive indicator to assess LUC impacts in SOM (Diekow et al., 2005; Ghosh et al., 2016; Oliveira et al., 2017).

Due to the recent agricultural expansion in the MATOPIBA region, little is known about the LUC effects on SOM dynamics. Although earlier studies indicated a possible C depletion, most of them focused only on total C stocks (Campos et al., 2020; Dionizio et al., 2020), and were limited to the upmost soil layers (up to 40 cm) (Gmach et al., 2018), making necessary more detailed and systemic assessment approaches to better understand the effects of the agricultural expansion on SOM aspects. Therefore, we conducted a comprehensive field study, aiming to investigate quantitatively and qualitatively soil C and N dynamic changes induced by land conversion from NV to CL under no-tillage and extensive PA in the MATOPIBA region. Our specific goals were: i) to assess the quantitative impact of LUC in total C and N stocks; ii) to evaluate LUC effects in the MAOM and POM fractions, and iii) to assess SOM quality alterations through the CMI. We hypothesized that agricultural expansion to CL and PA uses decreases SOM stocks compared to NV, leads to losses in both the POM and MAOM C fractions, and reduces the CMI. But the adoption of no-tillage in CL decreases the extent of these losses.

2.2. Material and Methods

2.2.1. Study site description

The study was carried out in the municipality of Tasso Fragoso, in the southern region of the state of Maranhão state (8° 31’ S, 46° 04’ W – mean altitude of 560 m a.s.l.) (Figure 1), considered a representative agricultural area within the newest Brazilian agriculture frontier, named MATOPIBA region. The region has a tropical climate (Aw) according to Köppen’s classification (Alvares et al., 2013), with rainy (October - April) and dry (May – September) seasons well-defined year-round, presenting a mean annual temperature of 27.2 °C and precipitation of 1300 mm. The soils are classified as a Typic Haplustox according to US Soil Taxonomy (Soil Survey Staff, 2014), and as *Latossolo Amarelo distrófico* in the PA area, and as *Latossolo Vermelho Amarelo distrófico* in the NV and CL areas according to the Brazilian Soil Classification System (Santos et al., 2018), with kaolinite, hematite, goethite, and gibbsite predominating in the clay fraction (Figure S1). The region is located within the *Parnaiba* basin, with parent material composed of sedimentary rocks (e.g., sandstones, siltstones, and shales) from the *Pedra de Fogo* formation (*Balsas* group) (Sousa et al., 2012).

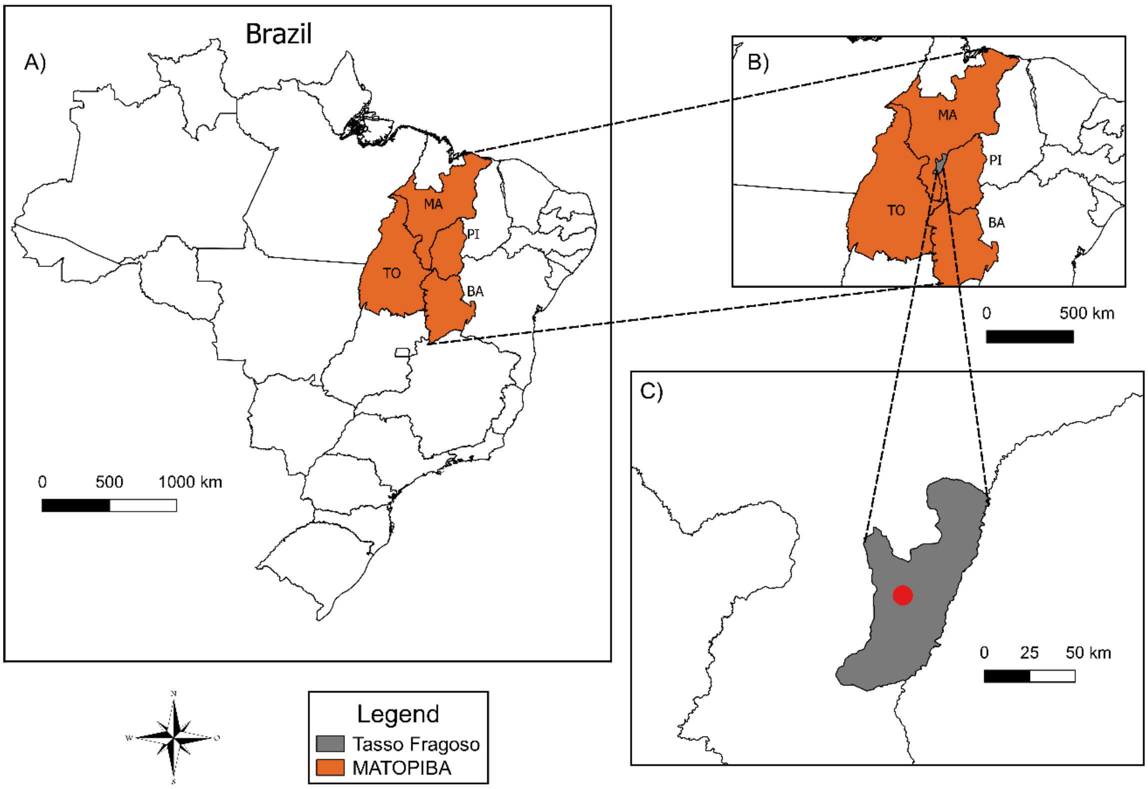

Figure 1. Geographic location of the MATOPIBA region (A); municipality of Tasso Fragoso, Maranhão state (B); and experiment location (red marker) (C).

We sampled three different land-uses in adjacent areas (i.e., under similar environmental conditions such as climate, elevation, and soil granulometry and mineralogy – Figure S1.) using a chronosequence approach, a method commonly used to evaluate land-use conversion effects on soil properties (Corbeels et al., 2016; Costa Junior et al., 2013). The chronosequence technique was chosen because there are no long-term field experiments in the region. The selected areas represent the most common LUC scenarios in the MATOPIBA region, i.e., from NV to CL and NV to PA (Zalles et al., 2019). A complete characterization of the study areas is presented in Table 1.

Table 1. Soil characteristics of the studied areas and information about land-use change and management history for native vegetation, pasture, and cropland in the MATOPIBA region - Brazil's new agricultural frontier.

Land-use	Soil layer	Sand	Silt	Clay	PD[a]	pH_{H2O}	pH_{KCl}	ΔpH[b]	P[c]	BS[d]	Land-use change and site history
	cm		$g\ kg^{-1}$		$Mg\ m^{-3}$				$mg\ dm^{-3}$	%	
Native vegetation	0-5	584	44	371	2.71	4.2	3.7	-0.5	2.33	12.78	*Cerrado sensu stricto* vegetation – characterized by the presence of many species of grasses and trees sparsely distributed, without the formation of a continuous covering canopy. The average height of the trees varies between 3 and 6 m (Ribeiro and Tabarelli, 2002)
	5-10	589	35	374	2.70	4.3	3.7	-0.5	2.00	8.98	
	10-20	576	28	395	2.72	4.2	3.9	-0.3	1.62	8.84	
	20-30	530	49	420	2.73	4.3	4.0	-0.3	1.44	27.43	
	30-50	474	50	475	2.74	4.4	4.1	-0.3	1.06	26.91	
	50-70	453	49	497	2.74	4.4	4.1	-0.3	1.02	45.81	
	70-90	443	12	544	2.75	4.3	4.2	-0.1	1.14	15.60	
	90-100	452	18	528	2.75	4.4	4.3	-0.1	0.79	24.33	
Pasture	0-5	624	26	348	2.68	4.3	4.1	-0.2	39.12	44.29	Area converted from NV to PA in 2000. At the conversion time, NV was burned, removed, and soil was prepared by plowing and disking. The pasture was established by local grasses species (i.e., predominantly composed of tropical grasses from *Urochloa* genus). Soil fertility management was restricted to lime applications to correct soil acidity. The area was grazed by cattle and sheep and supports ~ 1 UA ha^{-1} full year. At the sampling time, the area had clear signals of overgrazing and degradation (e.g., presence of weeds and a low forage cover).
	5-10	635	19	344	2.69	4.5	4.0	-0.4	33.02	38.49	
	10-20	634	20	344	2.70	4.4	4.0	-0.4	20.51	36.76	
	20-30	576	49	373	2.72	4.4	4.1	-0.3	26.68	35.89	
	30-50	514	38	447	2.74	4.4	4.2	-0.2	4.79	20.71	
	50-70	491	15	493	2.74	4.4	4.2	-0.2	4.16	16.65	
	70-90	481	17	501	2.74	4.5	4.3	-0.2	4.22	26.03	
	90-100	478	12	509	2.74	4.6	4.3	-0.3	2.76	31.68	
Cropland	0-5	704	23	271	2.66	4.9	4.7	-0.2	55.36	59.16	Area converted from NV to CL under a no-till system in 2009. Before CL implementation, NV was burned, removed, and the soil was prepared by plowing and disking. Soil acidity was corrected with the application of 1.6 Mg ha^{-1} of dolomitic lime, and regular doses were applied following soil analysis and recommendations. The area has been cultivated in a successional system of soybean (*Glycine max* L. Merr) + millet (*Pennisetum glaucum* L.) (used as a cover crop). Fertilization is carried out annually at an average rate of 90 kg ha^{-1} of P_2O_5 (simple superphosphate) and 100 kg ha^{-1} of K_2O (potassium chloride). The soybean mean yield since the implementation is 3300 kg ha^{-1}.
	5-10	689	12	298	2.70	4.6	4.1	-0.5	42.36	34.10	
	10-20	675	16	307	2.71	4.6	4.2	-0.3	14.54	34.04	
	20-30	644	17	337	2.74	4.4	4.1	-0.3	4.72	19.85	
	30-50	630	18	350	2.75	4.3	4.0	-0.2	2.74	11.50	
	50-70	584	18	397	2.75	4.4	4.1	-0.2	1.11	18.46	
	70-90	593	10	395	2.76	4.5	4.2	-0.3	1.88	65.57	
	90-100	613	17	368	2.75	4.6	4.2	-0.4	2.69	34.40	

[a] Particle density; [b] ΔpH = pHKCl (1 M) - pHH_2O; [c] Available P was extracted by Mehlich-1 solution; [d] Basis saturation on cation exchange capacity.

2.2.2. Soil sampling and laboratory analyses

Soil sampling was performed in November 2019, when the CL area had been desiccated to soybean sowing at the beginning of the rainy season. The soil was sampled in each land-use (NV, PA, and CL) based on a grid composed of nine points (3 × 3 cell grid) spaced 50 m apart from each other (Cerri et al., 2013). Disturbed samples were collected using a Dutch auger at eight soil depths: 0-5, 5-10, 10-20, 20-30, 30-50, 50-70, 70-90, and 90-100 cm, which resulted in a total of 218 samples (8 depths × 9 replicates × 3 land uses). Besides, small trenches (40 × 40 × 40 cm) were opened at three diagonal points of the grid (three replicates) to collect undisturbed soil samples by using Kopeck rings (5 × 5 cm, height × diameter) at 0-5, 5-10, 10-20 and 20-30 cm layers; and a central trench (2.0 × 2.0 × 1.5 m) was opened to collect samples from deeper layers (30-50, 50-70, 70-90 and 90-100 cm) (also in three replicates), composing a total of 72 rings.

In the laboratory, the rings were oven-dried at 105 °C for 48 hours, and soil bulk density (BD) was calculated based on the weight of oven-dried samples and the total volume of the rings (Teixeira et al., 2017). The disturbed samples were air-dried, sieved (< 2 mm), and roots and plant debris removed. Soil particle-size fractions (i.e., clay, silt, and sand) were determined by the hydrometer method following the procedure described by Gee and Or (2002), and particle density (PD) was assessed using a gas pycnometer (Flint and Flint, 2002). Soil pH [in water (1:2.5 v v^{-1}) and KCl (1 mol L^{-1})], available P (Mehlich-1) and basis saturation were measured and calculated following the methods described by Teixeira et al. (2017). Total C and N concentrations were determined in the nine replicates by the dry combustion method using an elemental analyzer (LECO CN-2000, St. Joseph, Mi, USA). All soil samples were ground and sieved (0.15 mm mesh) before total C and N determination.

Soil organic matter was physically fractionated into POM and MAOM in three replicates, following the particle-size method proposed by Cambardella and Elliott (1992). Here, 15 mL of sodium hexametaphosphate (5 g L^{-1}) solution was added to 5 g of soil (< 2 mm) and dispersed in a horizontal shaker for 16 h (140 rpm). Afterward, the dispersed solution was passed through a 53 µm mesh by adding a weak stream of distilled water. The coarse fraction (> 53 µm - POM) retained in the sieve and the flushed material (< 53 µm - MAOM) was oven-dried (50 °C) and ground (< 0.15 mm) for C determination.

2.2.3. Soil carbon and nitrogen calculations

Before calculating C and N stocks, the equivalent soil mass approach was used to adjust differences in soil mass between soil layers induced by LUC (Ellert and Bettany, 1995). The NV was set as the reference area, and the adjusted soil mass (based on an equivalent layer) was calculated according to the ratio between soil BD in the NV and the assessed land-uses (PA and CL) at each soil layer following the Eq. (1).

$$Equivalent\ layer\ = \frac{BD_{NV}}{BD_{CL\ or\ PA}}\ x\ layer\ thickness \quad (1)$$

where the equivalent layer and the layer thickness are in cm; BD_{NV} is the soil bulk density (Mg m^{-3}) in the NV use in a given depth; and $BD_{CL\ or\ PA}$ is the soil bulk density (Mg m^{-3}) in CL and PA uses, in a given depth.

Soil C and N stocks were then calculated following Eq. (2).

$$Soil\ C\ or\ N\ stocks = C, N_{layer}\ x\ BD_{layer}\ x\ equivalent\ layer \quad (2)$$

where C or N stocks are in Mg ha^{-1}; C, N_{layer} is the C or N content (%) for the bulk soil and the POM and MAOM fractions in a given soil layer; and BD_{layer} is the soil bulk density (Mg m^{-3}) in a given soil layer.

The N content/stocks within the POM and MAOM fractions were not shown, as the POM fraction's measured values were below the detection limit of the equipment.

The annual rate of C, N stock change for NV-CL and NV-PA conversion was calculated by the difference in the C, N stocks between the agricultural uses (i.e., CL and PA) and the reference area (i.e., NV), following Eq. 3 (Oliveira et al., 2016):

$$\Delta_{C,NLUC} = \frac{C,N_{CL\ or\ PA} - C,N_{NV}}{LUC_{time}} \quad (3)$$

where $\Delta_{C,\ NLUC}$ is the rate of C, N stocks change (Mg ha^{-1} yr^{-1}) after land conversion in a given layer; C, $N_{CL\ or\ PA}$ is the C, N stocks (Mg ha^{-1}) for CL or PA uses in a given layer; C, N_{NV} is the C, N stocks (Mg ha^{-1}) for the reference area (NV) in a given layer; and LUC_{time} is the time since land conversion (years).

2.2.4. Carbon management index

The CMI was calculated for the upmost soil layers (i.e., 0-5, 5-10, 10-20, 20-30, and 0-30 cm) according to the methodology proposed by Blair et al. (1995) and adapted by Diekow et al. (2005) - Eq. 4:

$$CMI = CPI\ x\ LI\ x\ 100\ (4)$$

where CPI is the carbon pool index and LI is the carbon lability index.

The CPI and the LI were calculated according to Eq. 5 and 6, respectively:

$$CPI = \frac{C\ pool\ in\ CL\ or\ PA}{C\ pool\ in\ NV}\ (5)$$

$$LI = \frac{L_{CL\ or\ PA}}{L_{NV}}\ (6)$$

where L is the carbon lability, calculated according to Eq. 7:

$$L = \frac{labile\ C}{non-labile\ C}\ (7)$$

where the labile and non-labile C are represented by the POM- and MAOM-C stocks, respectively. The NV was considered as the reference area (CMI = 100%).

2.2.5. Statistical analyses

Data normality and homogeneity were assessed by Shapiro-Wilk and O'Neill-Mathews tests ($p > 0.05$), respectively, and when violated, data were transformed using Box-Cox transformation to meet assumptions. A one-way ANOVA ($p < 0.10$) was used to test the significance among treatments (i.e., NV, CL, and PA) in each soil depth (i.e., 0-5, 5-10, 10-20, 20-30, 30-50, 50-70, 70-90 and 90-100) and to the accumulated C (including the MAOM and POM C stocks) and N stocks (i.e., 0-30, 0-50 and 0-100). When significant, Tukey's test ($p < 0.10$) was applied to compare the means of treatments. Soil C and N content and soil BD mean significance were compared through the least significant difference (LSD – Tukey) ($p < 0.10$). The CPI and CLI means were compared through the Student's t-test ($p < 0.10$). All statistical analyses were carried out using R software (R Core Team, 2019). Figures were performed using Origin software (Origin, Version 2020, OriginLab Corporation, Northampton, MA, USA).

2.3. Results

2.3.1. Soil carbon and nitrogen content and bulk density

The agricultural expansion in the MATOPIBA region changed soil C and N content and BD, but the effects varied according to land use (Figure 2A-C). Overall, soil C content decreased with depth, and changes were not observed only in the 10-20 cm layer ($p > 0.10$) (Figure 2A). In the upmost layers (0-5 and 5-10), average soil C content under NV was 21 g kg^{-1}, being increased by ~ 14% when converted to CL, and reduced by ~ 21% under PA use (CL > NV > PA) ($p < 0.01$). For the 20-30 cm layer, both agricultural uses (CL and PA) decreased soil C levels, which presented an average of ~ 10 g kg^{-1} in comparison to 12 g kg^{-1} under NV ($p < 0.01$). A similar pattern was observed in the 30-50 and 50-70 cm layers (i.e., both agricultural uses reduced the C levels), but the changes induced by CL occurred to a minor extent (average reduction of ~ 13% under CL, and ~ 33% in PA, compared to NV) (NV > CL > PA) ($p < 0.01$). In the deepest layers (70-90 and 90-100 cm), there was no change in C content after conversion from NV to CL, but the LUC from NV to PA induced a decrease of ~ 1.4 g kg^{-1} of C ($p < 0.01$).

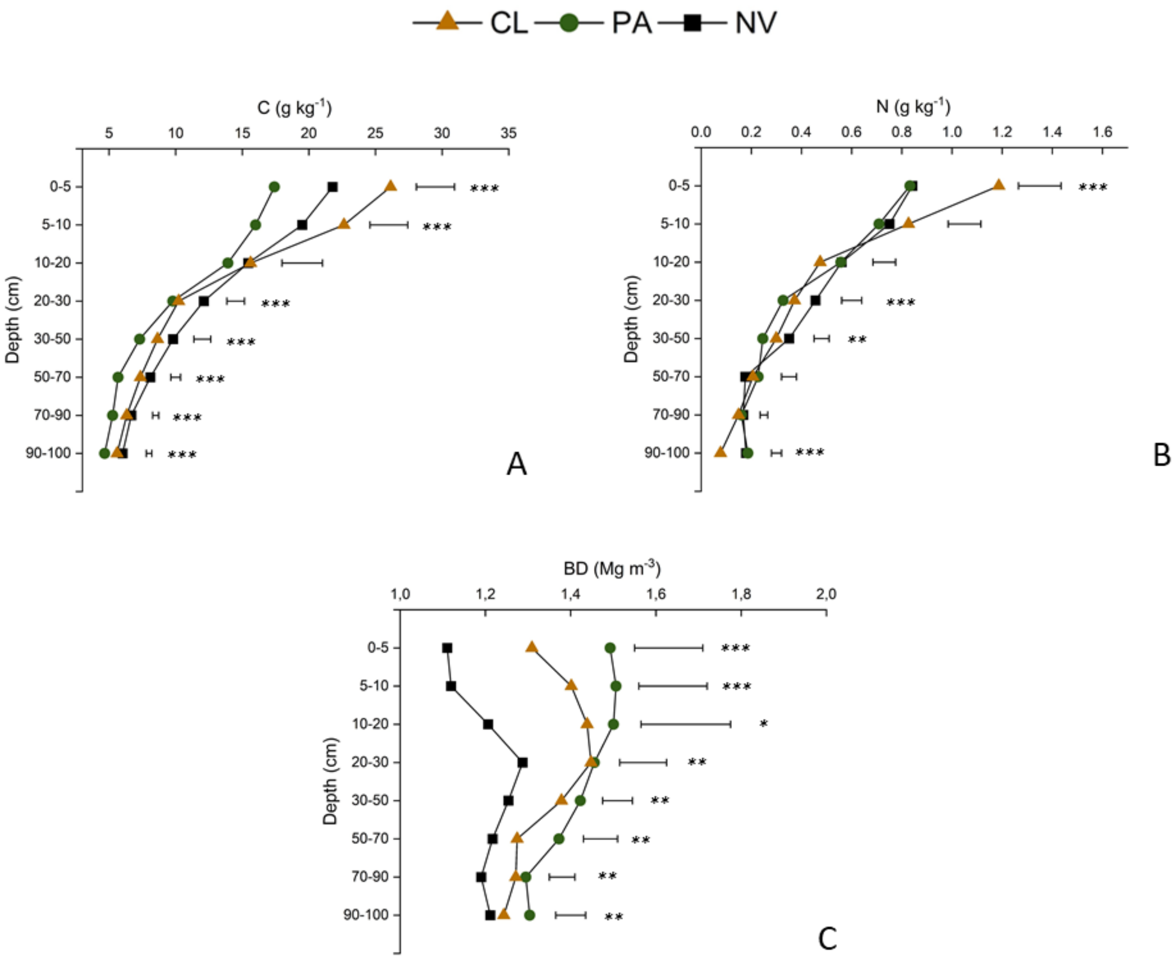

Figure 2. Soil carbon (A) and nitrogen content (B) (g kg^{-1}), and soil bulk density (C) (Mg m^{-3}) at 0-5, 5-10, 10-20, 20-30, 30-50, 50-70, 70-90 and 90-100 cm soil layers under native vegetation (NV), pasture (PA) (NV – PA conversion), and cropland (CL) (NV – CL conversion) in Brazil's new agricultural frontier. Error bars represent the least significant difference (LSD) according to Tukey test ($p < 0.10$). *, ** and *** indicate significant differences at 10, 5 and 1%, respectively.

Land-use change has also induced changes in soil N content, but to a minor extent than that observed for C levels (Figure 2B). In the superficial layers, differences were observed only for the 0-5 cm depth, where the NV-CL conversion increased N levels from 0.85 g kg^{-1} to 1.25 g kg^{-1} ($p < 0.01$). For the 20-30 and 30-50 cm layers, NV-PA conversion decreased the N content from 0.43 to 0.35 g kg^{-1} ($p < 0.01$), and from 0.35 to 0.25 g kg^{-1} ($p < 0.05$), respectively. In the deepest layers, changes induced by the LUC were observed only in the 90-100 cm soil layer, where CL decreased the N content from ~ 0.17 g kg^{-1} (average between NV and PA uses) to 0.09 g kg^{-1} ($p < 0.01$).

Regarding soil BD, the greatest changes were verified in the 0-20 cm layer. At this soil layer, CL and PA induced an average increase of ~ 21 and 30% in the BD, respectively, in comparison to NV (Figure 2C). For the 0-5 cm layer, LUC increased BD values from 1.11 under NV to 1.31 in the CL and 1.49 Mg m^{-3} in the PA site ($p < 0.01$). In the 5-10 and 10-20 cm layers, there were no differences in BD between CL and PA. However, compared with NV (average of 1.41 Mg m^{-3}), CL and PA soils had BD values increased by ~ 25% ($p < 0.10$). For the 50-70 and 90-100 cm layers, the NV-CL conversion did not affect soil BD, but NV-PA conversion led to an increase from 1.21 to 1.37 Mg m^{-3} at 50-70 cm and from 1.19 to 1.29 Mg m^{-3} at 90-100 soil layer. The other layers (20-30, 30-50, and 70-90 cm) followed a similar pattern observed at 5-10 and 10-20 cm layers, but changes occurred at a minor extent, where CL and PA land uses did not differ from each other but showed higher BD values when compared to NV ($p < 0.01$).

2.3.2. Total carbon and nitrogen stocks

Changes in C and N content (Figure 2A-B) induced by LUC were also observed in soil C and N stocks (Figure 3A-B). The most pronounced impacts were observed in the C stocks, where the NV-PA conversion induced a loss of ~ 9, 17 and 28 Mg ha^{-1} (i.e., ~ 19, 25 and 28%), for the 0-30, 0-50 and 0-100 cm layer, respectively ($p < 0.01$) (Figure 3A). Although these C losses were observed along with the whole soil profile (up to 100 cm), they were more intense in the deepest soil layers (30-100 cm), which accounted for an overall decrease of ~ 33% in C stocks. The rate of C stock change for the 0-100 cm layer due to NV-PA conversion was about -1.38 Mg ha^{-1} yr^{-1} (Table S1). On the other hand, no changes in the accumulated C stocks were observed after NV-CL conversion (i.e., 0-30, 0-50 and 0-100 cm) (Figure 3A), which kept similar C levels as in the NV use. Actually, the CL use under no-tillage increased the C levels in the upmost layers (0-10 cm) (i.e., an average increase of ~ 18% compared to NV. However, a significant loss of ~ 16% in C stocks was observed in the 20-50 cm layer compared to NV, which offset the C gains observe in the soil surface layers (Table S1). Soil C allocation within the soil profile was quite similar between the different land uses. On average (average between CL, PA and NV uses), ~ 48% of the total C stocks was accounted in the first 30 cm layer, while ~ 52% was allocated in the subsurface layers (30-100 cm) (Table S1).

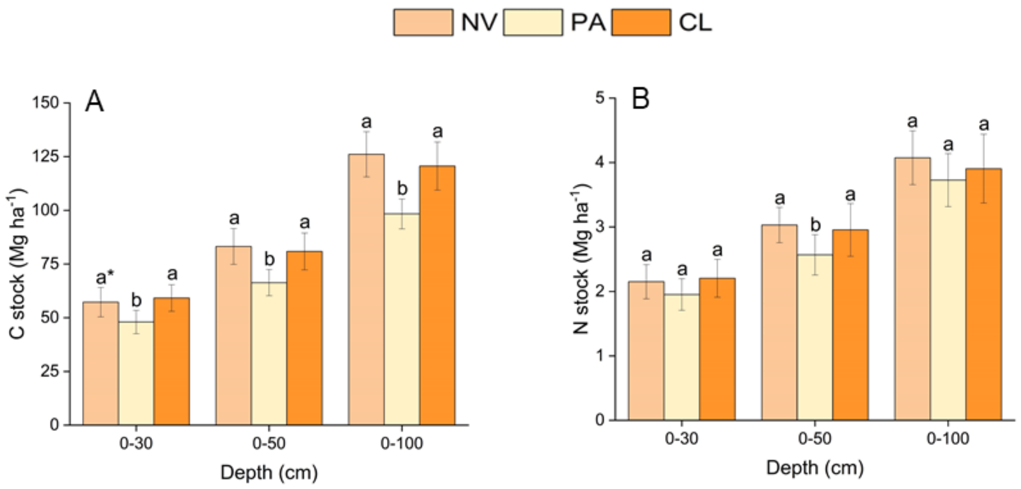

Figure 3. Soil carbon (A) and nitrogen stocks (B) (Mg ha^{-1}) at 0-30, 0-50 and 0-100 cm soil layers under native vegetation (NV), pasture (PA) (NV – PA conversion), and cropland (CL) (NV – CL conversion) in Brazil's new agricultural frontier. * Mean values followed by the same letter within the same soil depth do not differ by Tukey's test (p < 0.10). Error bars represent the standard deviation of the mean.

Changes in soil N stocks did not occur to the same extent as for the C stocks. For the accumulated layers (0-30, 0-50 and 0-100 cm), differences were found only in the 0-50 cm (Figure 3B), where the NV-PA conversion decreased the N levels from 3 Mg ha^{-1} under NV to 2.5 Mg ha^{-1} under PA (i.e., ~ 18%) (p < 0.01). Nitrogen loss was observed mainly in the 20-30 and 30-50 cm layers, where the stocks decreased (p < 0.01) from 0.58 and 0.87 in the NV to 0.42 and 0.61 Mg ha^{-1} in the PA, respectively (Table S1). The rate of N stock change was about -0.02 Mg ha^{-1} yr^{-1} for the 0-50 cm layer. Under CL, the N stock changes in each soil layer showed a response similar to the C stock alterations. The N levels under CL increased at 0-5 cm layer (from 0.46 Mg ha^{-1} in the NV to 0.65 Mg ha^{-1} in the CL) (p < 0.01) but losses of 0.11 and 0.13 Mg ha^{-1} were observed for the 20-30 and 90-100 cm layers, respectively (p < 0.01) (Table S1).

2.3.3. Particulate and mineral associated organic matter fractions

Soil C stock depletion due to NV-PA conversion was observed in both POM and MAOM fractions (Figure 4). However, the greatest effect occurred in the POM fraction, which had a decrease of ~ 52, 45 and 36% of C in comparison to the NV for the 0-30, 0-50 and 0-100 cm layers, respectively (p < 0.01). Although C losses occurred within the soil profile, the upmost soil layers were the most affected. At 0-5 and 5-10 cm layer there was a decrease of ~ 45% in PA compared to NV (0-5 cm = 3.5 Mg ha^{-1}; 5-10 cm = 1.64 Mg ha^{-1}; $p < 0.01$) (Table S2). The MAOM fraction had a similar effect ($p < 0.01$), but losses occurred at a minor extent, presenting a decrease of ~ 28, 27 and 34% in comparison to the NV, for the 0-30, 0-50 and 0-100 cm layers, respectively. Contrary to the POM fraction, the most significant C loss in the MAOM fraction occurred in the 30-100 soil layer, which had an overall reduction of ~ 40% compared with NV ($p < 0.05$) (Table S2).

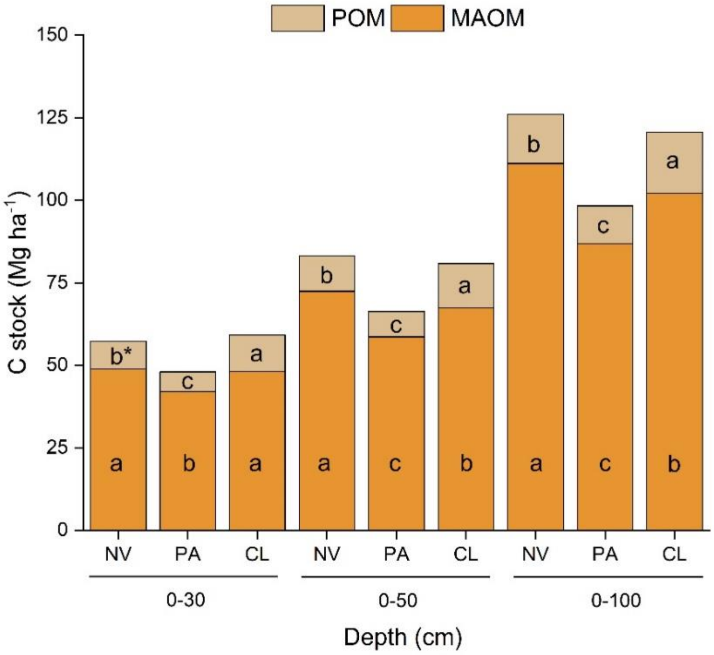

Figure 4. Carbon stocks (Mg ha^{-1}) on particulate organic matter carbon (POM) and mineral-associated organic matter carbon (MAOM) fractions at 0-30, 0-50, and 0-100 cm soil layers under native vegetation (NV), pasture (PA) (NV – PA conversion), and cropland (CL) (NV – CL conversion) in Brazil's new agricultural frontier. * Mean values followed by the same letter within the same soil depth and the same fraction (POM or MAOM) do not differ by Tukey's test ($p < 0.10$).

Although NV-CL conversion had no effects on total C stocks (Figure 3), significant changes were observed regarding the POM and MAOM fractions (Figure 4). The MAOM decreased from ~ 75 and 117 Mg ha^{-1} in the NV to ~ 67 and 101 Mg ha^{-1} in the CL for the 0-50 and 0-100 cm layers, respectively ($p < 0.01$). At the 20-30, 30-50 and 50-70 cm layers MAOM decreased by ~ 27, 20 and 24% ($p < 0.05$), respectively, in comparison to the NV use (Table S2). Contrary to MAOM, the POM fraction was positively impacted by the NV-CL conversion, offsetting the C depletion accounted for the MAOM fraction. The POM stocks had an increase of ~ 24, 19 and 16%, for the 0-30, 0-50 and 0-100 cm layers, respectively ($p <$ 0.01) (Figure 4). Overall, the greatest increase in the POM fraction was observed at 5-10 and 10-20 cm layers, which presented an average increase of ~ 40% in comparison to NV ($p <$ 0.01) (Table S2).

2.3.4. Carbon management index

The indexes were sensitive to LUC ($p < 0.10$), providing additional information regarding soil C dynamics induced by LUC (Table 2). An increase of ~ 30% in the carbon pool index (CPI) values was observed within the soil profile (0-30 cm) in the CL compared with PA (0.83), with the highest values observed at 0-5 (1.19) and 5-10 cm (1.16) layers. Similarly, the lability index (LI) was consistently higher in CL compared with PA, which the former was 2-fold higher along with the entire soil profile compared with de latter. These changes led to differences in the CMI index. The NV-CL conversion significantly increased the CMI, especially in the 0-5 and 0-30 cm average layer, while the NV-PA conversion decreased the CMI values in all assessed layers (Table 2). At the 5-10 cm layer, the CMI at CL use was about 142%, followed by the NV (100%) and the PA (71%) ($p < 0.01$). At 0-30 cm average layer, CMI values were 137, 100 and 75%, for CL, NV and PA areas, respectively ($p < 0.01$). At 0-5, 10-20, and 20-30 cm, CMI in CL had the same levels as those observed in NV and higher than those observed in PA ($p < 0.05$).

Table 2. Carbon pool index (CPI), lability (L), lability index (LI) and carbon management index (CMI) at 0-5, 5-10, 10-20, 20-30 and 0-30 cm soil layers under native vegetation (NV), pasture (PA) (NV – PA conversion), and cropland (CL) (NV – CL conversion) in Brazil's new agricultural frontier.

Soil layer (cm)	Land-use	CPI (2)	L (3)	LI (2)	CMI (%) (3)
0-5	NV (1)	-	0.29 (±0.01) a	-	100 a
	PA	0.79 (±0.01) b	0.18 (±0.008) b	0.63 (±0.05) b	50 (±4.59) b
	CL	1.19 (±0.06) a	0.33 (±0.05) a	1.12 (±0.20) a	134 (±27.03) a
5-10	NV (1)	-	0.17 (±0.01) b	-	100 (±0) b
	PA	0.82 (±0.07) b	0.14 (±0.01) b	0.87 (±0.02) b	71 (± 7.90) c
	CL	1.16 (±0.18) a	0.20 (±0.01) a	1.23 (±0.16) a	142 (±8.26) a
10-20	NV (1)	-	0.12 (±0.01) b	-	100 (±0) ab
	PA	0.91 (±0.16) a	0.13 (±0.003) b	1.02 (±0.13) b	93 (±22.24) b
	CL	1.02 (±0.18) a	0.21 (±0.01) a	1.58 (±0.10) a	148 (±23.04) a
20-30	NV (1)	-	0.11 (±0.008) b	-	100 (±0) ab
	PA	0.81 (±0.10) a	0.11 (±0.01) b	1.05 (±0.15) b	85 (±14.02) b
	CL	0.84 (±0.09) a	0.16 (±0.01) a	1.45 (±0.19) a	122 (±18.18) a
0-30	NV (1)	-	0.17 (±0.007) b	-	100 (±0) b
	PA	0.83 (±0.05) b	0.14 (±0.004) c	0.89 (±0.07) b	75 (±8.23) c
	CL	1.06 (±0.05) a	0.22 (±0.01) a	1.34 (±0.06) a	137 (±10.67) a

(1) Reference, with CMI = 100%; Means values followed by the same letter within the same soil layer do not differ by the Student-t test (2) and Tukey's test (3) ($p < 0.10$).

2.4. Discussion

2.4.1. Land transition effects on total carbon and nitrogen stocks

Land-use change induced by the agricultural expansion in the MATOPIBA region caused substantial changes in the C and N stocks, especially for the NV-PA conversion, which reduced the C and N levels by ~ 28 (C loss rate of ~ 1.3 Mg ha^{-1} yr^{-1} for the 0-100 cm) and 18% (N loss rate of ~ 0.02 Mg ha^{-1} yr^{-1} for the 0-50 cm), respectively, compared to NV use (Figure 3, Table S1). This C loss is in accordance with several studies conducted worldwide (Conant et al., 2017; Don et al., 2011) and in Brazil (Assad et al., 2013; Oliveira et al., 2016). For instance, a meta-analysis conducted by Conant et al. (2017) reported an average loss rate of ~ 0.13 Mg ha^{-1} yr^{-1} of C due to NV-PA transition. For the MATOPIBA region, Gmach et al. (2018) observed a decrease of ~ 24% in the C stocks (0-40 cm layer) only two years after PA implementation, being in line with our results.

The scenario found in the present study (i.e., C and N loss) is commonly observed in extensively managed pasturelands from the *Cerrado*, and it is attributed to the absence or poor adoption of best management practices (Assad et al., 2013; Pereira et al., 2018). The sampled pasture area had clear visual signals of degradation, presenting low forage offer due to overgrazing, bare soil spots, and a history of poor fertilization management, mainly regarding N fertilization. According to Pereira et al. (2018), ~ 18 million hectares of pasture in the *Cerrado* biome are degraded (~ 40% of the total), mainly within the MATOPIBA region. The overgrazing associated with the low N supply generally limits biomass production, which reduces the C input in the soil contributing to SOM depletion (Assmann et al., 2014; Wieder et al., 2015). Furthermore, as shown in Figure 2C, the PA use had BD values significantly greater than the NV area, possibly indicating soil compaction. Soil physical degradation (e.g., compaction) reduces C inputs (e.g., rhizodeposits) in soil by limiting root and plant growth development. Even though we did not measure the biomass production in the area, our results indicate (i.e., decrease in C levels) that the amount of C annually added in the soil is insufficient to counterbalance the C loss in tropical environments, which according to Sá et al. (2015) is in average 5.5 Mg ha^{-1} yr^{-1} of C (i.e., 12.5 Mg ha^{-1} yr^{-1} of plant biomass).

Overall, the LUC from NV to CL had no effects in total C and N stocks (Figure 3), although changes were observed in specific soil layers along with the soil profile (Table S1). For instance, C levels increased in the 0-5 and 5-10 cm layers and N in the 0-5 cm layer. However, this increase in C levels was offset by the losses observed in the deepest soil layers (20-50 cm layer). This highlight the importance of deep soil sampling (> 30 cm), since changes in C dynamics are not restricted to the upmost soil layers, and a superficial sampling may introduce a bias (Assad et al., 2013; Baker et al., 2007; Don et al., 2011; Oliveira et al., 2016). These results are in line with other studies carried out in the *Cerrado*, which also showed that CL under no-tillage can keep the C and N stocks at levels similar to the pristine vegetation (*Cerrado*), and in some cases, they may be increased, especially in the upmost layers (e.g., 0-40 cm) (Bayer et al., 2006; Carvalho et al., 2009; Corbeels et al., 2016; Ferreira et al., 2021). This is possible because conservation practices such as no-tillage help to minimize soil disturbances and increase soil stability and aggregation (Blanco-Canqui and Ruis, 2018), reducing SOM exposure to microbial oxidation and consequent depletion (Franco et al., 2020). Because soils from the *Cerrado* present low natural fertility (Lopes and Guimarães Guilherme, 2016) (Table 1), amendments in soil fertility associated with other sustainable management practices (e.g., no-till) can help to increase C input and maybe its stabilization in soil (O’Brien et al., 2015; Wiesmeier et al., 2019). The slight decrease in C and N stocks in the 20-50 cm layer can also be associated with the limited root development of cultivated species (e.g., soybean) in deeper soil layers (Calonego et al., 2017). Besides this is intrinsically related to the genetic selection of species, the soil acidity (Table 1) in the subsoil may also be a limiting factor for root growth, and consequent input of C (Inagaki et al., 2017; Lopes and Guimarães Guilherme, 2016).

The differences observed between CL and PA are primarily attributed to the lack of proper management in PA, such as grazing control (e.g., stocking rate control, improved grazing systems) and proper N fertilization (Assmann et al., 2014; Wieder et al., 2015) as previously discussed. We are aware that the age difference between areas is a factor that also must be considered, as at the sampling time, there were 10 years that NV had been changed to CL, and 19 years to PA. Indeed, soil C changes may proceeds over decades until that a new equilibrium level is reached (Don et al., 2011). However, the most significant changes usually occur in the first years after land disturbance, as observed by Corbeels et al. (2016), which found a new equilibrium 11 years after LUC from NV to CL under a no-till system in the *Cerrado*. In our case, the difference between the rate of C stock change for the uses (i.e., -1.38 Mg ha^{-1} yr^{-1} under PA vs. -0.41 Mg ha^{-1} yr^{-1} under CL – 0-100 cm layer – Table S1) reinforces the management effect over the land use time. We highlight that the extension of the period for reaching the new equilibrium is intrinsically related to soil management and the quantity and quality of C inputs added to the soil. Also, based on the gain of C stocks in the upmost layers under CL compared to NV, and the absence of statistical differences between the uses (CL and NV), we can confirm that proper soil management has been effective on C accrual and that the difference of ages between uses had less importance on C dynamics than the management adopted.

2.4.2. Land-use change effects in particulate and mineral associated organic matter fractions

The decrease in C stocks induced by PA expansion was observed in both POM and MAOM fractions (Figure 4). The former, which comprises the labile pool of SOM was lost in a higher proportion (~ 54% for the 0-30 cm layer), while the latter had a less intense loss (~ 28%), both compared to NV. This pattern is in line with several studies performed in tropical and subtropical environments (Campos et al., 2011; Figueiredo et al., 2013; Sá and Lal, 2009), including in the MATOPIBA region (Gmach et al., 2018), and it is justified by the different turnover rates of these fractions, which are mediated by microorganism and interactions with soil mineral matrix (Lavallee et al., 2020).

The greatest changes in the POM fraction can be attributed to its predominant composition (plant and fungal derived compounds - phenols, celluloses, chitin, xylanase, etc.)

(Baldock and Skjemstad, 2000; Six et al., 2001) and size (> 53 µm), which restrict the stabilization of this fraction in large aggregates, a less effective stabilization pathway, as it has a lower protective capacity (Gryze et al., 2006). This condition contributes to a high turnover rate of this fraction (von Lützow et al., 2007), which is considerably intensified in tropical humid environments (double than temperate regions) given the favorable environmental conditions of organic matter decomposition by soil organisms (Six et al., 2002). On the other hand, the lower impact in the MAOM fraction is probably linked to the capacity of organic compounds to interact with soil mineral matrix (Lavallee et al., 2020). The MAOM fraction (< 53 µm) is mainly composed of low molecular weight compounds (microbial and plant origin – polysaccharides, amino sugars, muramic acid, etc.) (Kögel-Knabner et al., 2008; Lehmann and Kleber, 2015; Six et al., 2001), which are stabilized through mineral associations (e.g., sorption onto mineral surfaces, organo-mineral clusters, occlusion in fine aggregates and micropores, etc.) (Cotrufo et al., 2013). These mechanisms effectively protect SOM against microbial access and decomposition, increasing its mean residence time in soil (i.e., low turnover rate) (Lavallee et al., 2020).

Changes in SOM fractions can also be attributed to the quality of the organic residues left on soil (Lavallee et al., 2020). This can be observed mainly in the CL site, where the MAOM fraction considerably decreased, while the POM increased (Figure 4). The stabilization of C in the mineral fraction (i.e., MAOM) is highly dependent on the quality of the organic material (Cotrufo et al., 2019). Residues with a lower C:N ratio and with more significant amounts of non-structural/soluble C compounds are more easily incorporated into the MAOM fraction (Castellano et al., 2015), because they are more efficiently processed by soil microorganisms, producing more chemically stable organic compounds. On the other side, low-quality residues (i.e., high C:N ratio, presence of structural and complex C chains) are preferentially accumulated by a "physical transfer path", being primarily accrued in the POM fraction (Cotrufo et al., 2015, 2013). This hypothesis fits our results because the CL use has been managed in a low-diversified successional system with soybean and millet. Although we did not measure the C input, we estimated (i.e., considering a harvest index of 0.43; Sisti et al. 2004) that soybean crop contributed with ~ 2 Mg ha^{-1} yr^{-1} of C (45 % of C in the biomass), assuming that the greatest contribution originated from the millet crop. Despite the great quantitative contribution, the low quality of the millet residue (e.g., C:N ratio of ~ 46) (Calvo et al., 2010) may have restricted the C accrual to the POM fraction, thus not maintaining the MAOM levels (Cotrufo et al., 2013). The behavior observed under CL use (i.e., depletion of MAOM and increase in the POM levels) is in line with Wuaden et al.

(2020), which reported a similar response under a no-tillage system in the southern Brazilian region.

2.4.3. Carbon management index and best management practices to enhance soil health in MATOPIBA

The CMI provides a quantitative and qualitative assessment of the SOM dynamics, and it is a sensitive indicator of the soil management effects on soil quality status (Blair et al., 1995). Overall, the greatest CMI values were associated with the CL land use, which was 37% higher than the NV in 0-30 cm layers. This result is justified by the increase in the C stock associated mainly with the labile fraction of SOM, here represented by the POM, as a consequence of best management practices adopted in the no-tillage system (Diekow et al., 2005). Although no differences were found between the NV and CL regarding total C stocks (Figure 3A), the C pools that integrate the CMI (e.g., POM) enabled to identify changes in SOM quality even in the medium-term basis (10 years), being thus an important tool for monitoring the early effects of soil disturbance over soil health. On the other side, the lowest CMI values associated with the PA use reflect the poor management of the area and the consequent decrease in the C pools due to the reduced C input (mainly the POM fraction). According to Blair et al. (1995), CMI values below 100% are clear indications of loss of soil health. This result is in line with several studies performed in other PA areas (Cherubin et al., 2016; Silva et al., 2014), which also linked the soil quality deterioration to the absence of appropriate management practices (e.g., overgrazing and poor fertilization).

The multiple effects of SOM to sustain soil health, including chemical, physical and biological functions is well-established in the literature (Lange et al., 2015; Mujdeci et al., 2017; Tiessen et al., 1994). Besides, SOM accrual has been linked as a feasible path for mitigating climate change effects, as soils have a large capacity to act as a carbon dioxide sink (Lal, 2020; Lal et al., 2015). For instance, Sá et al. (2017) estimated that the recovery of degraded pasturelands in South America would sequester ~ 2.5 Pg of C (from 2016 to 2050 period). Based on that, and in the results presented here, which suggested that the PA expansion in the MATOPIBA region has caused severe impacts on soil C dynamics, the adoption of best management practices that can alleviate the C depletion effects is mandatory to recover systems equilibrium and to avoid further environmental and economic problems.

Pasturelands in an advanced degradative condition normally require the adoption of harsh measures to restore soil health and its capacity to provide related ecosystem services.

Soil tillage, even though it is not considered a conservation practice, can be used to alleviate highly compacted soils in the short term (Peixoto et al., 2020). Reducing soil penetration resistance may decrease the root elongation inhibition, thus improving plant growth and consequently biomass production (Drewry et al., 2008). Furthermore, improving the soil fertility status (e.g., pH correction and N application) may also favor better grass development (Crusciol et al., 2019; Vasques et al., 2019). Moreover, practices such as animal stocking rate and grazing control (e.g., rotational grazing) are other feasible alternatives that can be applied in such areas as a strategy to increase C levels, mitigating carbon dioxide emissions, and improving soil quality (Abdalla et al., 2018; Assmann et al., 2014; Conant et al., 2017; Ribeiro et al., 2019).

Although in the CL site the no-tillage has effectively contributed to sustaining C stocks at the same levels as the *Cerrado* area, improvements can be performed toward more efficient and sustainable management. The inclusion of different species in a rotational system or even the diversification with cover crops during the off-season are promising options for improving C levels (Tiefenbacher et al., 2021). More diverse cropping systems increase the quality and eventually the quantity of C-inputs, thus contributing to soil C accrual (Lange et al., 2015; Lehman et al., 2017). The use of species from the *Urochloa* genus (tropical grasses), for example, has shown multiple benefits for soil health. Besides increasing C accrual through the significant shoot and root biomass additions, studies have shown promising results for aspects related to nutrient cycling (especially N and P), soil physical environment improvement, inhibition of nitrification/denitrification process (reduces the loss of N through nitrous oxide emissions and increases nutrient use efficiency), and soil stability and aggregation, which are all important attributes for proper plant development and consequently C accrual and stabilization in the soil (Baptistella et al., 2020; Nascente et al., 2015; Salton et al., 2008). Finally, investing in strategies to sequester C in deepest layers (e.g., improve subsoil fertility, crops with deepest root systems) may also be effective for improving soil C content. The C accrual in layers where SOM decomposition is reduced due to spatial separation from decomposers is a feasible long-term C sequestering tool (Chenu et al., 2019; Sokol and Bradford, 2019).

2.5. Conclusions

Long-term conversion from native vegetation (*Cerrado*) to poor-managed PA decreased the soil C and N stocks. Soil C losses were observed in both POM and MAOM fractions in the PA area, in which C levels decreased ~ 36 and 34%, respectively, in comparison to the NV use (0-100 cm soil depth). These losses in C stocks led to the smallest values for CMI, which were 25% smaller compared to NV (0-30 cm layer). On the other hand, contrary to our initial hypothesis, CL expansion with the adoption of conservation practices sustained total C and N stocks at the same levels observed in the NV. A slight decrease in the MAOM fraction was observed (compared to NV), as we hypothesized, but the C accrual in the POM fraction offset these losses (average increase of 40% in the upmost layers). Besides, the increase in the C levels from the POM led to the highest CMI, which showed an average of 137% for the 0-30 cm layer, indicating an improvement in soil health status. Overall, our findings suggested that PA restoration by adopting best management practices (e.g., proper fertilization and grazing control) is mandatory to alleviate the C depletion effects and to restore soil health. Meanwhile, we highlight the importance of adopting no-tillage coupled with diversified cropping systems towards more productive and climate-smart agriculture in the MATOPIBA region, Brazil.

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Supplementary Material

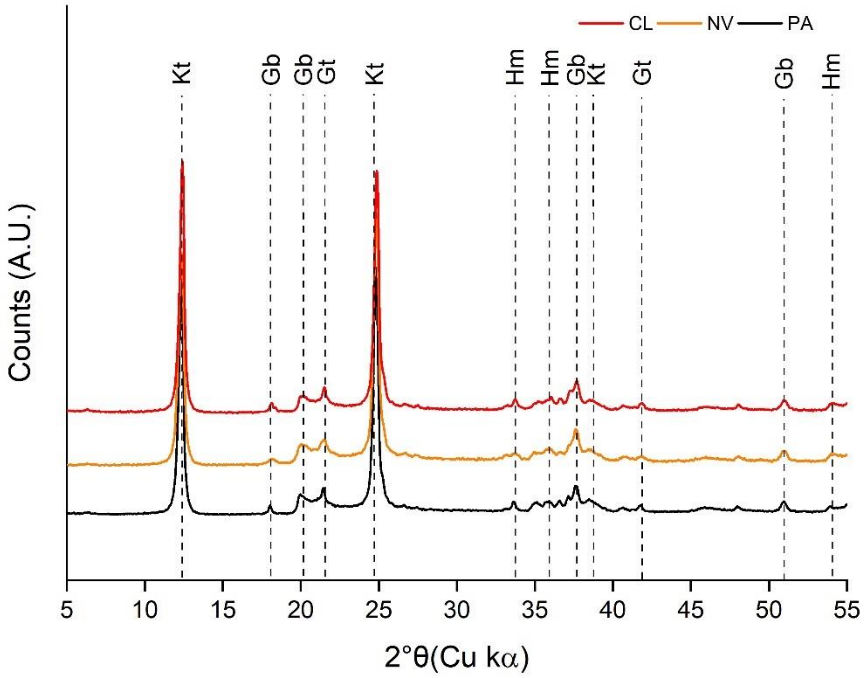

Figure S1. X-ray diffraction patterns of the clay fraction from a Typic Haplustox under native vegetation (NV), cropland (CL), and pasture (PA) in the MATOPIBA region – Brazil's new agricultural frontier. Kt: kaolinite, Gb: gibbsite; Gt: goethite, Hm: hematite.

Table S1. Soil carbon and nitrogen stocks (Mg ha^{-1}) at 0-5, 5-10, 10-20, 20-30, 30-50, 50-70, 70-90 and 90-100 cm soil layers under native vegetation (NV), pasture (PA) (NV – PA conversion), and cropland (CL) (NV – CL conversion) in Brazil's new agricultural frontier. * Mean values followed by the same letter within the same soil depth do not differ by Tukey's test ($p < 0.10$). Values in parenthesis represent the standard deviation of the mean.

Soil layer (cm)	C stock Mg ha^{-1}		
	NV	PA	CL
0-5	12.09 (±2.06) b*	9.66 (±1.04) c	14.51 (±1.41) a
5-10	10.91 (±1.82) b	8.95 (±1.07) c	12.66 (±1.70) a
10-20	18.63 (±3.50) a	16.79 (±2.26) a	18.84 (±4.29) a
20-30	15.59 (±1.61) a	12.59 (±1.57) b	13.15 (±1.86) b
30-50	24.59 (±1.53) a	18.30 (±1.61) c	21.66 (±2.83) b
50-70	19.72 (±2.29) a	13.81 (±1.08) b	17.89 (±1.62) a
70-90	15.88 (±0.84) a	12.54 (±1.42) b	15.05 (±1.00) a
90-100	7.29 (±0.57) a	5.66 (±0.34) b	6.79 (±0.60) a
ΔC_{0-30}⁽¹⁾	-	-0.48	0.19
ΔC_{0-50}	-	-0.81	-0.10
ΔC_{0-100}	-	-1.38	-0.41
	N stock (Mg ha^{-1})		
0-5	0.46 (±0.09) b	0.46 (±0.07) b	0.65 (±0.08) a
5-10	0.42 (±0.07) a	0.39 (±0.06) a	0.46 (±0.08) a
10-20	0.67 (±0.07) a	0.67 (±0.10) a	0.57 (±0.15) a
20-30	0.58 (±0.10) a	0.42 (±0.09) b	0.47 (±0.11) b
30-50	0.87 (±0.14) a	0.61 (±0.12) b	0.75 (±0.22) ab
50-70	0.42 (±0.17) a	0.51 (±0.09) a	0.46 (±0.08) a
70-90	0.38 (±0.05) a	0.38 (±0.06) a	0.33 (±0.04) a
90-100	0.21 (±0.05) a	0.20 (±0.03) a	0.08 (±0.03) b
ΔN_{0-30}⁽¹⁾	-	-0.010	0.002
ΔN_{0-50}	-	-0.023	-0.010
ΔN_{0-100}	-	-0.019	-0.024

(1) ΔC, N is the rate of C, N stock change in Mg ha^{-1} yr^{-1} for 0-30, 0-50 and 0-100 cm layers.

Table S2. Carbon stocks (Mg ha^{-1}) on particulate organic matter (POM) and mineral-associated organic matter (MAOM) fractions at 0-5, 5-10, 10-20, 20-30, 30-50, 50-70, 70-90 and 90-100 cm soil layers under native vegetation (NV), pasture (PA) (NV – PA conversion), and cropland (CL) (NV – CL conversion) in Brazil's new agricultural frontier. * Uppercase and lowercase letters within the same soil depth compare POM and MAOM, respectively. Means followed by the same letters do not differ by Tukey's test (p < 0.10). Values in parenthesis represent the standard deviation of the mean.

Soil layer (cm)	C stock (Mg ha^{-1})					
	Native vegetation		Pasture		Cropland	
	POM	MAOM	POM	MAOM	POM	MAOM
0-5	3.50 (±0.05) A*	11.83 (±0.34) a	1.45 (±0.06) B	7.72 (±0.38) b	3.85 (±0.58) A	11.64 (±0.20) a
5-10	1.64 (±0.16) B	9.69 (±1.44) a	1.12 (±0.10) C	7.55 (±0.19) b	2.20 (±0.07) A	10.52 (±0.88) a
10-20	2.23 (±0.18) B	17.32 (±2.35) a	1.98 (±0.10) B	15.06 (±0.51) a	3.28 (±0.33) A	15.41 (±2.45) a
20-30	1.56 (±0.18) AB	14.07 (±1.47) a	1.29 (±0.18) B	11.07 (±1.43) b	1.77 (±0.04) A	11.06 (±0.74) b
30-50	2.25 (±0.06) A	22.34 (±0.51) a	1.89 (±0.12) A	17.64 (±1.70) b	2.26 (±0.31) A	18.55 (±1.12) b
50-70	1.86 (±0.07) A	19.89 (±2.86) a	1.56 (±0.19) B	12.8 (±0.92) b	1.92 (±0.09) A	15.07 (±1.28) b
70-90	1.77 (±0.10) A	15.24 (±1.18) a	1.46 (±0.10) B	10.64 (±1.38) b	1.96 (±0.10) A	12.8 (±1.25) ab
90-100	0.86 (±0.03) B	6.66 (±0.44) a	0.71 (±0.02) C	5.05 (±0.55) b	0.96 (±0.02) A	6.32 (±0.35) a

3. CROPLAND AND PASTURE EXPANSION IMPACTS ON SOIL PHYSICAL PROPERTIES IN THE NEW BRAZILIAN AGRICULTURAL FRONTIER

ABSTRACT

The growing demand for food at global levels has increased the expansion and intensification of agricultural areas worldwide. In Brazil, the so-called MATOPIBA region (northeastern region) has experienced an accelerated agricultural expansion in the last decades. In this sense, we evaluated the magnitude that the agricultural expansion affects key soil physical indicators in the most common land-use change (LUC) scenarios from the MATOPIBA region: from native vegetation (NV) to pasture (PA) and cropland (CL). Soil samples were collected up to 30 cm soil layer in three adjacent areas (NV, PA and CL) located in the southern part of Maranhão. In the laboratory, the following attributes were determined: bulk density (BD), soil penetration resistance (SPR), total porosity (TP), macroporosity (MaP), microporosity (MiP), saturated hydraulic conductivity (K_s), wet-aggregate stability, and soil carbon (C) content. Additionally, we calculated a set of physical indicators: degree of compactness (DC), soil aeration capacity (SAC), soil water storage capacity, mean weight diameter (MWD) of the aggregates, and plant available water (PAW). We observed that BD and DC increased (0-30 cm layer) 23 and 19% in PA and CL compared to NV, respectively. Soil penetration resistance was increased in CL and PA, but only in the latter values above the critical limit for proper root development (> 2 MPa) were observed. Total porosity was decreased irrespective of LUC mainly associated with the decrease in MaP (-59%; 0-30 cm layer). These changes in pore size distribution negatively affected SAC and reduced K_s. An increase in PAW was observed only in CL, mainly at 0-5 and 5-10 cm. Soil C accrual was observed only in the upmost soil layer (0-5 cm) in CL, but no improvements in soil aggregate stability were observed. In CL, the MWD (0-30 cm layer) was 59% lower than in NV and PA. Soil physical quality loss was observed mainly by the increase on soil compaction indicators and the reduction of hydraulic and aeration of soil in PA. Our findings suggest that the agricultural expansion in the MATOPIBA region negatively affected soil physical attributes, which may compromise its environmental sustainability over time. Based on that, we highlight the necessity of monitoring soil physical attributes and adopting best management practices as a strategy to recover the soil's physical quality and avoid further degradation in the MATOPIBA region.

Keywords: Soil physical attributes; soil health; no-tillage; soil compaction; MATOPIBA

3.1. Introduction

The world population has been growing exponentially and it is expected to reach 9.7 – 12.7 billion inhabitants by 2100 (UN, 2019), increasing the global demands for food, fiber, and energy (Charles et al., 2010). Brazil is considered an essential player for supplying this expected global demand in the next decades (OECD-FAO, 2015) due to its large potential to expand agricultural areas. This has been recently observed in the MATOPIBA region, an area that extends over part of the states of Maranhão, Tocantins, Piauí, and Bahia (collectively

MATOPIBA) - northeastern part of Brazil, considered the new agricultural frontier of the country. This region has experienced an accelerated agricultural expansion driven mainly by soybean cultivation (which production increased ~ 4000% between 1990 and 2015) (Araújo et al., 2019), and estimates indicate a further increase of 30% in the cultivated area and 54% in grain production over the next 10 years (MAPA, 2019). Although this accelerated expansion/intensification of agriculture in the MATOPIBA region is important for supplying the global demands, concerns have been raised regarding soil physical degradation and sustainability of crop production over time (Donagemma et al., 2016; Lumbreras et al., 2015).

The MATOPIBA region extends over an area of 73 million ha, but due to the local characteristics (i.e., soil and climate), less than 35% of this territory is classified as having a "medium to good" capability to support intensive agriculture (Bolfe et al., 2016; Lumbreras et al., 2015). The limitations of the region are linked to the specific climatic characteristics (i.e., high temperatures and short-term rain season) and soil properties, which are characterized by having a high sand content (usually > 60%) and low soil organic matter (SOM) concentration, water retention capacity and natural fertility (Santos et al., 2011; Donagemma et al., 2016). All these conditions tend to be limiting factors in agricultural practice (Rawls et al., 2003; Yost and Hartemink, 2019), making sustainable soil management challenging to ensure suitable conditions for proper plant growth without jeopardizing soil functions (e.g. food production, water purification, nutrient cycling, biodiversity, and climate regulation).

Land-use change (LUC) from native vegetation (NV) to pasture (PA) or cropland (CL), commonly observed in the MATOPIBA region (Zalles et al., 2019), usually induces changes in soil physical quality, primarily associated with overgrazing and animal trampling in extensive PA, and heavy/non-controlled machinery traffic in CL areas (Defossez and Richard, 2002; Severiano et al., 2013). Overall, soil physical degradation in these areas is associated with the harsh conditions imposed by the increase in bulk density (BD) and soil penetration resistance (SPR); and the decrease in aggregate stability and restrictions in hydraulic parameters as agriculture expansion progresses (Cherubin et al., 2016; Green et al., 2007; Hunke et al., 2015b). These changes may lead to limited conditions for plant development and induce further degradative processes, such as erosion, greenhouse gases emissions (CO_2, N_2O, and CH_4), and loss of nutrients (Cunha et al., 2017; Grecchi et al., 2014; Hunke et al., 2015a), with a consequent reduction on soil capability to support wider ecosystems services.

Under the context above, the adoption of conservationist practices is paramount to maintain soil quality over time. Long-term no-tillage adoption, crop diversification, and grazing control are practices widely linked to positive impacts regarding soil physical attributes and may be promising tools to alleviate the negative impacts induced by LUC in the MATOPIBA. The C accrual induced by the long-term no-till adoption can alleviate compaction risk, improve soil structure and stability and soil water retention capacity (Anghinoni et al., 2019; Blanco-Canqui and Ruis, 2018; Savadogo et al., 2007). However, as most agricultural expansion in this region has occurred in the last decades (last 30 years), information regarding soil physical changes induced by LUC is still scarce. The few studies available so far have observed negative changes in soil BD, soil porosity, and hydraulic parameters, with a consequent increase in soil erosion when the NV (i.e., *Cerrado*) was converted into PA and CL systems in the MATOPIBA region (Dionizio and Costa, 2019; Gomes et al., 2019). Although these results suggest the occurrence of soil physical quality deterioration, they are focused on specific soil attributes and limited to specific soil layers (e.g., 0-5 cm), thus not allowing more conclusive results about the soil physical degradation caused by the agriculture expansion in the MATOPIBA region.

Therefore, we conducted a field study to quantify the impacts that the LUC from NV to CL under no-tillage and extensive PA induces on multiple soil physical attributes (e.g., pore size distribution, water, and air fluxes) and associated indexes (compaction indicators and soil stability indicators). We hypothesized that both CL and PA land-uses induce adverse changes in soil physical attributes compared to NV, but the conversion from NV to CL under long-term no-till can alleviate the LUC impacts on soil physical quality.

3.2. Material and methods

3.2.1. Study site description

The study site description is provided in 2.2.1 item.

3.2.2. Soil sampling and laboratory analyses

Soil sampling was performed in November 2019, when the CL area had been desiccated to soybean sowing at the beginning of the rainy season. The soil was sampled in a regular grid with nine points spaced 50 m apart in each land use (NV, PA, and CL). Disturbed samples were collected using a Dutch auger at four depths: 0-5, 5-10, 10-20, and 20-30 cm, which resulted in a total of 108 samples (4 depths × 9 replicates × 3 land uses). Besides, small trenches (40 × 40 × 40 cm) were opened at three diagonal points of the grid to collect undisturbed samples. Two types of undisturbed soil samples were collected: i) by using Kopeck rings (5 × 5 cm, height × diameter) to determine BD, soil porosity, soil penetration resistance (SPR); and ii) soil blocks (10 × 5 × 10 cm), which were used to determine soil water aggregate stability. Undisturbed samples were collected at the same depths (i.e., 0-5, 5-10, 10-20, and 20-30 cm), in the center of each layer, providing a total of 36 samples each (4 depths × 3 replicates × 3 land uses).

In the laboratory, the disturbed samples were air-dried, sieved (2 mm), and roots and plant debris removed. Subsamples were taken and ground (< 0.15 mm) for total soil organic carbon (SOC) determination using an elemental analyzer (LECO CN-2000, St. Joseph, Mi, USA). Undisturbed soil cores were used for the determination of saturated hydraulic conductivity (K_s) by the constant-head method. Device specifications and procedures are given in Klute (1965), and the K_s was calculated according to Eq. 1:

$$K_s = \frac{Q\ x\ L}{A\ x\ H\ x\ t} \quad (1)$$

where K_s is expressed in cm h^{-1}, Q is the leachate volume (cm^3), L is the height of the soil block (cm), A is the area of the cylinder (cm^2), H is the height of the soil block in addition to the groundwater column (cm), and t is the time (h).

Afterward, the soil cores were re-saturated and subjected to matric potentials of -6 and -10 kPa using a tension table. At equilibrium, the samples were weighed for water content determination, and then the SPR was measured (cores adjusted at -10 kPa) by using a bench-top penetrometer (Brookfield CT3 Texture Analyzer). The penetrometer was set at a rod displacement speed of 1 cm min^{-1}, with a data collection rate of 40 points per second. The cone had a semi-angle of 30°, and a base area of 0.1167 cm^2. The SPR values are an average of readings performed in the middle part of each sample (i.e., 3 cm).

Soil total porosity (TP) was calculated using BD and PD values (Eq. 2), the volumetric water content assessed microporosity (MiP) at the -6 kPa matric potential (Eq. 3), macroporosity (MaP) was calculated by the difference between TP and MiP (Eq. 4), and field capacity (θ_{FC}) was measured by the volumetric water content at the -10 kPa matric potential (Asgarzadeh et al., 2014) (Eq. 5)

$$TP = \frac{PD - BD}{PD} \quad (2)$$

$$MiP = \theta_{-6kPa} \quad (3)$$

$$MaP = TP - MiP \quad (4)$$

$$\theta_{FC} = \theta_{-10kPa} \quad (5)$$

where TP, MaP, and MiP are expressed in m^3 m^{-3}, BD and PD are expressed in Mg m^{-3}, $\theta_{-6\ kPa}$ is the volumetric water content at -6 kPa, and $\theta_{-10\ kPa}$ is the volumetric water content at -10 kPa.

Additionally, using the porosity parameters and the volumetric water content at $\theta_{-10\ kPa}$ (i.e., θ_{FC}), we calculated two indexes: the soil water storage capacity (SWSC) (Eq. 6) and soil aeration capacity (SAC) (Eq. 7) (Reynolds et al., 2002). Plant available water content (PAW) was estimated by the difference between the volumetric water content measured at θ_{FC}, and the water content at permanent wilting point (θ_{PWP}) (Eq.8) (Asgarzadeh et al., 2014). The θ_{PWP} was calculated through the van Genuchten equation (van Genuchten, 1980), in which clay content and BD were used as input variables for estimation of the θ_{PWP} at -1500 kPa matric potential, through pedotransfer functions available in the software RetC (van Genuchten et al., 1991).

$$SWSC = \frac{\theta_{FC}}{TP} \quad (6)$$

$$SAC = 1 - SWSC \quad (7)$$

$$PAW = \theta_{FC} - \theta_{PWP} \quad (8)$$

where SWSC and SAC represent the volume of pores occupied by water and air at θ_{FC}, respectively, ranging from 0 to 1; PAW is expressed in cm^3 cm^{-3}.

Finally, the rings were oven-dried at 105 °C for 48 hours. Bulk density was calculated from the weight of the oven-dried soil and the total volume of the soil rings. We estimated the maximum bulk density (BD_{max}) using clay and organic matter (OM) content (OM content was calculated using the conversion factor of 1.724) by the pedotransfer function described by Marcolin and Klein (2011). Based on BD and BD_{max}, we assessed the degree of compactness (DC), following Eq. 9:

$$DC = \frac{BD}{BD_{max}} x\ 100 \quad (9)$$

where DC is expressed in %, BD and BD_{max} are expressed in Mg m^{-3}.

Soil aggregate stability was determined through the wet method described by Elliot (1986). Briefly, undisturbed soil samples were air-dried and carefully sieved (8 mm). A sub-sample (50 g) from each replicate was taken and saturated by capillarity for 12 h and subjected to the wet-sieving on a vertical oscillator Yoder (Marconi MA148) at 30 rpm for 10 min. Three sieves with openings of 2000, 250, and 53 µm were used and obtained fractions dried at 45 °C until they reached a constant weight. Afterward, the percentage of water-stable aggregates (WSA%) for each fraction and the mean weight diameter of soil aggregates (MWD) were calculated (Eq. 10), following:

$$MWD = \sum_{i=1}^{n} x_i \, w_i \qquad (10)$$

where n is the number of aggregate classes, x_i is the mean diameter of each size class and w_i is the proportion of the total sample weight in the correspondent size fraction.

3.2.3. Statistical analyses

Data normality and homogeneity were assessed by Shapiro-Wilk and O’Neill-Mathews tests ($p > 0.05$), respectively, and when violated, data were transformed using Box-Cox transformation. A one-way ANOVA ($p < 0.05$) was used to test the significance among the treatments for each sampled depth (i.e., 0-5, 5-10, 10-20, and 20-30 cm). When significant, Tukey’s test ($p < 0.05$) was applied to compare the means of the treatments. Additionally, a canonical discriminant analysis was used to examine variable relationships and treatment differences in a multivariate approach. Biplot graphs were used to examine the dispersion of the canonical scores associated with original variables, as well as the impact of these variables on the discrimination of the treatments. All statistical analyses were carried out using R software (R Core Team, 2019), as well as the multivariate biplot graph (*candisc* package). Figures were performed using Origin software (Origin, Version 2019, OriginLab Corporation, Northampton, MA, USA).

3.3. Results

3.3.1. Bulk density, degree of compactness, and soil penetration resistance

Soil compaction indicators were sensitive to LUC (NV to PA and NV to CL) and varied differently, according to the land use and the assessed attribute (Figure 1A-C). Bulk density values (Figure 1A) ranged between 1.11 and 1.50 Mg m^{-3} and were relatively constant within the soil profile. In general, the most significant changes were observed for the 0-5 cm layer, where the BD values increased from 1.11 under NV to 1.30 and 1.49 Mg m^{-3} for CL and PA areas, respectively (PA > CL > NV) ($p < 0.01$). In the 10-20 cm layer, only the conversion to PA increased soil BD (an increase of ~ 25% compared to NV) ($p < 0.05$), while at 5-10 cm and 20-30 cm soil layers, the BD in PA and CL did not differ from each other but were in average 20% higher than the NV use ($p < 0.01$). Considering the whole soil profile (0-30 cm), LUC (PA and CL expansion) induced an average increase of ~ 23% in comparison to the NV (Figure 1A).

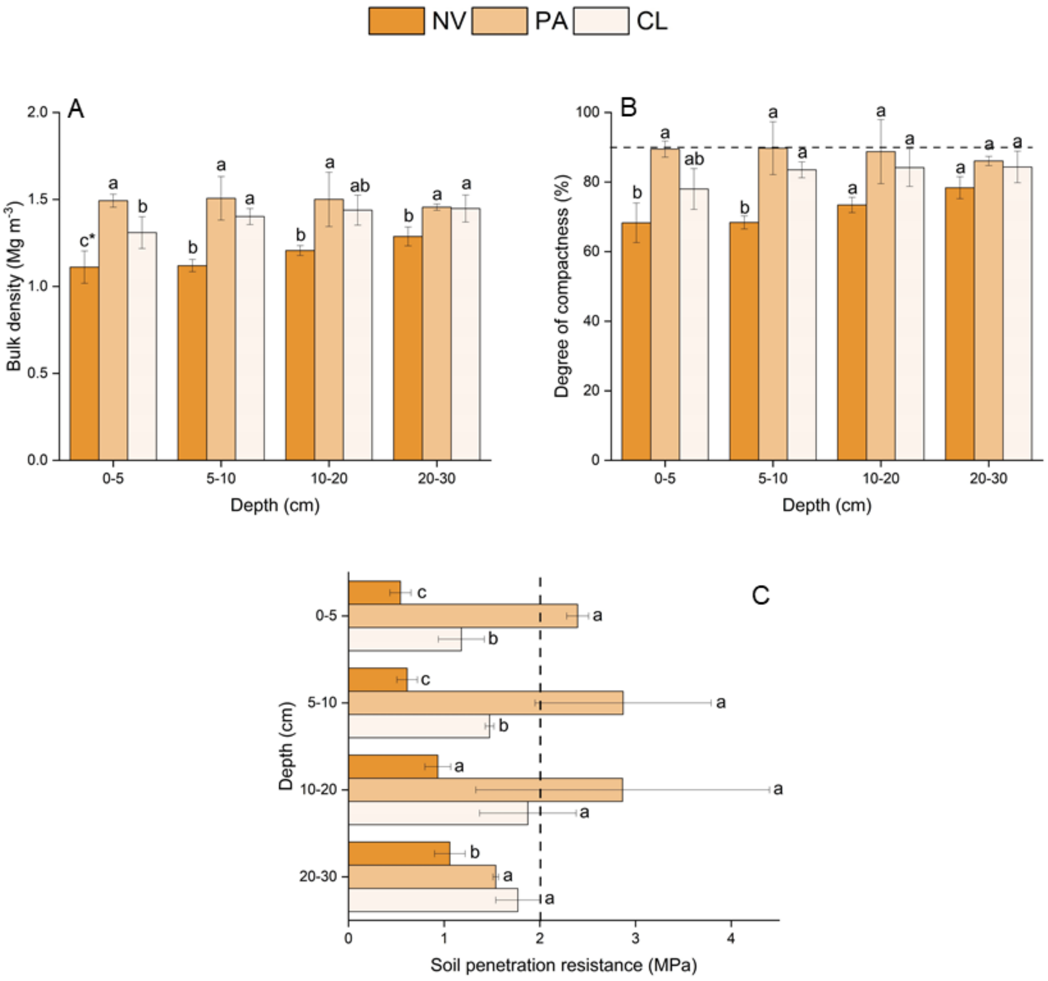

Figure 1. Bulk density (A), soil degree of compactness (B), and soil penetration resistance (C) at 0-5, 5-10, 10-20, and 20-30 cm soil layers under native vegetation (NV), pasture (PA) (NV – PA conversion), and cropland (CL) (NV – CL conversion) in Brazil's new agricultural frontier. Dashed lines indicate limiting values for suitable plant growth for soil degree of compactness (Reichert et al., 2009) and soil penetration resistance (Silva et al., 1994). *Mean values followed by the same letter within the same soil depth do not differ by Tukey's test ($p < 0.05$). Error bars represent the standard deviation of the mean.

The LUC also imposed changes in DC within the soil profile, which were driven by the increase in soil BD (Figure 1B). The conversion from NV to PA and CL induced significant changes in DC values at 0-5 and 5-10 cm layers ($p < 0.05$). At both soil depths, DC values increased from ~ 68% in NV to 89% in PA, and 85% in CL. The DC values ranged from 68 to 78% under NV, 86 to 89% under PA, and 78 to 85% under CL. An overall increase of ~ 19% in DC (0-30 cm layer) was observed after the LUC.

The SPR results followed the same pattern as for BD and DC values, however, SPR appeared to be a more sensitive parameter (Figure 1C). The most significant changes induced by the LUC process were observed in the 0-5 and 5-10 cm layers, where differences were observed among all land uses (PA > CL > NV) ($p < 0.001$). The largest effect was found in the NV-PA conversion, where the SPR values exceeded the threshold value for proper root growth (i.e., > 2 MPa) proposed by Silva et al. (1994) (2.39 and 2.87 MPa, for the 0-5 and 5-10 cm layers, respectively). At the same layers (0-5 and 5-10 cm), the NV-CL conversion induced an average increase of 130% in comparison to NV use, however, the observed values were below the critical threshold. For the deepest layer (20-30 cm), PA and CL SPR values were quite similar and showed an average increase of 56% in comparison to NV ($p < 0.001$).

3.3.2. Pore size distribution and hydraulic parameters

As a consequence of the compaction process induced by LUC, significant changes in pore size distribution were observed in all soil layers (Figure 2A-C). Total porosity values were reduced in all soil depths (Figure 2A), but the biggest changes were found in the 5-10 and 10-20 cm layers, where PA and CL effects on TP occurred to different extents (NV > CL > PA) ($p < 0.001$). In average (5-10 and 10-20 cm layers), NV-PA conversion decreased the TP values by ~ 25% (from 0.56 to 0.41 $m^3\ m^{-3}$), while the NV-CL conversion caused a decrease of ~ 15% (from 0.56 to 0.47 $m^3\ m^{-3}$). Land-use change reduced TP values at 0-5 and 20-30 cm layer at similar levels, roughly 20 and 13% for PA and CL, respectively ($p < 0.001$).

The MaP under PA and CL followed the same pattern as TP, being reduced in the whole soil profile, with major effects in the 5-10 and 10-20 cm layers (Figure 2B). The obtained values ranged between 0.07 and 0.31 $m^3\ m^{-3}$, with most values in CL and PA close and below the critical limit to adequate air diffusion of 0.10 $m^3\ m^{-3}$, respectively (Reynolds et al., 2002). Considering the soil profile (0-30 cm), the LUC from NV to PA and CL promoted an average reduction of 59% on MaP. On the other hand, MiP was increased by the LUC (Figure 2C), and changes were not observed only at 10-20 cm layer ($p > 0.05$). In the upmost layers (0-5 and 5-10 cm), the highest increase in MiP occurred mainly in CL (~ 30% higher in comparison with NV), while in the 20-30 cm layer, the greatest increase was observed in PA (~ 20% higher compared with NV) ($p < 0.001$).

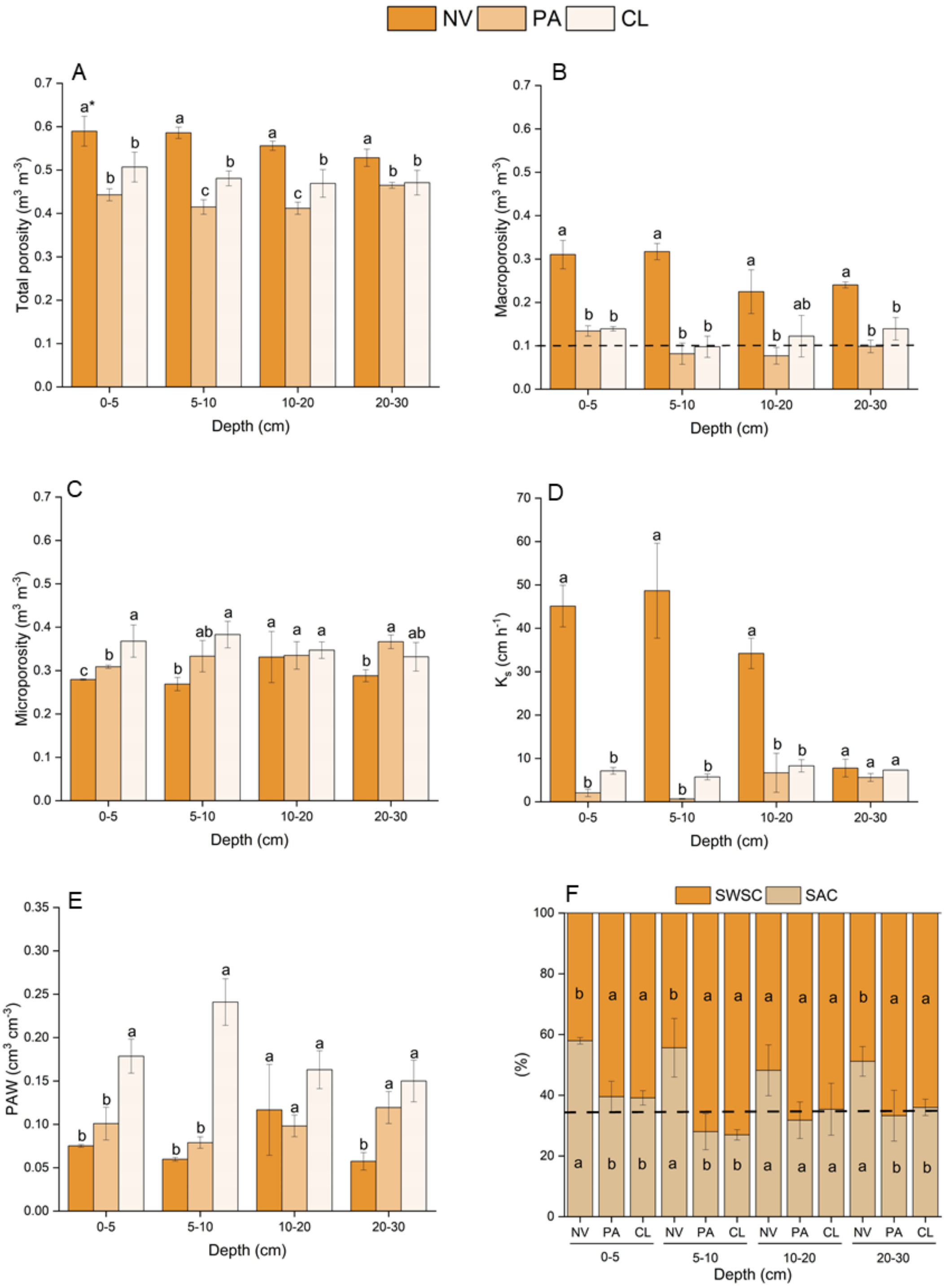

Figure 2. Total porosity (A), macroporosity (B), microporosity (C), saturated hydraulic conductivity (K_S) (D), plant-available water (PAW) (E) and soil water storage capacity (SWSC) and soil aeration capacity (SAC) (F) in 0-5, 5-10, 10-20, and 20-30 cm layers under native vegetation (NV), pasture (PA) (NV – PA conversion), and cropland (CL) (NV – CL conversion) in Brazil's new agricultural frontier. Dashed line indicates the critical limit to air diffusion for microporosity (0.10 m^3 m^{-3}) (B) and the ideal ratio between SWSC and SAC (0.66:0.34) (F) (Reynolds et al., 2002). *Mean values followed by the same letter within the same depth do not differ by Tukey's test (p < 0.05). Error bars represent the standard deviation of the mean.

The changes in pores size distribution induced by the LUC severely affected the K_s (Figure 2D). The measured values ranged between 0.66 and 48 cm h^{-1}, with significant changes ($p < 0.001$) observed in the 0-5, 5-10, and 10-20 cm layers. The lowest values of K_s were observed in the superficial layers (0-5 and 5-10 cm). At 0-5 soil layer, the K_s values in NV (45 cm h^{-1}) decreased to 2 and 7.1 cm h^{-1} in PA in CL uses, respectively. Similarly, the K_s diminished from 48 cm h^{-1} in NV to 0.7 cm h^{-1} in PA and 5.7 cm h^{-1} in CL at 5-10 cm layer. Although significant results were observed by comparing NV to PA and CL, no statistical differences ($p > 0.05$) were observed between PA and CL (Figure 2D).

The PAW estimate was significantly affected by the induced changes in pore size distribution (Figure 2A-C). Overall, the values ranged between 0.05 and 0.24 cm^3 cm^{-3}, with the greatest values associated with CL (Figure 2E). At 0-5 cm layer, the PAW value in the CL system was 52% greater than the average between NV and PA (0.08 cm^3 cm^{-3}) ($p < 0.001$). Similarly, this pattern was also observed in the 5-10 cm layer, with CL having the biggest PAW value (0.24 cm^3 cm^{-3}) ($p < 0.001$). No differences were observed between PA (0.11 cm^3 cm^{-3}) and CL (0.14 cm^3 cm^{-3}) at 20-30 cm soil layer. However, both sites had PAW values ~ 60% higher than those observed in NV (0.05 cm^3 cm^{-3}) ($p < 0.01$).

Finally, the LUC from NV to PA and CL also led to changes in the SAC and SWSC (Figure 2F) ($p < 0.01$). The effects caused by CL and PA were quite similar for all depths, except for the 10-20 cm layer, where the LUC did not induce significant changes ($p > 0.05$). The observed values within the soil profile ranged between 0.27 and 0.56 for SAC, and between 0.44 and 0.73 for SWSC. Overall, NV conversion into CL and PA decreased SAC by ~ 33 and 31%, respectively (average between 0-5, 5-10 and 20-30 cm layers), and the threshold value considered critical for having proper air/water diffusion (i.e., SAC < 0.34 and SWSC > 0.64; Reynolds et al., 2002) was reached in the 5-10 cm layer, for both CL and PA uses.

3.3.3. Soil organic carbon and aggregates stability

Overall, the SOC content decreased with soil depth and the most contrasting effects between land-uses were observed at 0-5 and 5-10 cm layers (Figure 3A). In the former, SOC levels were increased from 21 under NV to 26 g kg^{-1} in CL, while it was reduced to 17 g kg^{-1} (CL > NV > PA) ($p < 0.001$) in PA. In the latter, NV-CL conversion did not affect C levels, but PA decreased it to ~ 16 g kg^{-1} ($p < 0.001$). At the deepest soil layer (20-30 cm), SOC levels in NV (12 g kg^{-1}) were higher than in PA and CL (average of ~ 10 g kg^{-1}).

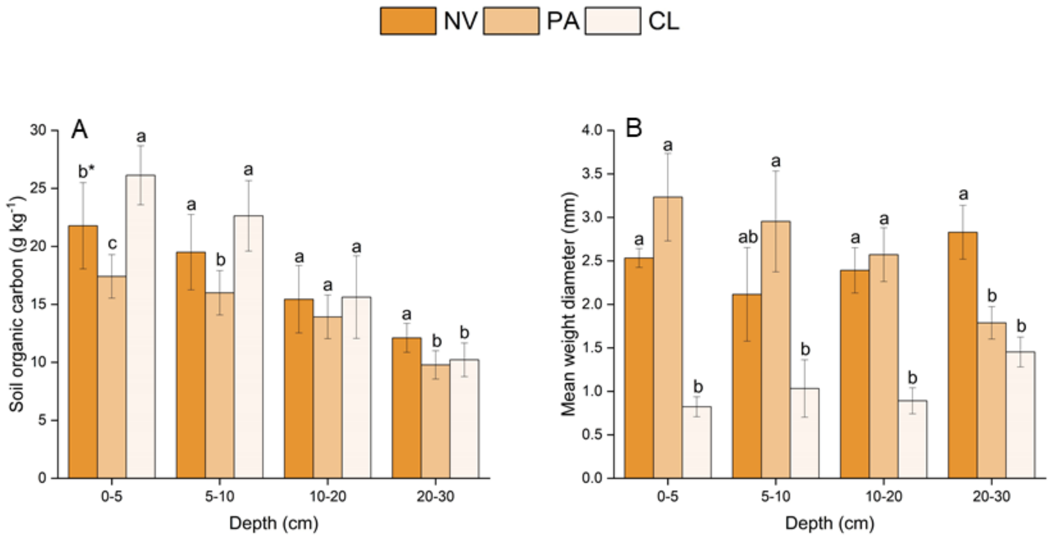

Figure 3. Soil organic carbon (A) and mean weight diameter of soil aggregates (B) at 0-5, 5-10, 10-20, and 20-30 cm layers under native vegetation (NV), pasture (PA) (NV – PA conversion), and cropland (CL) (NV – CL conversion) areas in Brazil's new agricultural frontier. *Mean values followed by the same letter do not differ by Tukey's test ($p < 0.05$). Error bars represent the standard deviation of the mean.

The most pronounced effects caused by LUC over MWD were observed under CL (Figure 3B). The CL system concentrated the greatest proportion of WSA in the smaller fractions (< 0.151 mm), with an average (0-30 cm layer) of 43% compared to 21% on PA, and 19% under NV (Figure 4A-D). This pattern severely affected the MWD under CL (average of 1 mm for the 0-30 cm layer), which represents a decrease of 58 and 60% in comparison to the MWD obtained in NV (2.46 mm) and PA (2.63 mm), respectively. The NV and PA showed similar behavior, except for the 20-30 cm layer, where the MWD under PA was 36% smaller than the NV area ($p < 0.001$). Overall, the distribution of the WSA fractions showed a clear pattern between the assessed depths (Figure 4A-D). Native vegetation and PA concentrated the greatest proportion of the aggregates in the greater fractions (> 1.125 mm), while CL showed an inverse behavior.

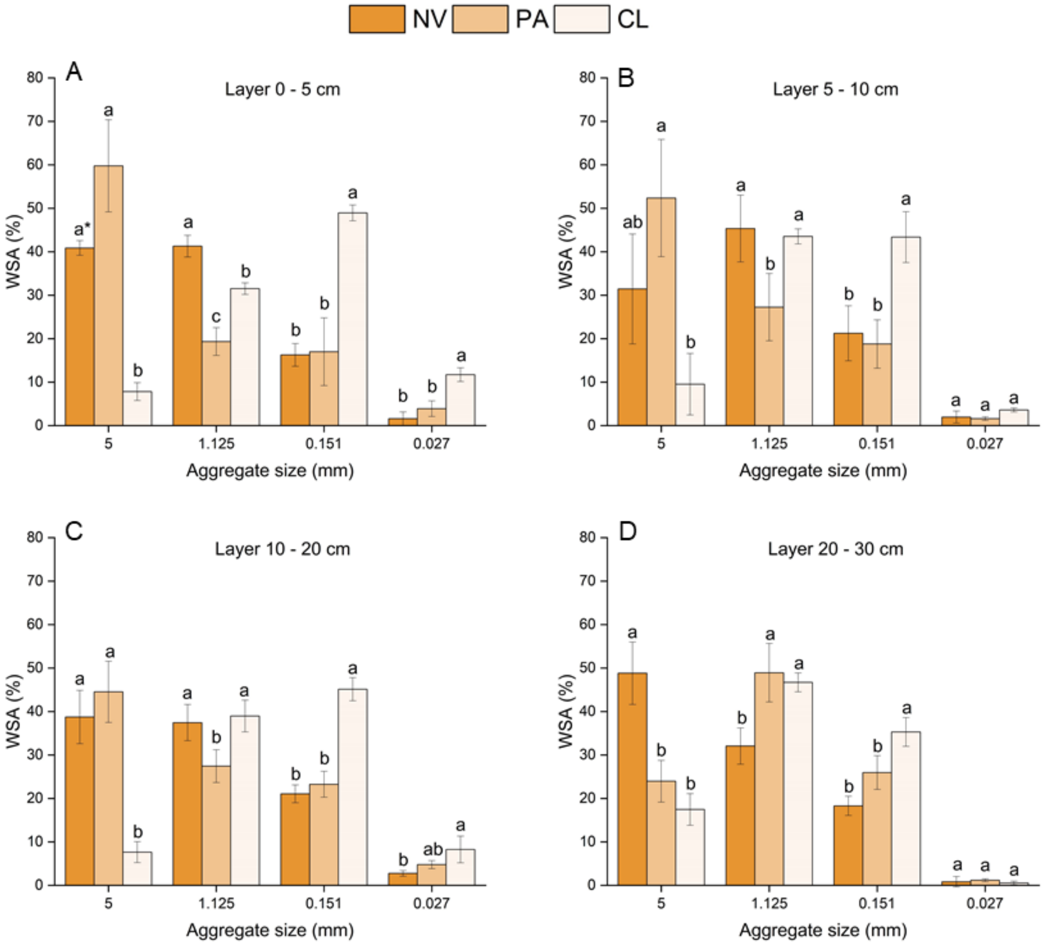

Figure 4. Water-stable aggregates fractions at 0-5 (A), 5-10 (B), 10-20 (C), and 20-30 cm (D) layers under native vegetation (NV), pasture (PA) (NV – PA conversion), and cropland (CL) (NV – CL conversion) areas in Brazil's new agricultural frontier. *Mean values followed by the same letter within the same depth do not differ by Tukey's test ($p < 0.05$). Error bars represent the standard deviation of the mean.

3.3.4. Relationship of soil physical indicators affected by the land use

The dispersion of the scores associated with the original variables represented 100% of the total experimental variability, which relates changes in CAN_1 (76%) and CAN_2 (24%) to treatments (Figure 5). The spheres represent the average of CAN_1 and CAN_2 and the respective 95% confidence intervals for NV, CL, and PA. The absence of overlap among the confidence spheres shows that NV, CL, and PA land uses present significant differences concerning soil physical quality. Soil indicators related to soil structural stability (MWD), large pore space (MaP), and water flow (K_s) were decreased with the transition from NV to PA and CL, whereas compaction (DC), strength (SPR), and water retention (MiP) indicators increased after converting NV to PA and CL (Figure 5). Soil organic carbon was reduced due to PA conversion and slightly increased in CL compared with NV. Overall, compaction and strength were slightly higher in PA, whereas PAW and C were higher in CL than NV.

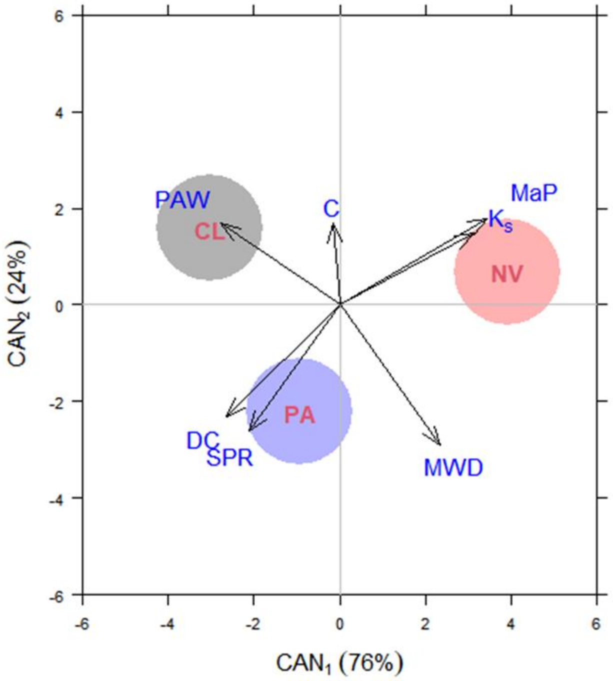

Figure 5. Dispersion of the canonical scores for the 0-30 cm layer under the native vegetation (NV), pasture (PA) (NV – PA conversion), and cropland (CL) (NV – CL conversion) land uses associated with compaction (DC = degree of compactness), strength (SPR = soil penetration resistance), larger pore-space (MaP = macroporosity), water retention (PAW), water flux (K_S = saturated hydraulic conductivity), soil structure stability (MWD = mean weight diameter) and organic carbon (C).

3.4. Discussion

3.4.1. Soil strength and soil compaction

The conversion from NV to agricultural land uses (PA or CL) led to soil compaction, which may compromise the soil's productive capacity and cause serious environmental degradation over time (Figure 1A-C-5). The increase in BD is the first signal of soil physical degradation and may represent an impedance to proper root growth (Jones, 1983; Reichert et al., 2003). Beutler et al. (2007), assessing soil compaction effect on soybean performance in Brazilian Oxisols (textural class similar to the present study) observed a decrease in root growth and grain yield when BD was higher than 1.50 Mg m^{-3}. Therefore, our data suggest that BD can be an important driver of crop yield decline in those areas. This can be further confirmed by the high values observed for DC (Figure 1B). The DC, which is based on the BD_{max} of the soil, presented values close to 90% and was significantly higher under PA and CL than in NV. Some studies have suggested that the best interval for proper root development ranges between 80 and 90% (Beutler et al., 2005; Reichert et al., 2009). However, despite the general adoption of 90% as a superior limit, Lipiec and Håkansson (2000) and Keller and Håkansson (2010) observed that lower DC values (~ 87%) could already cause restrictions on air diffusion and SPR values (Figure 1C-2F). Similarly, Ferreira et al. (2020) reported a decrease in soybean yield when DC values were greater than 85%. These data suggest that the management in both areas (DC values around 89 and 85% for PA and CL, respectively) might be constraining root growth, possibly affecting proper plant development.

The most significant increase in SPR was observed under PA areas (Figure 1C), where high values of DC were also observed. This pattern was also confirmed by the multivariate analysis (0-30 cm) (Figure 5), which showed the highest correlation between the compaction indicators and PA use. The measured values were above the general critical limit (2 MPa) for root development (Asgarzadeh et al., 2014; Lima et al., 2016), possibly being detrimental to pasture growth at some point. Despite the general adoption of 2 MPa as a threshold for SPR, some studies have shown that for soybean, values around 1.6 MPa already could represent some degree of constriction to root development with effects on grain yield (Beutler et al., 2008; Moraes et al., 2020). For instance, Lima et al. (2020) showed that SPR values above 1.6 MPa could reduce by 50% the root elongation rate under cultivated areas. This condition suggests that the CL use (e.g., SPR = 1.80 MPa in the 10-20 cm layer) could also be affecting crop growth since a low root development has a direct effect on water (Nosalewicz and Lipiec, 2014) and nutrients uptake (Schnepf et al., 2012).

The greater increase in the soil compaction indicators under PA compared to CL use might also be related to the higher period of use (19 years under PA vs. 10 years under CL). A more extended period of use may promote a cumulative effect, thus increasing the negative impacts caused by land use. Nevertheless, poor management of the area (e.g., overgrazing) may have contributed to the observed results. In Brazil, extensive pasturelands are careless of fertilization and grazing control (Valle Júnior et al., 2019), and are frequently associated with soil compaction caused by animal trampling (Azarnivand et al., 2010; Drewry et al., 2008). The absence of stocking rate control and grazing intensity associated with low forage productivity leads to overgrazing, which reduces biomass input and leads to C depletion (Carvalho et al., 2010), contributing to soil erosion processes (Tomasella et al., 2018). The C loss was confirmed by the results presented in Figure 3A, and it partially explains the compaction effect observed in PA, since SOM has a fundamental role in soil structure and stability and thus prevents soil compaction (Batey, 2009; Mujdeci et al., 2017).

The compaction process induced by CL systems is mainly related to intense/non-controlled machinery traffic (Hamza and Anderson, 2005; Lima et al., 2019; Reichert et al., 2009), and operations under high soil moisture levels, which increases the soil consolidation process (Reichert et al., 2018). The optimum range of soil moisture to execute mechanical operations is frequently neglected because the appropriate period for sowing crops generally does not fit with the operational capacity of farmers. Furthermore, the lack of crop diversification or the successional use of crops like the ones observed in this study (i.e., soybean - millet) also tends to be a limiting factor, since the restricted radicular systems of these species (i.e., crops specialized in grain production) explore a low volume of soil (Calonego et al., 2017). The examples aforementioned are typical causes related to soil compaction in CL systems and represent the current agricultural scenario in the MATOPIBA region, as confirmed by the results discussed previously.

3.4.2. Changes in pore size distribution and water flux

The increase in soil compaction directly affected pore size distribution and the water/air fluxes (Figure 2A-F-5). The most pronounced effects were observed in soil MaP, where values were close and below the critical limit for air diffusion of 0.10 $m^3 m^{-3}$ (Reynolds et al., 2002) in CL and PA, respectively. The multivariate analysis confirmed this behavior in the 0-30 cm layer, where high MaP values were strictly associated with NV use (Figure 5). The observed results suggest that the decreased MaP fraction after LUC was partially converted into MiP (0-10 cm layer for CL and 20-30 cm layer for PA). However, the reduced TP values indicate that the largest fraction of the pores was extinguished. Indeed, the decrease in MaP led to limiting SAC and SWSC values (0.34:0.66 optimum ratio) (Reynolds et al., 2002), affecting soil aeration. The soil oxygen diffusion is essential for root development, and in the case of soybean, has a special role in symbiotic nitrogen fixation (Siczek and Lipiec, 2011). Furthermore, the anoxic environment can favor the production of toxic substances, such as ethylene (He et al., 1996), and induce other mechanisms like denitrification (produces N_2O) and methanogenesis (produces CH_4) (Tullberg et al., 2018), which can lead to N and C loss, and are important greenhouse gases. Both scenarios might reduce grain yield and forage production.

Besides the reduced air diffusion, the decrease in MaP also had a drastic effect on K_s, which was reduced especially in the surface soil layers (0-20 cm) (Figure 2D). This effect is widely reported in the literature after LUC to PA and CL systems (Batista et al., 2019; Hunke et al., 2015b; Torres et al., 2011). In the MATOPIBA region, in particular, Dionizio and Costa (2019) observed a reduction from ~ 20 cm h^{-1} in *Cerrado* areas to ~ 5 cm h^{-1} under PA and CL use. A decrease in K_s capacity may increase the soil susceptibility to other degradation processes like superficial runoff, leading to soil erosion with consequent C and nutrients losses (i.e., loss of structural stability) (Gomes et al., 2019) and pesticide transport into adjacent lands and water flows (Correia et al., 2020).

Despite the drastic decrease in air/water fluxes, this change in pore size distribution had a positive effect on PAW under CL (Figure 2E), where the measured values were within the “good” interval for water supply and plant growth (0.15 to 0.20 cm^3 cm^{-3}) (Reynolds et al., 2009). The significant increase in MiP induced by soil compaction (i.e., machinery traffic) positively contributed to improving the soil water retention and thus increased the PAW. A similar result was reported by Moraes et al. (2018), who also observed an increase in PAW (~ 35%) due to soil compaction induced by machinery traffic in coarse-textured soils. However, an improvement in PAW values under the circumstances of the present study does not necessarily mean that crops will have a suitable environment to grow since the root development may be mechanically limited by soil compaction, as previously discussed (Figure 1A-C).

3.4.3. Soil structure stability

Soil C concentration was reduced by an average of 17% when NV was converted to PA (0-10 cm layer). This result is in accordance with findings reported by Carvalho et al. (2014), who observed an average loss rate of 0.25 Mg C ha^{-1} yr^{-1} due to the conversion from *Cerrado* to PA. This decrease in C storage may be related to the low biomass input promoted by degraded PA areas, which might be insufficient to keep the original C levels (Silva et al., 2004). On the other hand, an increase of 19% in C content was observed in CL in comparison to NV (0-5 cm layer), probably associated with the high biomass accumulation in the topsoil of no-till systems and the lack of soil disturbance, which reduce the risk of soil exposure and the C oxidation (Diekow et al., 2005; Bayer et al., 2006).

Even though the SOM plays an important role in sustaining soil structure and stability (Piccolo and Mbagwu, 1999; Six et al., 2002), the increase in C content under CL was not effective for keeping soil aggregation as high as those observed in NV and PA. This effect was observed in the whole soil profile (0-30 cm), as indicated by the multivariate analysis (Figure 5). Soil compaction caused by machinery traffic might have contributed to this reduction in soil aggregation. Soil compaction reduces pore size and consequently, the aggregates are pressed together, disintegrating their stable structures (Shah et al., 2017). Besides, the highest proportion of sand (average of 68%) in the mineral fraction (Table 1 – item 2.2.1) associated with the low activity of the clay type [predominantly composed by kaolinite (Figure S1 – item 2)], naturally reduces the soil aggregation capacity (Mamedov et al., 2017). Furthermore, the use of crops that produce easily decomposable residues (e.g., soybean) (Zhang et al., 2008), and the presence of mechanical operations (e.g., sowing, fertilization) can reduce soil coverage and induce soil disturbances to some extent, thus contributing to soil erosion processes (Theisen and Bastiaans, 2015). Under these conditions, the soil is more likely to disperse during high-intensity rainstorm events, for example, which decreases soil structure and stability (Shi et al., 2017).

Contrarily to CL, PA had MWD values as high as in the NV. This result is expected since the PA area was kept without mechanical operations (e.g., sowing and fertilization). Also, the continuous presence of growing shoot and root biomass has a significant contribution to soil aggregation (Demenois et al., 2018). Even though a low amount of biomass is produced in these degraded areas (Silva et al., 2004), the soil surface is minimally kept protected from raindrops and the surface runoff, thus reducing its exposure and consequently the loss of structural stability. Furthermore, the higher abundance of macrofauna groups, particularly those named “ecosystem engineers” in pastures may also have a relevant role in soil structure stability in pasturelands (Franco et al., 2020). These results are in agreement with Sarto et al. (2020), which also observed higher aggregate stability in PA than in CL use in the *Cerrado* biome.

3.4.4. Best management practice to enhance soil physical quality in MATOPIBA

Our findings suggest that the agricultural expansion in the MATOPIBA region greatly impacted soil physical quality. In this sense, the adoption of management techniques that can offset/alleviate these effects (i.e., physical degradation) is mandatory to restore the soil functionality and to avoid further environmental and economic problems. The adoption of rotational systems or even the diversification with cover crops during the off-season can have positive effects. The use of species from the *Urochloa* genus, for example, has shown great benefits on soil compaction alleviation, air and water fluxes, and positive impacts in the root development and grain yield from the crops (e.g., soybean) cultivated in the systems (Anghinoni et al., 2019; Bertollo et al., 2021; Favilla et al., 2020; Moura et al., 2021). Furthermore, crop diversification can increase SOM input qualitatively and quantitatively, thus contributing to improving soil C stocks, soil structure, stability, and microbial activity (Lange et al., 2015; Mujdeci et al., 2017), which are desirable characteristics for keeping a healthy and functional productive environment.

Moreover, monitoring soil moisture for mechanical operations and controlled traffic are low-cost and feasible options for CL areas, especially in the MATOPIBA region, where emergent agriculture is in general highly technified. Controlled traffic can contribute to restoring soil physical attributes (McHugh et al., 2009), improve grain yield (Kingwell and Fuchsbichler, 2011), and also reduce greenhouse gas emissions (Tullberg et al., 2018). Furthermore, recent research has pointed to the use of occasional tillage (e.g., mechanical operations with 4 – 10 years of interval) in highly compacted no-till systems as a potential tool for soil compaction alleviation (Blanco-Canqui and Wortmann, 2020; Peixoto et al., 2020). Occasional tillage does not necessarily stand as a permanent solution for these areas, once it may bring negative consequences regarding soil erosion and C storage (Melland et al., 2017). However, it may be a way to reset the system and establish a new rotational/diverse system with efficiency. Similarly, this practice could be applied to restore the quality of the PA areas, which could also be substantially improved by adjusting the animal stocking rate, grazing control (e.g., rotational grazing), and improving soil fertility (Sone et al., 2020; Vasques et al., 2019). Finally, the adoption of more complex productive models such as integrated crop-livestock systems is also a promising option to recover and improve the soil quality of these areas. Integrated crop-livestock systems have been showing encouraging results regarding food production (e.g., production stability) and soil quality (e.g., C storage) (Lemaire et al., 2014), which are mandatory aspects to keep the ecosystem’s functionality and our subsistence.

3.5. Conclusions

Our study provided a quantitative measurement of the agricultural expansion effects on multiple soil physical attributes in the MATOPIBA region, the new Brazilian agricultural frontier. The results confirmed our hypothesis that both CL and PA led to soil physical degradation compared to NV, but no-till adoption in CL use can alleviate LUC impacts. The LUC from NV to CL or PA increased soil compaction, decreased soil porosity, aeration capacity, and soil hydraulic conductivity, but values above the general critical limits for proper plant growth were mainly associated with PA use. The conversion from NV to CL under no-till improved the C content in the superficial soil layer, while C levels were reduced in PA, regardless of the soil layer. Despite the observed increase in C content under CL, soil aggregate stability was significantly smaller in CL than NV and PA. The only physical property positively affected by the LUC was PAW, which increased in CL. Overall, our results revealed that the recent agricultural expansion in the MATOPIBA region negatively affected the soil's physical indicators compared to the NV areas, and possibly decreased the soil capacity to provide its ecosystem functions, especially in PA areas. The adoption of conservationist management practices such as no-till could soften the LUC effects on soil physical properties in CL areas. However, we highlight the necessity for improving soil management techniques in these areas (e.g., crop diversification and rotational grazing), to recover soil physical quality in areas under current use and avoid further degradation in future LUC scenarios.

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4. FINAL CONSIDERATIONS

The growing demand for primary resources (e.g., food, fiber and energy) induced important changes in the global patterns of agricultural activity, triggering a process marked by land-use intensification and expansion. In Brazil, this has been recently observed in the MATOPIBA region (acronym formed by the states of Maranhão, Tocantins, Piauí and Bahia - Brazilian northeastern), considered the new Brazilian agricultural frontier. However, due to the specific characteristics (e.g., soil and climate) found in the region, concerns were raised regarding the effects associated with the native vegetation (NV) removal and the expansion of cropland (CL) and pasture (PA) areas on soil properties. In this study, we hypothesized that agricultural expansion (i.e., conversion from NV to CL and PA) harmed soil properties and led to soil degradation. To test this hypothesis, we conduct a field-study experiment in a representative site from the MATOPIBA region, where we assessed the overall impacts of land-use change (LUC) in soil organic matter (SOM) dynamics and the main soil physical indicators.

Our findings suggested that LUC in the MATOPIBA region caused significant changes in soil properties and varied according to the land use. In chapter 2, we observed that extensively managed PA negatively affected SOM dynamics. The lack of best management practices such as proper soil N fertilization and grazing control led to C and N depletion. Carbon losses were observed in both mineral-associated organic matter (MAOM) and particulate organic matter (POM) fractions, which led to the lowest carbon management indexes (CMI) values. Contrary, the LUC from NV to CL under no-tillage did not affect total C and N stocks. A slight decrease in the MAOM fraction was observed compared to NV, but the C accrual in the POM fraction offset these losses. The increase in the POM under CL led to the highest CMI (0-30 cm layer), indicating that the CL under no-tillage had positive effects on overall SOM quality. In chapter 3, we found that the LUC (independently of the use - CL or PA) negatively affected soil physical indicators compared to NV. Land-use change associated with animal trampling and C depletion in PA use and the constant machinery traffic in CL increased the soil compaction indicators, which affected pore size and distribution, and consequently reduced air and water diffusion in the soil. Besides, CL expansion had significant effects on soil structure and stability, increasing soil susceptibility to erosive processes. Despite the overall depletion of physical indicators under CL and PA use (compared to NV), critical values for proper plant growth were reached especially in PA use, indicating that plant growth is probably being constrained.

Overall, our results indicated the urgent need to adopt best management practices in the region, especially in PA land-use, that showed the most significant harmful effects in the assessed soil indicators. The adoption of conservationist practices such as proper soil fertilization associated with grazing control strategies (e.g., stocking rate control, rotational grazing) could mitigate the negative impacts observed. At CL use, although the no-tillage adoption appeared to be an effective practice regarding SOM dynamics, soil physical indicators were affected (compared to NV) and they reached values close to the critical levels for proper plant growth. Thus, adopting practices such as crop diversification and controlled traffic are feasible alternatives that may be used in the region to avoid further soil degradation. The improved management in these areas could contribute to restoring soil health, decreasing the risk of environmental degradation, and thus improving soil capability to provide wider ecosystem services in the MATOPIBA region.