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

Soil organic matter dynamics and physical quality changes associated with the agricultural expansion in the Matopiba region, Brazil

Rafael Silva Santos

Thesis presented to obtain the degree of Doctor in Science.
Area: Soil and Plant Nutrition

Piracicaba
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versão revisada de acordo com a Resolução CoPGr 6018 de 2011

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"O correr da vida embrulha tudo,
a vida é assim: esquenta e esfria,
aperta e daí afrouxa, sossega e depois desinquieta.
O que ela quer da gente é coragem.
O que Deus quer é ver a gente aprendendo a ser capaz
de ficar alegre a mais, no meio da alegria,
e inda mais alegre ainda no meio da tristeza!"

"A vida inventa!
A gente principia as coisas,
no não saber por que,
e desde aí perde o poder de continuação
porque a vida é mutirão de todos,
por todos remexida e temperada"

João Guimarães Rosa - Grande Sertão: Veredas

CONTENTS

RESUMO

Dinâmica da matéria orgânica e mudanças na qualidade física do solo associadas à expansão agrícola na região do Matopiba, Brasil

A mudaça no uso da terra (MUT) e o manejo inadequado do solo tem influência direta sobre a qualidade do solo, podendo comprometer a capacidade do solo de promover os serviços ecossistêmicos, incluindo a produção de alimentos e a regulação do clima, em função da magnitude que os atributos do solo são modificados. Na região do Matopiba, nordeste do Brasil, grandes áreas de vegetação nativa do Cerrado tem sido convertidas em áreas agrícolas (ex.: produção de soja e algodão) nos últimos anos. No entanto, pouco se sabe sobre os impactos que essa MUT pode ocasionar a longo prazo nas propriedades físicas do solo e funções a elas relacionadas bem como na dinâmica da matéria orgânica do solo (MOS). Dessa forma, conduziu-se um estudo em três áreas de uso agrícola consolidado (~23 anos) distribuídas ao longo de um transecto de 1000 km dentro da região do Matopiba, considerada a nova fronteira agrícola do Brasil, para avaliar os efeitos da conversão da vegetação nativa (VN) para áreas agrícolas sob plantio direto (PD) sobre a qualidade física do solo e a dinâmica da MOS. Especificamente, i) foi realizado uma avaliação quantitativa dos impactos que a conversão do Cerrado para a agricultura impôs à qualidade física do solo; ii) foi realizado uma avaliação quantitativa e qualitativa da dinâmica da matéria orgânica extraível em água (MOEA); e iii) o modelo DayCent foi utilizado para prever como o manejo atual adotado na região do Matopiba pode afetar os estoques de C do solo ao longo de um período de 50 anos com base no clima atual e em cenários de mudança climática projetados bem como avaliar como a intensificação desse sistema agrícola (ex.: integração lavoura-pecuária - ILP) pode contribuir para aumentar o sequestro de C do solo. A conversão da VN para agricultura sob PD aumentou o processo de compactação e reduziu a porosidade total do solo, desequilibrando a proporção entre o armazenamento de água e ar do solo a níveis considerados críticos. O índice de qualidade física do solo (IQFS) foi reduzido em ~33% no PD, indicando efeitos prejudiciais da expansão da agricultura na funcionalidade do solo. Além disso, a disponibilidade de água e a difusão do ar foram as funções do solo mais afetadas pela MUT de acordo com o IQFS. Ainda, foi observado que embora o C orgânico do solo tenha diminuído ao longo do perfil do solo após a conversão da VN (4,2-20,7 g kg^{-1}) para o PD (3,8-14,2 g kg^{-1}), os níveis de C orgânico extraível em água (3,6-79,3 mg L^{-1}) foram semelhantes entre os usos da terra. O MOEA apresentou menor aromaticidade e peso molecular no PD do que na VN; e uma maior decomposição de compostos alifáticos e polissacarídeos em relação a compostos aromáticos e amina/amida foi observada após a MUT. O modelo DayCent indicou que a intensificação agrícola por meio da conversão da rotação soja-algodão em sistemas integrados lavoura-pecuária (ILP) pode aumentar os estoques de C orgânico do solo em relação a VN (36,6 Mg ha^{-1}), independentemente dos sistemas utilizados. A mudança climática teve pouco efeito sobre os estoques de C nos sistemas ILP simulados, cuja tendência foi a mesma observado para o clima atual. Por fim, nossos resultados indicam a necessidade de melhorar as práticas de PD atualmente utilizadas na região do Matopiba com o objetivo de aliviar a compactação do solo e melhorar a estrutura do solo, bem como a importância de adaptar os sistemas de ILP às condições da região do Matopiba como estratégia para aumentar o C do solo. Estas ações em conjunto são fundamentais para aliviar a pressão antropogênica sobre o ambiente e restaurar a funcionalidade do solo, garantindo uma produção de alimentos sustentável e a geração de serviços ecossistêmicos.

Palavras-chave: Matéria orgânica do solo; Qualidade física do solo; Matéria orgânica dissolvida; Daycent; Cerrado

ABSTRACT

Soil organic matter dynamics and physical quality changes associated with the agricultural expansion in the Matopiba region, Brazil

Land use change (LUC) and soil mismanagement have significant effects on soil quality, which may compromise soil's capacity to promote ecosystem services, including food production and climate regulation, depending on the extent to which soil attributes are modified. In the so-called Matopiba region in northeastern Brazil, large areas of the Brazilian savannah (Cerrado biome) were converted to agricultural areas (e.g., soybean and cotton production) in recent years. However, little is known about the long-term impacts of this land-use change on soil physical properties and related soil functions as well as soil organic matter (SOM) dynamics. For this purpose, we carried out a field experiment in three consolidated agricultural areas (~23 years old) across a 1000-km transect within the Matopiba region, Brazil's new agricultural frontier, to assess the extent to which the land-use change from native vegetation (NV) to agricultural areas under no-tillage (NT) has impacted soil physical quality and SOM dynamics. Specifically, we i) quantitatively assessed the impacts that the conversion from the Cerrado to agriculture has imposed on soil physical quality; ii) quantitatively and qualitatively assessed water extractable organic matter (WEOM) dynamics; and iii) used the DayCent model to predict how the current management adopted in the Matopiba region can affect soil C stocks over a 50-yr period based on the current climate and projected climate change scenarios, as well as how the intensification of this agricultural system (e.g., integrated crop-livestock - ICL) can contribute to increasing soil C sequestration. We observed that the conversion from NV to agriculture under NT increased the compaction process and reduced total soil porosity, unbalancing the proportion between soil water and air storage to critical levels. The soil physical quality index (SPQI) was reduced by ~33% in NT, indicating detrimental effects of agriculture expansion on soil functionality. Also, water availability and air diffusion were the soil functions most affected by LUC according to the SPQI. In addition, we observed that although soil organic C decreased along the soil profile after NV (4.2-20.7 g kg^{-1}) conversion to NT (3.8-14.2 g kg^{-1}), water-extractable organic C levels (3.6–79.3 mg L^{-1}) were similar between land uses. WEOM had lower aromaticity and molecular weight in NT than NV; and a higher decomposition of aliphatic and polysaccharides than aromatic and amine/amide was observed after LUC. The DayCent model indicates that the agricultural intensification through the conversion of the soybean-cotton rotation to integrated crop-livestock (ICL) systems increased soil organic C stocks compared to the NV (36.6 Mg ha^{-1}), irrespective of the systems used. Climate change had little effect on C stocks under the simulated ICL systems, which trend was the same as the current climate. Finally, our findings indicate the need to improve the NT practices currently used in the Matopiba region towards alleviating soil compaction and improving soil structure as well as the importance of tailoring ICL systems to the Matopiba region as a strategy to increase soil C. These concerted actions are paramount to alleviate the anthropogenic pressure on the environment and to restore soil functionality, ensuring sustainable food production and provision of ecosystem services.

Keywords: Soil organic matter; Soil physical quality; Dissolved organic matter; Daycent; Cerrado

1. GENERAL INTRODUCTION

Brazil is considered one the largest food producer in the world, having a major role in supplying the future global food demand due to its potential to expand agricultural areas and productivity of crops (Alexandratos and Bruinsma, 2012; OECD-FAO, 2015; Tollefson, 2010). Most of the agricultural expansion in Brazil over the last decades has occurred in the Cerrado biome, particularly in the Matopiba region. This region occupies an area of ~73 million hectares that extends over part of the states of Maranhão, Tocantins, Piauí, and Bahia (collectively Matopiba), being considered the new agricultural frontier of Brazil due to its edaphoclimatic conditions favorable to intensive agricultural production and possibility of expanding agricultural areas (Gibbs et al., 2015; Zalles et al., 2019).

The Matopiba region has experienced a vertiginous agricultural expansion characterized by rapid changes in the land use with large areas of the native vegetation (i.e., Cerrado) directly converted to intensive and mechanized large-scale agricultural systems (Gibbs et al., 2015), mostly driven by soybean cultivation. Between 2005 and 2014, for example, the area devoted to grain cultivation increased three times more than the national average (~29%) (Lahsen et al., 2016); and estimates indicate a 30% increase in planted area and 54% in grain production over the next 10 years (MAPA, 2019). Currently, the region is responsible for the production of approximately 24 million tons of grains occupying a planted area of 22 million ha (2017/18 harvest - CONAB, 2019).

This intensive agricultural use (e.g., overuse of machinery) associated with inherent characteristics of the soils from this region [i.e., highly weathered soils, low clay content, carbon (C) level, aggregation, water, and nutrient retention capacity (Donagemma et al., 2016)], have raised questions about the potential physical degradation of these areas in the long term. Additionally, because land-use change (LUC) and soil mismanagement (Sanderman et al., 2017; Smith et al., 2016; Wei et al., 2015) can induce and intensify soil organic matter (SOM) decomposition (Don et al., 2011; Sanderman et al., 2017), the agricultural expansion in the Matopiba region may contribute to increasing soil C loss to the atmosphere. Besides, because the Matopiba region represents the largest undisturbed remnants of the Cerrado vegetation and there are still native areas that can be legally replaced by agriculture (Polizel et al., 2021), the preservation of the native Cerrado in this region plays a key role to avoid increasing C emissions in Brazil, where 66% of the greenhouse gas (GHG) emissions are already attributed to land-use change (SEEG, 2021). Therefore, improving soil management practices and prioritizing the intensification of agricultural systems instead of incorporating native vegetation areas into agriculture as an alternative to increasing food production might be strategic to tackle the ongoing climate change. This is particularly important because soils play a major role in regulating gases exchange with the atmosphere, having a direct impact on global warming due to their capacity to store carbon (C; ~1500 Pg down to 1-m depth) (Bossio et al., 2020; Lal, 2018), mainly as SOM.

Although climate-smart practices (e.g., no-tillage/reduced tillage, crop rotation) have been broadly used as a strategy to alleviate the detrimental impacts of agriculture on soil, some studies have shown that the agricultural expansion in the Matopiba region can increase soil loss (Gomes et al., 2019), decrease saturated hydraulic conductivity and soil water content, thus affecting soil water dynamics (Dionizio and Costa, 2019), and reduce C levels (Campos et al., 2020; Gmach et al., 2018). However, these studies are focused on single aspects that do not provide a comprehensive picture of the agricultural expansion impacts on soil physical functions and C dynamics in the long term. Therefore, we carried out a field-study at three representative sites with one of the most common land-use change (i.e., from Cerrado to agriculture under NT) across a 1000-km transect within the Matopiba region to better understand the extent to which the agricultural expansion in this region has affected soil physical quality and SOM dynamics. Specifically, we aimed to i) quantitatively assess the impacts that the conversion from Cerrado to agriculture has imposed on soil physical properties; ii) quantitatively and qualitatively assess water-extractable organic matter (WEOM) dynamics to 1-m depth through spectroscopic analyses (i.e., UV-Vis and DRIFT) and quantification of different SOM pools (i.e., SOM, WEOM, and microbial biomass); and iii) use the DayCent model to predict how the current management adopted in the Matopiba region can affect soil C stocks over a 50-yr period based on the current climate and projected climate change scenarios, as well as how the intensification of this agricultural system through distinct management practices (e.g., integrated crop-livestock systems, irrigation, scarification/harrowing) can contribute to improving soil C sequestration.

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