University of São Paulo
“Luiz de Queiroz” College of Agriculture

Functioning and quality of soils cultivated with sugarcane under different tillage and soil management systems

Aline Fachin Martíni

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

Piracicaba
2024

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Agronomist

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Advisor:
Prof. Dr. **MIGUEL COOPER**

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Dados Internacionais de Catalogação na Publicação
DIVISÃO DE BIBLIOTECA – DIBD/ESALQ/USP

Martíni, Aline Fachin

Functioning and quality of soils cultivated with sugarcane under different tillage and soil management systems / Aline Fachin Martíni. - - Piracicaba, 2024.

111 p.

Tese (Doutorado) - - USP / Escola Superior de Agricultura "Luiz de Queiroz".

1. Plantio direto 2. Saúde do solo 3. Sistemas conservacionistas 4. Sustentabilidade I. Título

ACKNOWLEGDMENTS

My sincere acknowlegdments to:

- University of São Paulo - "Luiz de Queiroz" College of Agriculture (USP-ESALQ) and to Graduate Program in Soil and Plant Nutrition for providing the opportunity to get my Doctor in Science degree.

- My advisor prof. Dr. Miguel Cooper for accepting me to be part of his research team. I extend my heartfelt appreciation for your unwavering guidance, insightful teachings, understanding, support, and remarkable patience during the entirety of my doctoral journey. Your dedicated mentorship played a pivotal role in fostering my growth and molding me into a more proficient scientist. I am sincerely thankful for your constant availability to address my inquiries and for the empathetic support you provided throughout this challenging expedition.Our scientific and personal conversations have been invaluable to me, and I deeply cherish the wisdom gained from them. I am at a loss for words to adequately express my gratitude for your indispensable assistance and the genuine friendship you've extended. Thank you immensely for everything!

- Dr. Denizart Bolonhezi, researcher at the Sugarcane Center of the Instituto Agronomico of Campinas (IAC) and coordinator of the project on conservation systems and practices in sugarcane, which was the subject of my research, for conducting the experiment and for the scientific partnership. And through Denizart, I would like to extend my gratitude to the entire IAC team who collaborated in making this research possible.

- Louisiana State University - Agricultural Center (LSU-AgCenter), School of Plant, Environmental, and Soil Sciences (SPESS), and Soil Microbiology laboratory for providing infrastructural support during my research internship.

- My supervisor Dr. Lisa Fultz for accepting me as a visiting scholar in your research team. I am very thankful for your hospitality, patience, and valuable mentorship in my research. I would also like thank the Dr. Fultz students, especially Andres Carillo and Hector Mendoza for friendship and for helping a lot throughout my research internship collecting samples and processing it at laboratory

- My professors of the Graduate Program in Soil and Plant Nutrition for your contributions in my academic formation.

- Colleagues of the Cooper Trupe, season 2018-2023 (graduate students, interns, post doctorates), I appreciate all the help, especially during the field work and laboratory analysis.

My sincerelly thanks to Gustavo Valani for your active contribution in all steps of my research. Thanks a lot my friend!

- Dr. Laura F. S. da Silva, Dr. Raquel Stuchi and Dr. Simone Di Prima for the scientific partnership.

- The soil physical and micromorphological laboratory staff (Rossi, Sônia and Chiquinho) for the help in my laboratory analysis.

- The São Paulo Research Foundation – FAPESP, I express gratitude for the doctoral and research internship abroad (BEPE) scholarships awarded under processes #2018/20570-0 and 2021/08625-6. Additionally, I extend my thanks to the Brazilian Federal Agency for the Support and Evaluation of Graduate Education (CAPES) for the scholarship received at the start of my doctorate.

- The friends I met and the friendships I built during my doctorate, especially the members of the "piscininha/titios amor" group, I thank for making the journey lighter and more fun.

- My family for always understanding my career decisions, which reflect on my distance and absence. I love you!

- My love Samuel for introducing me to ESALQ and encouraging me to dream big. I appreciate all the help with my research and academic journey, whether collecting and analyzing samples, creating statistical scripts, making figures, or reviewing my writing. I also really appreciate for the partnership, support, friendship, patience and understanding during this important stage of my/our live, both in Brazil and abroad. I am so grateful to share life with you, and now with our beloved daughter Annelise. You will always be my motivation. I love you!

THANK YOU ALL!

SUMMARY

RESUMO

Funcionamento e qualidade de solos cultivados com cana-de-açúcar sob diferentes sistemas de preparo e manejo do solo

A sustentabilidade de produção do cultivo de cana-de-açúcar tem sido alvo de preocupação nos últimos tempos, sobretudo porquê o sistema de cultivo utilizado pela maioria dos produtores tem causado degradação da qualidade do solo e comprometido a produção agrícola. Logo, a fim de atender a demanda global de biocombustíveis é impressindivel que os sistemas de cultivo utilizados não comprometam a qualidade dos solos e a sustentabilidade econômica e ambiental. A fim de levantar informações sobre o cenário atual, buscou-se investigar como a qualidade do solo tem sido abordada nas pesquisas sobre manejo da cana-de-açúcar, e então identificar lacunas que precisam ser mais exploradas em pesquisas futuras. Uma revisão bibliométrica mostrou a existência de lacunas em estudos envolvendo cana-de-açúcar cultivada sob sistemas conservacionistas, como o plantio direto; que avaliem de forma abrangente a qualidade do solo por meio da integração de indicadores físicos, químicos e biológicos; e que utilizem análises de aspectos físico-hídricos, micromorfológicos e da macrofauna como indicadores da qualidade do solo. Com base nesses achados, objetivou-se avaliar o funcionamento e a qualidade do solo cultivado com cana-de-açúcar sob diferentes sistemas de preparo e manejo do solo (incluindo sistemas conservacionistas), para identificar o sistema que mais contribui para melhorar a sustentabilidade da produção de cana-de-açúcar. Para isso, utilizou-se um ensaio de longo prazo (conduzido desde 1998) em que cana-de-açúcar e soja são cultivadas em sistema rotacional, sob os sistemas de preparo convencional e plantio direto e diferentes doses de calcário, e por meio de análises físicas, físico-hídricas, e análises visuais da estrutura do solo, avaliamos o funcionamento e a qualidade do solo. De modo geral, os resultados obtidos mostraram que o sistema plantio direto em conjunto com a aplicação de calcário (4 Mg ha^{-1}) surge como o sistema mais viável para a conservação do solo e para a sustentabilidade ambiental e econômica do cultivo da cana-de-açúcar.. Esse sistema combina as vantagens da correção da fertilidade do solo por meio da calagem com os benefícios do plantio direto, melhorando os atributos físico-hídricos e a estrutura do solo.

Palavras-chave: Plantio direto, Saúde do solo, Sistemas conservacionistas, Sustentabilidade

ABSTRACT

Functioning and quality of soils cultivated with sugarcane under different tillage and soil management systems

The production sustainability of sugarcane cultivation has been a growing concern, especially because the cultivation system used by the majority of producers has led to soil quality degradation and compromised agricultural production. Therefore, in order to meet the global demand for biofuels, it is essential that the cultivation systems employed do not compromise soil quality and economic as well as environmental sustainability. To gather information about the current scenario, an investigation was conducted into how soil quality has been addressed in research on sugarcane management, aiming to identify gaps that need further exploration in future studies. A bibliometric review revealed gaps in studies involving sugarcane cultivated under conservationist systems, such as no-tillage, that comprehensively assess soil quality through the integration of physical, chemical, and biological indicators. Additionally, there is a need for analyses of hydrophysical, micromorphological, and macrofauna aspects as indicators of soil quality. Building upon these findings, the objective was to evaluate the functioning and quality of soil cultivated with sugarcane under different soil preparation and management systems, including conservationist systems, to identify the system that most contributes to improving the sustainability of sugarcane production. For this purpose, a long-term trial (conducted since 1998) was utilized, where sugarcane and soybeans are cultivated in a rotational system under conventional tillage and no-tillage systems with varying lime doses. Through physical and hydrophysical analyses, as well as visual assessments of soil structure, the functioning and quality of the soil were evaluated. Overall, the results indicated that the no-tillage system in conjunction with lime application (4 Mg ha^{-1}) emerges as the most viable system for soil conservation and the environmental and economic sustainability of sugarcane cultivation. This system combines the advantages of correcting soil fertility through liming with the benefits of no-tillage, enhancing hydrophysical attributes and soil structure.

Keywords: Conservationist systems, No-tillage, Soil health, Sustainability

1. INTRODUCTION

The cultivation of sugarcane (*Saccharum officinarum*) stands out globally due to its versatility in the food and fuel industries (Surendran et al., 2016). In the Brazilian economic context, sugarcane plays a significant role as one of the main commodities in the country's agro-industrial sector. Currently, Brazil leads as the top producer of sugarcane, covering an area of approximately 10 million hectares, resulting in a production of 654 million tons (Conab, 2021). Additionally, the country holds the position of the second-largest global producer of bioethanol, contributing 29.7 billion liters of ethanol derived from sugarcane (Conab, 2021).

In recent years, the growing global demand for this biofuel has led countries, including Brazil, to expand the areas dedicated to sugarcane cultivation (Cherubin et al., 2021). Over a decade, there has been an observed increase of about 50% in the cultivation area in the country (Cherubin et al., 2021; Conab, 2021; Luz et al., 2020), with projections indicating a further expansion trend (de Andrade Junior et al., 2019; Luz et al., 2020). However, this increase in cultivation area, combined with the soil and crop management practices widely used by most sugarcane producers, raises concerns about soil quality degradation and its negative implications for ecosystem functions (Cherubin et al., 2016) and prompts questions about environmental sustainability (Baquero et al., 2012; Cavalcanti et al., 2020; Cherubin et al., 2017a, 2021; Oliveira et al., 2019).

As a semi-perennial crop involving successive cuts throughout its cycle, sugarcane cultivation requires careful soil management. The conventional system, widely adopted by sugarcane producers in Brazil, employs practices such as plowing, harrowing, and subsoiling to prepare and reform the sugarcane fields, aiming to mitigate compaction, incorporate lime and fertilizers, control pests, and level the soil (Barbosa, 2013). However, while these operations seek to create temporary favorable conditions for plant growth, recent studies indicate adverse effects on soil quality in the long term, whether physical (Canisares et al., 2019; Cherubin et al., 2017b, 2016; Franco et al., 2017), chemical (Cury et al., 2014; Marasca et al., 2016; Umrit et al., 2014), or biological (Evangelista et al., 2013; Franco et al., 2017; Stirling et al., 2010). Among the main adverse effects are low carbon accumulation in the soil, low porosity, soil compaction, reduction in biomass and microbial community, increased soil erosion, and greenhouse gas emissions (Crittenden et al., 2015; La Scala et al., 2006; Miura et al., 2013; Prove et al., 1995; Segnini et al., 2013; Silvia et al., 2014; Sousa et al., 2012; Surendran et al., 2016; Tenelli et al., 2019).

Soil quality is understood as the soil's capacity to perform its functions in nature, whether in a natural or managed ecosystem, to support plant and animal productivity, maintain or improve air and water quality, and promote the health of plants, animals, and humans (Doran, 1997). It cannot be directly measured but can be estimated by attributes or conditions of the soil that may interfere with plant development (Reichert et al., 2003), indicators obtained through physical, hydrophysical, chemical, biological, micromorphological analyses, and/or visual analyses of soil structure (Cavalcanti et al., 2020; Franco et al., 2016; Rodrigues et al., 2021).

Knowledge of the quality of a particular soil contributes to decision-making regarding the management of agricultural systems based on sustainability principles (Doran and Zeiss, 2000). Therefore, soil quality is closely related to agricultural sustainability, as it is considered an auxiliary tool in decision-making regarding soil management practices.

Soil preparation and management systems considered suitable for soil functioning and quality should maintain favorable physical conditions for plant development, controlled soil acidity, and sufficient nutrients to meet crop requirements, especially in the surface soil layers (Aratani, 2008). According to Vezzani and Mielniczuk (2009), agricultural systems that do not disturb the soil have better quality because soil structure is maintained, favoring the retention of chemical elements and organic matter in the soil.

In this context, the no-tillage system emerges as a highly effective alternative to alleviate soil quality degradation (Barbosa et al., 2019; Blanco-Canqui e Ruis, 2018; Pires et al., 2017). This is because it emphasizes minimal soil disturbance (limited to the seeding area) and maintains at least 30% of the soil surface covered (Denardin et al., 2012). Moreover, this method promotes enhanced nutrient cycling, efficient carbon sequestration, increased biological activity, reduced water losses in the soil, and by protecting the soil from erosion, no-till significantly contributes to increasing system productivity in the medium and long term (Crittenden et al., 2015; Miura et al., 2013; Pittelkow et al., 2015; Prove et al., 1995; Segnini et al., 2013; Silvia et al., 2014; Sousa et al., 2012; Surendran et al., 2016; Tenelli et al., 2019). However, this cultivation system is rarely used in sugarcane cultivation. Many argue that this system compromises pest control, including insects and weeds, correction of soil acidity in depth and soil compaction (Barbosa et al., 2019; Barbosa, 2013; Cherubin et al., 2021). Nevertheless, little is known about the functioning and quality of the soil in sugarcane fields, especially when cultivated under conservationist systems and practices. Therefore, there is a significant demand for studies addressing this topic and generating information in real agricultural environments for better soil management planning and improvement of soil quality.

Taken all into consideration, this study aimed to: i) investigate how soil quality has been addressed in research on sugarcane management to identify gaps that need investigation in subsequent studies; ii) evaluate the functioning and quality of soil cultivated with sugarcane under different soil preparation and management systems to identify the system that contributes most to improving the sustainability of sugarcane production.

Given the previous context, this thesis consists of five chapters. Briefly, the first one provides a short introduction to the researched topic. The second chapter presents a bibliometric review of the scientific literature on soil quality in sugarcane crops in which the evolution, emerging trends, and gaps on the topic, as well as institutions, authors, research areas, most-cited articles, and co-authorship networks, information useful for directing future studies on sugarcane cultivation and sustainability. The third chapter evaluates the effect of liming and soil preparation systems on the soil hydrophysical attributes (saturated soil hydraulic conductivity, soil bulk density, soil total porosity, macroporosity, microporosity, and soil resistance to penetration) of a long-term cultivated sugarcane field in the tropical region of Southeast Brazil. This study brings information about the hydrophysical functioning of the soil in sustainable preparation systems, such as no-tillage. The fourth chapter assesses the physical quality of soils cultivated under different long-term tillage and management systems to identify the system that most contributes to sustainable sugarcane production. In this investigation, visual analyses of soil structure and indicators directly and indirectly related to soil structure were used to identify the effects of no-tillage and conventional tillage, with or without lime application, on soil structural quality in sugarcane fields. For this chapter and the previous one (chapters 3 and 4), we started from the hypothesis that no-tillage, especially when used in association with lime application, is the system that least impacts the sustainability of sugarcane production by promoting soil conservation through minimal soil disturbance, maintaining soil cover, and providing ecosystem services. This would be beneficial for enhancing soil physical quality compared to conventional cultivation systems. Finally, the fifth chapter presents a summary of the main results of this study, providing key conclusions and recommendations for future research.

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2. IS SOIL QUALITY A CONCERN IN SUGARCANE CULTIVATION? A BIBLIOMETRIC REVIEW

2.1. Introduction

Sugarcane (*Saccharum officinarum*) is a crop of global importance as it is used for sugar and biofuel (ethanol and alcohol) production (Surendran et al., 2016). During 2018, the world's harvested area of sugarcane was 26,269,819 ha and the world sugarcane production was 1,907,024,730 Mg (FAO, 2020). From this total, 93% was grown in the Americas and Asia (FAO, 2020). In the Americas, Brazil is the largest sugarcane producing country. For Brazil, sugarcane is important for the country's economy, as it is the second commodity of the agribusiness sector, covering an area of 10,039,100 hectares, which produced 642,717,800 Mg in the agricultural year of 2019/2020. Most of the sugarcane production (90%) is concentrated in the south-central region of Brazil (CONAB, 2020).

As the agro-industrial development and the demand for biofuels have grown globally over the past years, land use was intensified worldwide (Canisares et al., 2019; Niswati et al., 2018; Surendran et al., 2016; Umrit et al., 2014). Such intensification raised questions about environmental sustainability (Carvalho et al., 2016), as well as concerns about soil quality degradation and its negative implications on ecosystem services (Cherubin et al., 2016c). In Brazil, for example, a significant increase in the sugarcane area will be necessary (Goldemberg et al., 2014) to attend to national and international biofuel demands, and an increase in soil conservation practices in favor of soil and environmental sustainability (Carvalho et al., 2016) is expected.

Associated with intense land use, most of the areas where sugarcane is currently grown are cultivated under conventional soil management and monoculture systems. Nevertheless, such management has been a matter of concern as it promotes soil quality degradation, including physical (Canisares et al., 2019; Cherubin et al., 2017a, 2016c; Franco et al., 2017), chemical (Cury; De Maria; Bolonhezi et al., 2014; Marasca et al., 2016; Umrit et al., 2014) and biological soil quality degradation (Evangelista et al., 2013; Franco et al., 2017; Stirling et al., 2010).

The concern about environmental sustainability had been the focus of various research initiatives related to sugarcane cultivation; however, little is known about research relating sugarcane to soil quality. In this sense, we believe that the use of bibliometric research techniques is promising to perform an integrated systematic analysis of scientific publications related to sugarcane management and soil quality. This will enable researchers to evaluate the evolution and emerging trends, address gaps, as well as, to identify institutions, research areas, most cited papers and co-authorship networks (Chueke and Amatucci, 2015; Liu et al., 2020) useful for future studies in sugarcane cultivation and sustainability. Bibliometric studies that summarise and discuss the scientific production of a given topic contribute significantly to increase the relevance and rigor of new research (Chueke and Amatucci, 2015) and to support research decisions and project development (Liu et al., 2020; Romanelli et al., 2018; Song and Zhao, 2013; Tao et al., 2015).

This bibliometric study aims to investigate how soil quality has been addressed in sugarcane management research and by whom. We will use this information to identify possible knowledge gaps to be considered in future research.

2.2. Conclusions

1) Concerns about soil quality in sugarcane cultivation have increased in recent years, especially in the last 9 years, when 74% of the total papers were published.

2) Brazil was responsible for 99 out of 160 publications found in this bibliometric search, with 12 institutions and 13 authors responsible for the largest number of publications.

3) From a total of 160 published articles found, 97% were part of the Agriculture research area and 71% were related to Soil Science.

4) The most widely reported category of soil science was soil use and management, followed by soil chemistry and soil physics.

5) There are gaps in the literature regarding studies with sugarcane cultivated under no-tillage systems that assess soil quality by integrating physical, chemical, and biological indicators, including hydrophysical, micromorphological and macrofauna analyses as indicators of soil quality.

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3. LONG-TERM TRIAL OF TILLAGE SYSTEMS FOR SUGARCANE: EFFECT ON TOPSOIL HYDROPHYSICAL ATTRIBUTES

3.1. Introduction

Sugarcane (*Saccharum officinarum*) is an important crop worldwide due to its multipurpose in both food and fuel industries [1]. As a result of a higher demand for its by-products, sugarcane production has increased in recent years, combined with an expansion in the crop area, improvement of soil fertility and the use of agricultural machinery in all its cultivation stages. Although soil use intensification has boosted sugarcane production by means of crop area extension, lime application and mechanized agriculture, it has also led to changes in soil structure, including structural degradation [2–4]. Soil structure and its related soil hydrophysical attributes are of primary importance for plant growth and development, as they influence soil aeration, soil water storage, water retention and drainage [5].

In agricultural fields, soil and crop management is considered one of the main factors controlling soil structure [3], in which the extent of possible changes depend upon the operations performed. As sugarcane is a semi-perennial crop, successive cuts are performed through its cultivation, which demands proper correction of soil fertility, given that the intense nutrients export reduce soil fertility. In this sense, liming is used to correct soil acidity, which neutralizes toxic effects of some elements, including aluminum and manganese, it also supplies calcium and magnesium, it increases the availability of some nutrients, like phosphorus, and it contributes to the improvement of soil structure and microbial activity [6]. However, the amount of lime applied, as well as the way in which lime is applied (in the soil surface only or incorporated into the soil) may degrade soil structure in the long-term [4,7]. Therefore, it is important to study liming and tillage systems in sugarcane fields.

In most sugarcane fields, the soil is tilled to promote favorable physical conditions for plant growth and development. However, depending on soil characteristics (such as particle size distribution, organic matter content and soil moisture), as well as the tilling depth and equipment used, tillage may lead to the breakdown of soil aggregates and loss of soil organic matter, resulting in an undesirable condition for soil structure [8,9]. Furthermore, tillage operations may also influence soil attributes or processes related to soil structure [3], such as soil porosity (macro and microporosity), soil bulk density, soil resistance to penetration, soil water infiltration and soil hydraulic conductivity [10].

Soil tillage is a common practice between sugarcane-producing farmers, and the conventional farming system is widely used. Although it may promote a temporarily favorable physical environment for plant growth, it also increases the number of macropores and decreases soil bulk density, especially in the topsoil, changing soil structure and the related soil hydrophysical attributes [11], including the saturated hydraulic conductivity, which is also temporarily increased in such condition [12]. In contrast, conservational systems as the no-tillage system, which maintains the soil covered and minimally disturbs the soil, are known to restore soil structure through aggregation, as well as to mitigate soil erosion and supply soil organic matter [13,14], improving water storage in the soil. Nevertheless, the effects of no-tillage system on soil hydrophysical attributes, especially in relation to water infiltration and saturated hydraulic conductivity, are still scarce and conflicting [5,15], especially for sugarcane fields [16].

In a review about tillage effects on soil hydraulic properties, Strudley et al. [15] reported inconsistent responses on experimental studies, as comparisons between no-tillage and conventional tillage systems led to intermediate results for soil porosity, bulk density, hydraulic conductivity and soil water infiltration. This is because the hydrophysical attributes of cultivated soils may vary in time and space [15,17], and depend on topography, soil type, climate, crop specie, machinery and implements used, waste management, management period and management history [15]. So, the outcomes of farming systems cannot be standardized from one study site to another [15]. Therefore, studies within such scope should be site-specific and thus they should be carried out in several regions in order to understand each region specifically.

In the tropical region of Brazil, studies about soil hydrophysical attributes in sugarcane fields under no-tillage systems with liming are scarce [16], especially for long-term no-tillage systems. This data scarcity from long-term experiments limits the understanding of the influence of tillage systems and liming on soil structure and soil hydrophysical attributes [10], given that these soil attributes differ from those of short-term experiments due to the effect of the management system persistence on a longer temporal scale [15].

It is important to note that while conventional tillage is the system most used for cultivating sugarcane, it is known to impact the environment and its sustainability, especially due to soil degradation and its negative implications on ecosystem functions [2,16,18]. Considering that sugarcane is usually grown as a source for renewable energy, contributing to environmental sustainability, it is important to cultivate sugarcane in a system that promotes soil conservation instead of soil degradation. Thus, studies about conservation tillage and management systems in sugarcane are of primary importance for a more sustainable production of this crop, especially if the life-cycle assessments of sugarcane biofuel are considered.

Thus, this work aimed to assess the effect of liming and tillage systems on soil hydrophysical attributes of a long-term cultivated sugarcane field in the tropical region of Southeast Brazil. This study is important to provide essential information about sustainable tillage systems, such as no tillage, in sugarcane cultivation.

3.2. Conclusions

The highest values of soil hydraulic conductivity were found in the native forest and in conventional tillage without lime as a consequence of the lowest values of bulk density and the highest values of soil total porosity and macroporosity.

Conventional tillage system with 4 Mg ha^{-1} of lime and no-tillage system with 0 Mg ha^{-1} of lime may need soil amelioration through soil tillage and management practices, especially because of their high bulk density values, which are over one of the suggested critical bulk density limits for plant growth and development.

Overall, the no-tillage with 4 Mg ha^{-1} of lime is suggested as the most viable system for conservation agriculture in sugarcane fields because it combines the benefits of correcting soil fertility through liming with the benefits of no-tillage, which improves the hydrophysical attributes and soil structure, promoting soil conservation and the system's sustainability. This system presented intermediate values of saturated hydraulic conductivity, soil density, total porosity, macro and microporosity and resistance of the soil to penetration, which promotes a favorable environment for a better soil hydrophysical functioning.

Future research should study the benefits of conservation tillage in sugarcane in the whole soil profile, and include more detailed analysis to better understand the improvement of soil functioning and its impacts on soil conservation and the sustainability of sugarcane as a source of renewable fuels. To accomplish this, we suggest the description and quantification of pore continuity by 2D and 3D image processing techniques, which are correlated to a variety of soil functions, as well as the assessment of aggregate stability, soil water retention and soil structural quality.

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4. SOIL PHYSICAL QUALITY RESPONSE TO MANAGEMENT SYSTEMS IN A LONG-TERM SUGARCANE TRIAL

4.1. Introduction

Biofuels are considered essential to meet sustainable energy needs (Oliveira et al., 2019). Worldwide, sugarcane (*Saccharum officinarum* L.) is considered one of the main sources of raw material and one of the most sustainable crops used for biofuel production (Bordonal et al., 2018; Conab, 2021; Oliveira et al., 2019), as ethanol produced from sugarcane can reduce greenhouse gas emissions by 85% in relation to those from fossil fuels (Barbosa et al., 2019; Börjesson, 2009).

In order to support the production of raw materials for biofuel productions, many countries have expanded the area where sugarcane is cultivated. In Brazil, this area increased, approximately, 50% in the last 10 years (Cherubin et al., 2021; Conab, 2021; Luz et al., 2020) and projections indicate that it will further increase (de Andrade Junior et al., 2019; Luz et al., 2020). Brazil is currently the largest producer of sugarcane, with an area of around 10 million hectares that produces 654 million megagrams (40% of global production), and the second largest producer of bioethanol, accounting for 29.7 billion liters of ethanol from sugarcane (Conab, 2021).

Although sugarcane is considered one of the most sustainable crops for biofuel production, the expansion of its cultivated area, together with current soil and crop management practices, raised controversial issues regarding its sustainability (Baquero et al., 2012; Cavalcanti et al., 2020; Cherubin et al., 2017b, 2021; Oliveira et al., 2019). This is mainly due to critical changes on soil structural quality, impairing soil physical functions and consequently sugarcane growth, development and productivity (Baquero et al., 2012; Barbosa et al., 2019; Cavalcanti et al., 2020, 2019; Cherubin et al., 2017b, 2016b, 2016c, 2016a).

In Brazil, the conventional cultivation system is widely used by sugarcane producers. This system makes use of soil tillage through plowing, harrowing and subsoiling operations for planting and reforming sugarcane fields, which aim to reduce soil compaction, incorporate lime and fertilizers, control pests and for soil leveling (Barbosa, 2013). However, recent studies show that soil tillage may negatively affect soil physical properties related to soil structure, such as porosity, bulk density, resistance to penetration and aggregate stability (Canisares et al., 2019; Carpenedo and Mielniczuk, 1990; Cavalcanti et al., 2020; Cherubin et al., 2016c; Pires et al., 2017), affecting, thus, related soil processes, as hydraulic conductivity, soil water retention, carbon sequestration, soil erosion (Awe et al., 2020; Cherubin et al., 2016c; Luz et al., 2020; Martíni et al., 2021; Scarpare et al., 2019), and nutrient leaching. Furthermore, tilled soils are more prone to soil recompaction due to machinery traffic (Cherubin et al., 2016c).

No-tillage is an excellent alternative to mitigate the degradation of soil structural quality (Barbosa et al., 2019; Blanco-Canqui and Ruis, 2018; Martíni et al., 2021, 2020; Pires et al., 2017) as it values minimal soil disturbance (only in the sowing row) and maintains at least 30% of the soil surface covered (Denardin et al., 2012). Moreover, it promotes a higher nutrient cycling and carbon sequestration, higher biological activity, reduces soil water losses, protects the soil from erosion, and, consequently, increases the system's medium- and long-term productivity (Crittenden et al., 2015; Miura et al., 2013; Pittelkow et al., 2015; Prove et al., 1995; Segnini et al., 2013; Silvia et al., 2014; Sousa et al., 2012; Surendran et al., 2016; Tenelli et al., 2019).

Despite the well-known benefits from no-tillage, it is rarely used for sugarcane cultivation, and the main obstacles are related to pest management (weeds and insects), subsoil acidity, as well as soil compaction (Barbosa et al., 2019; Barbosa, 2013; Cherubin et al., 2021). As discussed by Martíni et al. (2020) in a bibliometric review, there is a lack of studies about long-term sugarcane cultivation under no-tillage which assess the system's impacts on soil physical quality in order to verify the system's efficiency and thus overcome the current obstacles, mainly the correction of acidity in the subsoil.

As sugarcane is a semi-perennial crop and successive cuts are carried out throughout its cultivation, exporting nutrients, and reducing soil fertility, liming is of primary importance in the cultivation of sugarcane by correcting soil acidity, neutralizing the toxic effect of some elements, providing and increasing the availability of some nutrients and contributing to the improvement of soil structure and microbial activity (Rossetto et al., 2004). However, the way lime is applied (over the soil surface in no-till systems or incorporated into the soil in the conventional systems) may not correct subsurface acidity and may degrade the soil structure in the long term (Albuquerque et al., 2003; Nunes et al., 2017). Therefore, it is essential to study liming systems linked to soil tillage and management systems in sugarcane fields in order to promote soil physical quality.

Soil physical quality may be assessed by means of soil properties or soil processes, known as soil quality indicators (Rodrigues et al., 2021), which might directly or indirectly relate to soil structure. These indicators include soil bulk density, soil porosity, soil resistance to penetration, aggregate stability, soil water retention curve and the S-index (which are all indirectly related to soil structure), as well as visual evaluations of soil structure, including VESS (Visual Evaluation of Soil Structure) or DRES (Rapid Diagnosis of Soil Structure) (directly related to soil structure) (Cavalcanti et al., 2020; Franco et al., 2016), among others.

In order to meet the global demand for biofuels, as well as to support national public policies and international agreements in favor of reducing greenhouse gas emissions by using biofuels (Brasil, 2017, 2015), the areas of sugarcane production will probably increase substantially in the upcoming years. Such expansion should not bring negative impacts to economic and environmental sustainability; thus, conservation strategies must be used to enable soil management practices without impairing physical soil quality. Therefore, quantifying and monitoring agronomic and environmental impacts from different management systems of long-term sugarcane cultivations is of primary importance to identify the system which most contributes to improving the sustainability of sugarcane production.
Given the above, we hypothesize that no-tillage is the system that least impacts the sustainability of sugarcane production by promoting soil conservation through minimally disturbing the soil, maintaining the soil cover and delivering ecosystem services (Lal, 2013), which would be beneficial to support a better soil physical quality in relation to the conventional cultivation system.

4.2. Conclusion

Considering the different soil tillage and management systems for sugarcane cultivation and the traditional soil physical quality indicators studied (soil bulk density, total soil porosity, soil resistance to penetration, S-index, pore distribution, water content at field capacity, gravimetric water content, available soil water), it was not possible to identify the system with the best soil physical quality. However, the soil water retention curves indicate an improvement trend in the surface layer, mainly in the no-tillage treatment with 4 Mg ha^{-1} of lime.

Visual assessments demonstrated that soil structural quality was poor and unsatisfactory in the soil subsurface of the conventional tillage system, regardless the liming status, as well as for the no-tillage system without liming, requiring immediate changes in management practices.

Results from visual assessments also suggest that no-tillage with 4 Mg ha^{-1} of lime is the system that least compromises soil structural quality. Thus, this system is considered a viable alternative for soil conservation and for environmental and economical sustainability for sugarcane cultivation, as it is able to correct soil acidity down to 30 cm, minimally disturbing the soil and maintaining the soil covered, which results in numerous benefits for sugarcane production and ecosystem services.

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5. FINAL CONSIDERATIONS

While sugarcane is acknowledged as one of the more sustainable options for biofuel production, the expansion of its cultivation areas, coupled with prevailing soil and crop management practices, has generated debates over its overall sustainability. This is particularly concerning as the cultivation methods employed by many sugarcane producers have been linked to soil quality degradation and adverse impacts on crop production. Addressing the growing global biofuel demand involves anticipated expansions in sugarcane cultivation areas. Therefore, it becomes essential that the management systems in place prioritize not only meeting this demand but also safeguarding the functioning and soil quality and ensuring economic and environmental sustainability. Hence, the second chapter of this thesis, aimed to investigate how soil quality has been addressed in research on sugarcane management, to identify gaps that need further exploration in future research. For that a bibliometric review was carried out. In addition to the existing gaps, we were able to gather information about evolution, trends, institutions, authors, research areas, most-cited articles, and co-authorship networks, information useful for directing future studies on sugarcane cultivation and sustainability.

The overall findings for this chapter shows that Concerns surrounding soil quality in sugarcane cultivation have escalated in recent years (74 % of the total of publications concentrated in the last 9 years). Brazil played a significant role in this bibliometric search, contributing with approximately 62 % of the publications, with 12 institutions and 13 authors accounting for the majority of these publications. The research areas that lead the studies are Agriculture (97%) and Soil Science (71%). Within the realm of soil science, the most frequently addressed categories were soil use and management, followed by soil chemistry and soil physics. Literature reveals gaps in studies related to sugarcane cultivated under no-tillage systems that comprehensively assess soil quality through the integration of physical, chemical, and biological indicators. This includes analyses of hydrophysical, micromorphological, and macrofauna aspects as indicators of soil quality.

Based on results of this preliminary investigation (chapter 2), the chapters 3 and 4 aimed to evaluate the functioning and quality of soil cultivated with sugarcane under different soil preparation and management systems (including conservationist systems), to identify the system that most contributes to improving the sustainability of sugarcane production. So, with a long-term trial (conducted since 1998) in which sugarcane and soybean are cultivated in a rotational system, comparing different cultivation systems (conventional tillage and no-tillage) and different doses of lime, we evaluate the functioning and quality of the soil. We started from the premise that the no-tillage system, particularly when employed alongside lime application, is the approach that has the least effect on the sustainability of sugarcane production. This is achieved by fostering soil conservation through minimal disruption, preserving soil coverage, and providing ecosystem services.

The findings for the third chapter that evaluated the effect of liming and soil preparation systems on the topsoil hydrophysical attributes like saturated soil hydraulic conductivity, soil bulk density, soil total porosity, macroporosity, microporosity, and soil resistance to penetration, shows that in general, the no-tillage system with lime application emerges as the most feasible system for conservation agriculture in sugarcane fields. This system combines the advantages of correcting soil fertility through liming with the benefits of no-tillage, enhancing hydrophysical attributes and soil structure. This contributes to soil conservation and overall system sustainability. Intermediate values of saturated hydraulic conductivity, soil density, total porosity, macro and microporosity, and soil resistance to penetration in this system create a favorable environment for improved soil hydrophysical functioning.

Corroborating with the findings of third chapter, the findings of the fourth chapter that used visual analyses of soil structure and indicators directly and indirectly related to soil structure to identify the effects of tillage and management systems on soil structural quality in sugarcane fields, also showed that no-tillage associated whit 4 Mg ha^{-1} of lime (NT4) is the system most viable for soil conservation and for environmental and economical sustainability for sugarcane cultivation. The visual assessments showed that this system presented a satisfactory soil structural quality, both on the surface and subsurface, unlike the conventional tillage system, regardless the liming status, and of the no-tillage system without liming, that presented poor and unsatisfactory soil structural quality in the soil subsurface, requiring immediate changes in management practices.

While this thesis has uncovered promising findings, indicating that NT4 may be the cultivation system that contributes the most to enhancing the productive sustainability of sugarcane fields, forthcoming research in extended experiments should encompass the incorporation of biological indicators for soil quality. This includes assessments of both micro and macrofauna, along with evaluations of soil structure using advanced 2D or 3D imaging techniques, aiming to establish a more robust scientific foundation on this subject.

Additionally, considering sugarcane's semi-perennial nature, with cultivation cycles lasting five years or more, it is recommended that future assessments of soil physical and structural characteristics be conducted throughout the entire cultivation cycle of sugarcane. This approach would provide a comprehensive understanding of soil quality under various soil tillage and management systems over time.